STRUCTURED VARIATION IN BRITISH ENGLISH LIQUIDS: THE ROLE OF RESONANCE.

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Abstract

This dissertation provides a declarative, non-segmental account of the phonetics and phonology of English liquid consonants, paying particular attention to cross-dialectal variation and the resonance characteristics associated with secondary articulation.

Liquids pose a particular challenge for current theories of phonological and phonetic constraints and representations. Phonologically, they straddle the border between consonants and vowels. Phonetically, they are made up of multiple gestures with complex acoustic output. *Clear* and *dark* are resonance attributes often associated with laterals, but they apply equally well to rhotics; different dialects have different patterns of clear or dark [l] or [ɹ]. These patterns are not restricted to the single segment.

I provide temporal and spectral analyses of newly-collected data from a representative range of varieties of British English: both rhotic and nonrhotic varieties, and varieties both with typically clear [l] and with typically dark [l]. I explore and evaluate several methods designed to tease out the spectral detail associated with resonance characteristics.

The neo-Firthian declarative phonology adopted in this dissertation is characterised by being abstract, relational and polysystemic. It expones a finely-detailed phonetics in an arbitrary but systematic manner: phonetic interpretation is structure-dependant but variety-specific. Phonetic interpretation is explicit and extrinsic: there is no phonetic content within the phonology. I claim that extrinsic phonetic interpretation provides for a felicitous account of phonetic variation and phonological abstraction. I argue that the prosodic and melodic branches of phonology should be conflated in a single hierarchical structure, leaving no equivalent to the skeletal tier or a segmental string. I propose a new abstract and nonsegmental phonological analysis of liquids in English and show how it can account for a number of instances of variation in the language.

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Author's Declaration

I hereby declare that this dissertation is entirely my own work. Some of the data and parts of the analysis in Chapters 5 and 6 have appeared in Carter (1999) and Carter (to appear).

1 Introduction

'You set too much store by those little bits at the bottom.'
J.R.Firth, quoted by Whitley (ms.).

1.1 Background

This dissertation provides a declarative, non-segmental account of the phonetics and phonology of English liquid consonants, paying particular attention to cross-dialectal variation and resonance characteristics. Conclusions are drawn concerning the nature of phonetic interpretation within the framework of declarative phonology and a partial typology of dialects will be constructed.

In particular, I show that:

- clear and dark liquids may differentiate varieties
- varieties can be arranged typologically
- the precise acoustic details of resonance vary
- resonance extends beyond the single segment
- phonetic interpretation is dependent on phonological systems in the language

1.1.1 Liquids

The term *liquid* as a cover term for laterals and rhotics originated in the Latin *liquidus*. The definition of liquidus would today be identified as phonological: the liquid consonants were fluid in their syllable affiliation (as practised in poetry). In the context of British English adopted in this dissertation I use the term straightforwardly to refer to laterals and rhotics as found in British English.

Liquids pose a particular challenge for current theories of phonological and phonetic constraints and representations. Phonologically, they straddle the border between consonants and vowels and — remaining true to the etymology of the term — have different phonetic shapes dependent on metrical position. Phonetically, they are made up of multiple gestures with complex acoustic output. Liquids are known to vary cross-dialectally and over time, both in language change and in language acquisition. This dissertation lays out the ground for an experimentally-based description and theoretical account of the phonological, phonetic and variational constraints on British English liquids by examining the phonetic detail of some of the patterns of clear and dark resonance of [l] and [ɹ] in different syllabic positions in a representative range of varieties of British English.

1.1.2 Resonance

One dimension of the cross-dialectal variation in liquids involves their *resonance* characteristics. In modern phonetic and phonological texts, the term *resonance* is most often used with the meaning of acoustic resonances in the vocal tract, otherwise known as natural frequencies, the filter component of the source-filter model of speech production. In this respect, of course, all speech sound has resonance. In this dissertation, I use the term in a more restricted sense, related to the articulatory term *secondary articulation.* Resonance in this sense refers to the quasi-vocalic quality audible in consonantal productions.

Resonance in English has most often been discussed in relation to lateral consonants; extending this discussion to liquids in general presents a useful and informative field for research. Liquids tend to pattern as a group in distributional terms and also display noticeable dialectal variation both in their distributions and in their resonance characteristics. *Clear* and *dark* are resonance attributes often associated with laterals, but they apply equally well to rhotics; different dialects have different patterns of clear or dark [l] or [ɹ].

1.1.3 Declarative phonology and phonetic interpretation

Declarative phonology research uses more constrained formalisms than derivational theories. It requires a strict demarcation between phonetics and an abstract phonology which deals with relationships and contrasts. Declarative phonology aims to produce economical non-procedural statements of phonology: there is one step between phonology and phonetics. Consequently, the mechanism of extrinsic rule-ordering (the means by which derivational phonology classically handles dialectal variation) is not available in a declarative approach.

However, very little declarative phonological work has produced detailed accounts of cross-dialectal variation. Research into variation is therefore a valuable means of testing and developing the theory.

The brand of declarative phonology which will be used in this study is one informed by the tradition of Firthian Prosodic Analysis. It is characterised by having an abstract, relational and polysystemic phonology which expones a finely-detailed phonetics in an arbitrary but systematic manner. Phonetic interpretation is explicit and extrinsic: there is no phonetic content within the phonology.

Extrinsic phonetic interpretation makes use of abstract phonological categories which are related to, but do not equate to, phonetic features. Extrinsic phonetic interpretation mechanisms are found in some contemporary frameworks, particularly in those versions of declarative phonology influenced by Firthian Prosodic Analysis. In such approaches, phonology is made up not of phonetic features but of abstract relational categories primarily concerned with contrast and not uniquely associated with phonetic events. Extrinsic phonetic interpretation forces the analyst to recognise the need for explicit phonetic interpretation since phonological categories have no intrinsic phonetic content. Phonetics is done with phonological glasses, though this is in fact the case for all phonetics. Phonologies with some degree of intrinsic interpretation have the potential to mask the need to be explicit about how any particular piece of phonetics relates to a particular piece of phonology.

In this dissertation I will argue that extrinsic phonetic interpretation provides for a felicitous account of phonetic variation and phonological abstraction.

1.1.4 Non-segmental phonology

Both phonetic and phonological analyses will be nonsegmental. Nonsegmental phonetics allows the analyst to take account of the dynamic nature of articulation and the speech signal; nonsegmental phonology permits a greater degree of sophistication in describing the distribution and domain of categories. I will argue that the prosodic and melodic branches of phonology should be conflated in a single hierarchical structure, leaving no equivalent to the skeletal tier or a segmental string.

Some recent work on resonance in liquids in English has reported on effects with long temporal extents. In this dissertation I aim to take neo-Firthian approaches down to the lowest level in that prosodo-melodic hierarchy. The effects I describe are not long-distance in the temporal sense, but are long-distance in a structural sense, since one part of structure has an effect on a 'distant' (i.e. non-adjacent) part of structure.

1.2 Layout of the dissertation

In Chapter 2 I present an apologia for declarative phonology as practised within the framework of laboratory phonology. In connection with this, I discuss the relationship between phonological theory and data and justify the use of detailed, first-hand, nonsegmental phonetics and observed variation and patterns as a starting point for phonological analysis. I also discuss the nature of phonetic interpretation both in the generative tradition and in the Firthian tradition which has led to the extrinsic phonetic interpretation which is an important aspect of much work in declarative phonology.

In Chapter 3 I review the literature on the phonetics and phonology of liquids in English, paying particular attention to work on the articulation and acoustics of liquids, their resonance quality and their nature as complex segments with both consonantal and vocalic aspects. I discuss a variety of phonological representations of liquids.

Chapter 4 introduces two experiments designed to investigate the role of resonance in liquids in a number of varieties of English.

Chapter 5 outlines the experimental method.

In Chapter 6 I present and discuss spectral and temporal results from Experiment 1 on liquids and syllable structure in rhotic and nonrhotic varieties of English, incorporating the technique of cluster analysis. I will show that the data echo the polarity effect identified by Kelly & Local (1986, 1989), by which varieties with a relatively clear syllable-initial lateral have a relatively dark syllable-initial rhotic, and vice versa. However, I identify a fundamental difference between rhotic and nonrhotic varieties, with the phonetic interpretation of onset liquids dependent on the liquid contrasts which obtain in the (structurally non-adjacent) rime of the syllable. Whatever their absolute resonance quality, the relationship between onset liquids in rhotic varieties resembles the relationship between onset liquids in the nonrhotic variety which has a clear lateral.

In Chapter 7 I present a dynamic analysis of the spectral details of Experiment 2, which was designed to examine in more detail the resonance quality of liquids in the syllable onsets of nonrhotic varieties. I also propose, on the one hand, classification and regression trees and, on the other hand, spectral moments analysis as useful tools for investigating resonance in liquids. As in previous chapters, F2 (along with measures based on F2) is identified as the major acoustic locus for resonance variation.

In Chapter 8 I develop a phonological analysis of English liquids. I suggest that the data are best accounted for by an abstract phonology with an extrinsic phonetic interpretation mechanism which has the potential to differentiate (polysystemic) phonological categories. I use the temporal analysis to deduce information about the phasing of articulatory gestures and call into question previous analyses based on intrinsic content of syllable structure. I argue that liquid resonance is not determined simply by proximity to the syllable nucleus, but by extrinsic specification which is variety-specific as well as structure-dependent. I propose and evaluate a set of phonological attributes which is more abstract than previous declarative analyses and discuss how those attributes might relate to prosodic structure. I apply this analysis to data drawn from examples of contemporary variation in British English.

Chapter 9 concludes the dissertation with a discussion of some of the implications of the research and suggestions of possible directions for future work.

2 Phonological background

This chapter outlines the theoretical background to the phonetic and phonological analysis presented in this dissertation.

I begin with a discussion of laboratory phonology, examining the sort of data which phonology treats. Declarative phonology is then introduced and its formal advantages in comparison with procedural phonologies are outlined. Throughout the chapter I identify links with Firthian Prosodic Analysis, which may be seen as the first generation of declarative phonology. The intensional and abstract nature of the phonology I adopt is outlined, with particular attention given to the concomitant requirement for extrinsic phonetic interpretation. I then outline the non-segmental and polysystemic nature of the phonology I use.

2.1 Laboratory phonology

2.1.1 Phonology in the laboratory

The term Laboratory Phonology has come to prominence through a series of conferences and the published papers from those conferences (Kingston & Beckman, 1990: Docherty & Ladd, 1992; Keating, 1994; Connell & Arvaniti, 1995; Broe & Pierrehumbert, 2000; Local *et al.*, to appear). The research field has blossomed in recent years thanks to a rediscovery of the value of detailed empirical phonetic research in combination with phonological theorising. Kingston & Beckman, in their (1990:1-16) introduction, trace how phonetics and phonology moved from being synonymous terms for the investigation of speech to being separate and mutually distrusting academic disciplines. Laboratory phonology is offered as a plea for reconciliation in the feuding family which is the science of speech sounds. Where formal advances in phonology and technological advances in phonetics once served to cleave the discipline apart, now researchers are keen to bring it back together again.

This concern for linking linguistic theory with close attention to empirical phonetic detail is identified as 'linguistic-phonetic investigation' in Local *et al.*'s (to appear) introduction to a recent collection of laboratory phonology papers. Local *et al.* explicitly connect the laboratory phonology approach to the aims of the Firthian linguists:

> '... over 40 years ago the linguist, phonetician and phonologist J. R. Firth wrote of taking "linguistics into the laboratory" (1957[a]:25). The point of doing this, Firth was at pains to emphasise, was not to engage in an "experimental phonetics" ("a very different scientific procedure") but rather to support the exploration of the relationships between phonetics, phonology and the "grammar" of language. Revisiting this matter in 1959, he writes: "The linguist will, of necessity, have in mind tentative analysis at the phonological and grammatical levels, and unless the results of laboratory experiments throw light on findings at these levels there is no profit in them ..." (Firth 1959:34-35).'

Although Broe & Pierrehumbert, in their (2000:1-7) introduction allude to the emergence in the laboratory phonology community of 'a theory of phonology' (p.7), their comments more accurately refer to a theory of how to do phonology. Indeed, Pierrehumbert *et al.* (1996:535-6, 2000:274) are keen to point out the diverse theoretical backgrounds of contributors to the laboratory phonology series. In this regard, Declarative Phonology (the theoretical background of this dissertation) has been identified as a useful framework within which to carry out the enterprise of laboratory phonology, as Pierrehumbert (in Bird *et al.*, 1992) comments:

> 'Phonologists who work in the laboratory do not fall into any particular theoretical school. However, many laboratory phonologists are likely to find declarative phonology congenial because of its empirical orientation, and the capability it provides for building and testing models.'

2.1.2 Phonology and data

Linguistic signs, including phonological representations, within a declarative formalism are descriptions of linguistic objects and, as such, are a product of the relationship between theory and data. In this section, this relationship will be explored and it will be claimed that theory and data are not and cannot be independent of each other. Phoneticians and phonologists must therefore be aware of the theoretical assumptions they and others make. A theoretical background is always implicit in experimental questions; I aim to make it explicit.

At first glance, it would seem to the casual outside observer that the set of linguistic theories and the set of linguistic data are mutually exclusive, and that relationships between the two are arbitrary in the Saussurean sense. Data lead to the induction of theories which, in turn, are used to predict hitherto unanalysed (and independently existing) sets of data. The degree of success in prediction is taken to be an evaluation metric of the theory.

On closer inspection, however, it becomes clear that the state of affairs outlined in the preceding paragraph does not correlate well with the actual development of linguistic theory. Robins (1990:3) points out that

> '"The facts" and "the truth" are not laid down in advance, like the solution to a crossword puzzle, awaiting the completion of discovery. Scientists themselves do much to determine the range of facts, phenomena, and operations that fall within their purview, and they themselves set up and modify the conceptual framework within which they make what they regard as significant statements about them'.

Note also a comment by Ladefoged (1990:344):

> 'For the phonetician there is no universal truth independent of the observer'

and Firth (1968a:30):

> '... there are no scientific facts until they are stated ... The common view of facts as brute and basic ultimates for everybody is misleading.'

Indeed, it seems as if an awareness of this relationship between theory and data in linguistics goes back at least as far as Saussure (1916:23),

> 'Bien loin que l'objet précède le point de vue, on dirait que c'est le point de vue qui crée l'objet, et d'ailleurs rien ne nous dit d'avance que l'une de ces manières de considérer le fait en question soit antérieure ou supérieure aux autres'.

although it must be noted that Saussure was primarily referring to the use of distinct linguistic levels of analysis, rather than to researchers using different theoretical constructs. Nevertheless, the various methods of analysis employed in, for instance, phonetics, semantics and etymology (Saussure's examples) are every bit as distinct as are approaches based on competing theories.

It is not data which lead to the induction of theories, but the examination of data. Data are observed from within a particular 'conceptual framework' which, in turn, derives from theoretical predictions. Such frameworks define how phonetic data are used as evidence to support theories. For example, in Firthian Prosodic Analysis, syntax and morphology have a large role to play (this is the congruence of levels). A Firthian phonologist might, for example, observe that a certain language (Spanish is a good example) has a relatively restricted set of syllable-final consonants (all apicals in this case); a Government phonologist would not allow the data to be presented as evidence in this way since there can be no such thing as a syllable-final consonant if there is no such thing as a syllable (as is the case in Government Phonology).

If data is unavoidably bound to the theory under which it was observed, then it is also true that precisely what counts as evidence in differing theories is rarely the same. In much phonological work, one researcher provides the data, usually in a broad segmental phonetic transcription. The preliminary analysis (almost always segmental) implicit in this transcription is then carried on into the phonological analysis, whether produced by the same researcher or not. Some features may become autosegmental, but the aim is still to generate the final output string, which is still segmental on the skeletal tier and broadly phonetic in nature. The purpose of an autosegmental analysis is to provide an account of similarity of features between segments. Compare this to the approach taken in Kelly and Local (1989) in which first-hand, nonsegmental data are paramount, and someone else's broad transcription is simply not adequate as data.

If it is accepted that data do not exist entirely independently of the theories which are used to analyse them, it follows that it makes little sense to reinterpret in terms of theory Y data originally presented within the context of theory X. The data will have something of theory X inherent in their expression, thus jeopardising the independence of theory Y with respect to theory X. The range of hypotheses in theory Y which might be entertained about the data will necessarily be limited by the form in which the data are presented under theory X.

So, for instance, Scobbie (1993a,b) analyses some aspects of Imdlawn Tashlhiyt Berber syllable structure. His purpose in so doing was to demonstrate that Declarative Phonology could account more neatly for the data presented than could Optimality Theory (Prince & Smolensky, 1993). Scobbie reinterprets Prince & Smolensky's data, which in turn was second-hand (the data were originally presented in Dell & Elmedlaoui, 1985, 1988). Scobbie was well aware of this but, in common with many linguists, seemed to overlook the theoretical bias inherent in any set of data in order to further his theoretical argument. Coleman (1996) argues along similar theoretical lines to my own, and provides his own declarative analysis of syllables in Tashlhiyt Berber based on first-hand data rather than a reinterpretation of data originally presented under an incompatible theory. By doing so, he allows himself to hypothesise that Dell & Elmedlaoui's syllabification may not be the most felicitous (an option not available by Scobbie's reanalysis method). Indeed, comparison with closely related dialects and close inspection of first-hand phonetic data (such as the variable presence of 'intrusive' vowels and the resonance quality of consonants) leads Coleman to suggest precisely that an alternative syllabification with vowels as well as consonants is appropriate, and the Berber words which appear to contain only consonants can be analysed as instances of coproduction between consonant and vowel. Scobbie has, in fact, since revised his position on the use of first-hand phonetic data in phonological argumentation. He comments (Scobbie, 1997:xvii):

> 'I've become convinced that an even greater reassessment of the basics is required. Phonological data is often shuffled around, like a strange game of Chinese whispers. It seemed perfectly respectable to produce a phonological dissertation ... where real speech data is absent and where no checking of the analysis against a corpus is performed. This now seems merely expedient. ... We all owe it to ourselves as phonologists to be a little more scrupulous about our raw materials.'

The nearest it is possible to get to avoiding this theoretical independence problem is to analyse as much data as possible without a priori discarding any as 'redundant'. The sizeable phonetic literature on acoustic cues, their nature and relationships, bears witness to the fact that the speech signal is informationally rich and includes what appears to be a considerable amount of redundancy. Within much phonology, the 'redundancies' are simply discarded as predictable at an early stage in the analysis (compare the Firthian concept in which abstraction does not *remove* data from the phonic stream). If one is to make allowances for looking through theoretically-tinted spectacles, then the data seen through those spectacles should be as detailed as possible. This is the line of argumentation taken in Kelly and Local (1989: for example, p.26, p.149ff.), allowing for such insights into phonetic and phonological patterning as have been demonstrated by Ogden (1997b), who shows how a reexamination of primary data in great detail can lead to a felicitous account of phonetic variation in function words.

The independence problem is also eased by theoretical explicitness: it is imperative that theoretical analyses are formal and explicit, enabling the analysis to be easily deconstructed by other researchers.

In addition to ensuring the quality of the data, theory must be defined from its own primitives rather than from those of rival theories. If data excised from its original theoretical context can threaten the validity of its analysis in terms of another theory (since some of the original theoretical analysis is necessarily inherent in the data as presented), then also the very description of a theory in terminology pertaining to another is a dangerous enterprise. Support for this argument can be found in Ogden & Local's (1994) criticism of Goldsmith (1992), in which Goldsmith reinterprets FPA (intending to be positive) in terms of Autosegmental Phonology, with the aim of demonstrating that there are cross-paradigm links. Firth (1968a:27-28), in fact, also identified this danger:

> [there is a tendency] 'to equate American supra-segmental phonemes ... with the British use of the word *prosodies*, or indeed the American phoneme and what I may call the 'Joneme' [Daniel Jones's theory of the phoneme — see Abercrombie (1991:46) on Firth's jocular use of the term 'joneme']. This sort of thing does not help the student much.'

In this spirit, the remainder of this chapter will outline my own theoretical phonological background.

2.2 Declarative phonology

In this section I will outline some of the background to Declarative Phonology and the advantages of Declarative Phonology in comparison with procedural phonologies. Then I will go on to discuss the intensional, non-segmental, polysystemic and abstract nature of the phonology adopted in this dissertation.

Since the early 1990s, several works have been published explicitly within a DP framework. The papers in Bird (1991) and Ellison & Scobbie (1993), along with Bird (1990, 1995), Bird and Klein (1994), Coleman (1991 and later works), Local (1992 and later works), Ogden (1992 and later works), Scobbie (1991a and later works) and Simpson (1992a) are examples in the field.

Bird & Klein (1994:3) claim that a constraint-based phonology 'represents a fundamental split with the generative tradition' but it is perhaps more accurate to claim it as a fundamental split from generative *derivational* phonology.

2.2.1 Background to Declarative Phonology

Declarative phonology grew out of unification grammar as exemplified in approaches such as Generalised Phrase Structure Grammar (Gazdar *et al.*, 1985) and Head-Driven Phrase Structure Grammar (Pollard & Sag, 1987, 1994) but some declarative phonologists are also deeply influenced by Firthian Prosodic Analysis, a framework which shares Declarative Phonology's monostratal characteristic of static representations. Broe (1991) identifies a strand of theory from the Firthians through Halliday to the unification grammar tradition, but it is particularly in the work of Local, Ogden and Simpson that the Firthian influence is greatest.

It is possible to identify a general trend in more recent mainstream phonological theory which encompasses a movement away from a system of rules towards a system of constraints on surface forms: Scobbie (1991b) gives just such an interpretation of the history of generative phonology. Generative Phonology began with a wholly rule-based approach which generated strings of segments but, over its three or four decades of development up to the present, there has been increasing use of surface-level phonotactic constraints as a means of accounting for apparent 'rule conspiracies' (in which formally unrelated rules acted together to produce some easily identifiable aspect of surface phonotactics). This development has culminated during the last decade in the expression of Optimality Theory, in which phonological phenomena are depicted as entirely an interaction of constraints. Optimality Theory is currently the most widely used constraint-based theoretical phonological framework.

Optimality Theory involves the selection of phonological outputs from a pool of candidate outputs by the interaction of a set of violable constraints. The constraints are typically (though by no means always) expressed as negative constraints, barring particular structures from appearing as surface forms. Grammatical variation is accounted for by variable ranking of the constraints, so that the effect of a more highly ranked constraint will outweigh the effect of a constraint placed lower in the hierarchy. However, McMahon (2000) has shown how it is not always the case that the reranking of constraints can adequately account for variation and change in language.

Practitioners of Optimality Theory claim that it is non-derivational because inputs are not actually changed during the course of the production of an output; rather, the output is merely selected from the set of candidates.

However, there are two aspects of Optimality which reveal that it is essentially equivalent to a derivational theory. Firstly, the postulation of negative constraints (of the form *ABSENT STRUCTURE) shows that constraints are methods of expressing rule conspiracies: Optimality constraints are filters on the output of some other component of the grammar. This is a necessary situation if constraints are negative, since filters must filter something out: candidate outputs have to be generated first in order to test them against negative constraints.

Secondly, the extrinsic ranking of constraints is formally equivalent to extrinsic rule ordering (see, for example, Karttunen, 1998). A simple example to illustrate this observation is found in a paper from the Laboratory Phonology series, Steriade (2000:325), in which American English alternations such as *atom* [ˈærəm], *atomic* [əˈtʰamɪk], are analysed in terms of the interaction between two constraints, FORTITION (‘consonants are realised with increased closure duration at the onset of stressed syllables’) and TAPPING (‘alveolar stops are tapped in intervocalic contexts, where tap refers to: extra-short duration of closure, lack of a concomitant jaw raising gesture and lack of a glottal opening gesture’). FORTITION outranks TAPPING, resulting in the situation depicted in the tableaux in Figure 1.

	/atómic/	FORTITION	TAPPING
☞	əˈtʰamɪk		*
	əˈɾamɪk	*!	

	/átom/	FORTITION	TAPPING
☞	ˈæɾəm		
	ˈætəm		*!

Figure 1. OT-style tableaux for instances of F*ORTITION and* T*APPING (adapted from Steriade, 2000:325).*

In the case of *atomic*, the candidate form [əˈɾamɪk] violates FORTITION and is therefore rejected despite the fact that the alternative form [əˈtʰamɪk] violates TAPPING. It is as if, once the higher-ranked constraint is implemented, the remaining constraint is no longer relevant since it is of lower rank. In the case of *atom*, neither candidate violates the higher-ranked constraint, FORTITION, since neither has a consonant in the onset of the stressed syllable. Attention is then paid to the lower constraint, and [ˈætəm] is rejected since it violates TAPPING.

This analysis is formally equivalent to a pair of extrinsically-ordered context-sensitive rewrite rules: say, F and T as in Figure 2.

$$\text{(F)} \qquad t \rightarrow t^h \;\Big/\; \overset{\sigma_s}{\underset{O}{|}}$$

$$\text{(T)} \qquad t \rightarrow ɾ \,/\, V \_\_ V$$

Figure 2. Rule-based equivalent of Figure 1.

Rule F is ordered earlier in the derivation than rule T. In the case of *atom*, rule F does not apply, and the grammar moves on to rule T, which causes flapping. In the case of *atomic*, however, rule F adds aspiration to the alveolar plosive, thereby bleeding rule T of its context. The constraints violated by the optimal candidate (which do not have an impact on the output because of the satisfaction of higher-ranked constraints) are equivalent to the rules which do not apply to an underlying form (thereby having no impact on the output) because of the application of earlier rules in the derivation.

Ranking of violable constraints is therefore equivalent to rule bleeding (Kiparsky, 1968:198ff); but it is also equivalent to rule feeding (Kiparsky, 1968:196ff), since candidate forms also exist which are equivalent to the output of early rules and to which lower-ranked constraints may be relevant. The technical advantage of Optimality is not that it removes the mechanism of extrinsic rule ordering, but that it collapses the two effects of extrinsic rule ordering (bleeding and feeding) into a single account (ranking of constraints). However, it does so at the cost of producing a candidate set which may be infinite or, given conservative estimations, at the very least impracticably large (Walther, 2001).

Optimality replaces derivational rules with a formally equivalent system of constraints; it is therefore no more *constrained* as a grammar mechanism than its derivational predecessors.

2.2.2 Advantages of Declarative Phonology

Declarative approaches to phonology have increased in popularity in recent years (see for example Bird, 1991), at least in part following an acknowledgement that derivational theory is excessively powerful (Coleman, 1995) and, moreover, does not lend itself easily to computational implementation (see, for example, Coleman, 1998; Local, 1992 and the references therein; on a related point, see also Walther, 2001, on how the mathematics of the standard Optimality mechanism of Correspondence makes OT analyses completely impractical to check manually). The rewrite rules in derivational phonology involve deletion and cyclicity, resulting in an unrestricted grammar. See Coleman (1995, 1998:77ff) for a detailed argument against the appropriateness of an unrestricted grammar of this type.

There may also be cognitive psychological problems with derivational (non-monotonic) theory (which permits structure change), since structure change is equivalent to deletion (followed by addition), and deletion amounts to destruction of information. If information is destroyed during the generation of a surface form, it is unclear how that information might be rebuilt in the mind of the hearer. In terms of derivational rules, if the grammar contains a rule such as (2.1):

(2.1) ɹ → ∅ / V __

then, presented with the output [pɑː], a perception mechanism can only produce the underlying form [pɑː(ɹ)*], that is, there is no way of telling whether the input was [pɑː] (i.e. *pa*),[pɑːɹ] (i.e. *par*), or even [pɑːɹɹ]. While the grammar may be constrained to have as few rules as possible, from the point of view of the perceiver it is not obvious how to tell how few rules count as 'as few as possible'.

Declarative Phonology, on the other hand, is monotonic: only structure-building operations are permitted. Constraints in Declarative Phonology, unlike the negative constraints often found in Optimality Theory, are positive, constructive and compositional. Constraints are partial descriptions of linguistic objects: there is no need to pre-generate candidate output forms (as in OT), since the forms themselves are simply constructed by the composition of a set of constraints. Information may only be added to a representation; information may never be taken away. Declarative Phonology is therefore agnostic with respect to implementation: it is equally adequate for production and perception. Moreover, in offering representations which form partial information about linguistic objects, Declarative Phonology necessarily involves underspecification. Composition of constraints reduces the underspecification and adds information.

Researchers developing monostratal approaches have shown that it is possible to avoid the problems endemic in derivational analyses by describing utterances at a single level rather than in terms of rules which alter representations of lexical entries. Nevertheless, it is important to note that the Declarative Phonology employed here is formal and nominalist: no claims are made as to the extent of its psychological reality, although the theoretical formalism is not of itself incompatible with cognitive approaches. Indeed, Hawkins & Smith (2001) have begun to explore how a polysystematic declarative linguistic formalism might relate to psychological and neuropsychological experimental data.

2.3 Intensional and abstract phonology

2.3.1 Intensional phonology

One characteristic which sets declarative phonology apart from mainstream generative phonology is that it is intensional rather than extensional in nature. Phonology is not a matter of organisation of linguistic objects; it is a description (in the geometric sense) of the set of linguistic objects. This view is prefigured by the work of the prosodic analysts. For example, Firth (1948a) makes the point that phonology is about relationships between sets, rather than the content of the sets themselves:

> 'We must distinguish between such a conceptual framework, which is a set of relations between categories, and the serial signals we make and hear in any given instance.'

In this way, the relationship between phonology and phonetics can more easily be construed as a semantic relationship (Pierrehumbert, 1990:380), with the phonology-phonetics relationship being akin to that between lexical items and the concepts they denote.

Each phonological statement within declarative phonology is a partial description of the linguistic object being studied. This partiality interacts with the monotonic nature of the grammar under composition: the meaning of a phonological expression is the sum of the meaning of its parts and the rules for combining the parts (the unification of partial descriptions). In the composition of more complex phonological statements, the set of objects described is refined as pieces of information (other partial descriptions) are added. The grammar is still monostratal, since composition (a more suitable term than 'addition of information', since it does not imply the existence of an underlying form of some kind to which more is 'added') may occur in any order with the order making no difference to the results. In this sense, there are no more levels than the single level of phonological description.

Since Declarative Phonology is compositional, there is no sense in which previously generated forms are checked against negatively-expressed constraints (as they would be in Optimality

Theory). The constraints in Declarative Phonology *are* the representations. Phonological forms are built up from the composition of partial descriptions, known as constraints.

2.3.2 Abstract phonology

An intensional phonology is, by its very nature, going to be abstract. Intensional phonology is about describing sets of linguistic objects. Even when constraints are unified with each other to describe smaller subsets, then phonology remains a description of sets of objects. There is no point at which the description of sets becomes the content of the sets themselves.

Phonological categories are then labels for the sets, and are therefore not of the same nature as the linguistic objects, although they may be named according to some mnemonic scheme to remind the analyst of the content of the sets.

A consequence of this view is that variability can be built into the content of the sets, allowing straightforwardly for shifts over time (such as the move from [ɹ] to [ʋ] in many varieties of British English) and the knowledge children must develop to acquire their native (variety of a) language. See, for example, Docherty & Foulkes (2000) who, as a result of work on phonetic detail in varieties of British English, wonder (p.120)

> ‘whether the statistical information that is amassed will over time lead language-acquirers to reason that there may be abstract categories underlying the complex representations that they have amassed’.

The ‘statistical information that is amassed’ involves knowing what in the speech stream is comparable with what. What, for example, is comparable with [l]? Is [ɫ]? Or [ɹ]? The acquirer of language must learn what relationship [l] has to [ɫ] and to [ɹ]. The acquirer is then necessarily hypothesising abstract sets as categories. The process of phonological acquisition would then involve postulating relationships between the sets and learning the content of each set. The phonological quest for a minimal set of universal distinctive features or elements is taken to its logical conclusion in focussing solely on the contrast and the relationship rather than the phonological objects themselves. There would then be no universals in phonology, except perhaps for the existence of sets in contrast: $\exists xy, x \neq y$.

In the Firthian tradition, there is a compounding motivation for abstractness in phonology: the structuralist view of meaning in context. Firthian analyses are based around *terms* in *system*: the same item does not have the same value in a two-term system as it does in a three-term system. However, as Sprigg (1957:107) acknowledged, even the analyst's phonetic description of the data is an abstraction:

> 'Since all abstractions at the phonological level, whether prosodic or phonematic, are stated through the medium of *ad hoc* systems, and the value of each term in a system is in proportion to the total number of terms in that system; it is clear that the phonological symbols are purely formulaic, and in themselves without precise articulatory implications. In order therefore to secure "renewal of connection" with utterances, it becomes necessary to cite abstractions at another level of analysis, the Phonetic level: abstractions at the Phonetic level are stated as criteria for setting up the phonological categories concerned, and as exponents of phonological categories and terms.'

A truly formal phonology would consist of entities and relationships; names matter for nothing. Phonology is then to do with relations between sets of things, rather than the things themselves, directly. But a Hjelmslevian (1953) expression-plane algebra is not sufficient: there must be detailed exponency statements to relate the phonology back to the phonic substance, so that the phonology is a phonology *of something* (Anderson, 1985:183). Note particularly the Firthian insistence on continually returning to the phonic data in order to justify an analysis — this they called 'renewal of connection' (see, for example, Sprigg, 1957, 1961). Firth (1968c:17), in discussing the necessity for renewal of connection after making abstractions, refers to Whitehead (1938). Whitehead comments (p.2) that

> '[system] is necessary for the handling, for the utilisation, and for the criticism of the thoughts which throng into our experience',

a notion which corresponds well with Firth's (1957a:XII) belief that

> 'an isolate is always an abstraction from the language complex which is itself abstracted from the mush of general goings-on.'

However, Whitehead also notes (p.121) that '[abstracted relations] require for their full understanding the infinitude from which we abstract' and (p.147) 'if we forget the background, the result is triviality.' Whitehead admits of a circular process of abstraction and returning to substance (pp.169-170):

> 'it is interesting to note that in the entertainment of abstractions there is always present a preservative instinct aiming at the renewal of connection, which is the reverse of abstraction ... there is the sense of realities behind abstractions ... there is the process of abstraction arising from the concrete totality of value-experience, and this process points back to its origin'.

If phonology is to be abstract, then its connections to the phonetic level need to be carefully defined.

An intensional basis to phonology (as outlined in Section 2.3.1) in which phonological categories are labels for sets which describe phonetic objects necessarily means that phonological categories are abstract. They may be labelled in a mnemonic fashion, as a shorthand for the content of the sets they describe, but phonological entities (the sets) are a fundamentally different sort of thing from phonetic entities (the content of the sets). In this view, phonetic interpretation cannot be intrinsic to the phonological category.

2.3.3 Extrinsic phonetic interpretation

Recent attempts to articulate coherent theories of non-segmental and non-linear phonology have encouraged a re-examination of the relationship between phonetics and phonology (Beckman, 1991; Browman & Goldstein, 1989; Clements & Hertz, 1991; Harris & Lindsey, 1995; Keating, 1990, 1995; Local, 1992; Ogden, 1992). Researchers are increasingly paying attention to ways of providing a robust phonetic interpretation which accounts for the observable detail in the speech signal (Hawkins, 1995; Local, 1995b).

In this section I will sketch some of the interpretative mechanisms in other phonological theories before justifying extrinsic phonetic interpretation in a declarative phonology. Firstly I examine phonetic interpretation in classical generative phonology and the subsequent tradition. Then I discuss phonetic interpretation in two recent phonological theories which provide a serious account of phonetic interpretation, namely Articulatory Phonology (Browman & Goldstein 1989) and Government Phonology (Kaye *et al.*, 1985, 1989, 1990; Kaye, 1990; Harris & Lindsey, 1995). These two theories are particularly appropriate to examine in the light of declarative phonology, since they both seek to account for phonological phenomena by general principles and parameters (such as hiding of gestures or government of structural positions) rather than by extrinsically ordered rules of some kind. However, in Government Phonology, elements may be 'delinked' from structure. Since elements are never re-linked, delinking seems to give Government Phonology equivalent power to the structure-changing rules of classical generative phonology.

2.3.3.1 Phonetic interpretation in the classical generative phonology tradition

The presence of derivations in a generative grammar leads to one of three states of affairs in the grammar:

(i) a phonological representation is at some stage somehow changed into a phonetic representation, or
(ii) the rules operate only on phonetic representations, or
(iii) the rules operate only on phonological representations.

Note that even the phonetic symbols are just symbols in need of interpretation (Keating, 1990; Coleman, 1998).

Hayes's (2000) analysis of alternation in the resonance of laterals in English provides an example of the confusion between phonetic and phonological levels: despite all Optimality constraints supposedly being constraints on the output, there is variation in the type of brackets used. So, one of Hayes's constraints, PRETONIC /l/ IS LIGHT uses phonemic slash brackets while another, DARK [ɫ] IS POSTVOCALIC, uses phonetic square brackets. However, the prosodic structure which reveals the pretonic nature of phonological /l/ does not *precede* the prosodic structure which reveals that the phonetic lateral is postvocalic, as would be the case if the phonetics is derived from the phonology. Following this process, there will inevitably be stages at which parts of the representation (such as postvocalic [ɫ]) are phonetic while other parts (such as pretonic /l/) are still phonological.

If phonetics and phonology are prohibited from existing in the same string, it would be possible to apply only one phonology-to-phonetics rule to any given underlying form. A consequence of this is that extrinsic rule ordering (a set of rules are extrinsically ordered if their output differs depending on the ordering of the rules so that the order is not intrinsic to the nature of the rules themselves), or extrinsic constraint ranking, as discussed in Section 2.2.1 would be barred. Phonology and phonetics would then be kept apart and any other rules could apply either only to phonology or only to phonetics. If there were no other rules apart from those which convert phonology to phonetics, then the result would in effect be a declarative grammar, comprising a phonological form with exponency statements (of phonetic interpretation).

In effect, therefore, derivational rules change phonological entities into phonological entities, with no word as to how the final output "surface form" should be interpreted phonetically.

The current mainstream (generative) paradigm of phonological work came to the fore with the publication of Chomsky & Halle (1968). Chomsky & Halle's phonology claims to keep distinct its phonological matrices and the phonetic matrices which are the output of the phonological component of the grammar. The distinctive scalar phonetic features are universals but their precise physical manifestation depends on their context.

However, in Chomsky & Halle's approach, phonetic interpretation is of a firmly intrinsic nature. They (p.295) claim that arbitrary phonological features would lead to *ad hoc* rules and an inability to generalise about rules applying to sets of phonetically similar items. However, phonological representations must be abstracted away from phonetic representations in order to account for variation in the phonetics due to context. Phonological representations are 'abstract in the sense that the phonological representation is not necessarily a submatrix of the phonetic representation.' (p. 297). This is not abstractness in the declarative phonology sense since phonological and phonetic representations are of the same substance: phonological representations *could* be submatrices of the phonetic representations.

Chomsky & Halle reject extrinsic interpretation of phonological categories, although they describe an unsophisticated concept of extrinsic interpretation. They describe the filling in of 'empty' categories (p.169) which are then subject to entirely redundant rules which effectively do little more than change the names of the categories from the arbitrary A, B, etc. to the more phonetically recognisable [vocalic], [consonantal] and so on.

McCawley (1967, 1972) points out the need for a 'feature interpretation component' associated with the Jakobsonian feature set (Jakobson *et al.*, 1952), in order to fill in non-distinctive values for features, predict which phonetic values were appropriate in which context (his example is the decision between labialisation and pharyngalisation associated with [+flat]), and provide rules to realise the features as physical values. Having intrinsic content in the features leads to a repetition of statements in the feature interpretation component.

Bromberger & Halle (1989:53) admit that derivational rules change one set of phonological entities into another set of phonological entities, although they claim that their phonology has intrinsic phonetic content:

> 'Phonology ... is primarily concerned with the connections between surface forms that can serve as input to our articulatory machinery (and to our auditory system) and the abstract underlying forms in which words are stored in memory ... phonology is concerned with the relationship between *representations that encode the same type of information* — phonetic information — but do so in ways that serve distinct functions: articulation and audition, on the one hand, and memory, on the other'. (emphases added)

Note that Bromberger & Halle's 'surface forms' are, in fact, still an input to phonetic mechanisms. Nevertheless, they adopt an extreme intrinsic interpretation hypothesis which would be called into question by any serious examination of phonetic data. For them, segmental representations represent the (supposedly) essentially segmental nature of speech (p.54). All specified features are 'linguistically significant' and mostly are 'actualised' by a single articulator so, for example, [voicing] is supposed to be always implemented by the larynx. Here there is a confusion between the linguistic significance of phonological contrast and the way in which contrasts are signalled in the phonetics which, when coupled with their strict view on intrinsic interpretation, necessarily leads to unsupported (and, indeed, unsupportable) claims such as 'when producing consonants, English speakers do not deliberately round the lips or spread them' (p.55) as a motivation for the non-use of the feature [round] in contrastive representations of English consonants. Their argument may lead to more appropriate representations of contrasts in the phonology of English, but it sits somewhat uncomfortably with phonetic observations in examples such as the presence of lip rounding in English productions of (amongst other consonants) [ɹ], [ʃ] and [w] (Brown, 1981).

2.3.3.2 Phonetic interpretation in articulatory phonology

Another possible status for phonological rules is that the rules describe only phonetic information, rather in the manner of Articulatory Phonology (Browman & Goldstein, 1989, 1990, 1992), in which the phonology is comprised of a gestural score with each articulator operating semi-independently from the others. A gesture is an abstract characterisation of the input to a task-dynamic model of articulator movement (see Hawkins, 1992, for an introduction to task dynamics in speech). The parametric nature of an Articulatory Phonology gestural score means that it is non-segmental.

From an intensionalist perspective, there seems to be some confusion about the units of phonology. In an overview article, Browman & Goldstein, (1992:156) say that

> '... gestures are basic units of contrast among lexical items as well as units of articulatory action ... phonology is a set of relations among physically real events, a characterisation of the systems and patterns that these events, the gestures, enter into.'

If different gestures are different phonologies then if different speakers adopt different articulatory strategies (such as bunched versus retroflexed [ɹ] in American English or postalveolar [ɹ] versus labiodental [ʋ] in British English) then their phonologies are presumably different since they have different gestures. It then becomes difficult to know what a phonology might be at any level other than the idiolectal. If, on the other hand, phonology is a set of *relations*, then its atoms are presumably not the *objects* connected by those relations.

Where parametric phonetics represents the *output* of a task-dynamic model, the actual movements of the articulators, the gestural score is more abstract: it represents the *input* to a task-dynamic model. To the phonetician, the Articulatory Phonology approach is appealing as it describes a much greater detail of phonetics than its rivals. In so doing, however, the nature of phonology as a system or systems of relations and contrasts risks being lost. Indeed, in discussing contrasts, Articulatory Phonology may resort to phoneme-like segments (see, for example, Gick, to appear, on liquids). Articulatory phonology is an extreme example of a phonology having an intrinsic phonetic interpretation: the gestures themselves are the phonology. However, if phonology comprises the set of relations between phonetic objects (such as knowing that [ɹ] is not [l]), then a gestural score could be the interpretation of the phonology (allowing for the variants [ɹ] and [ʋ]) and an input to a phonetic model of articulator movement.

Such an approach would also have the advantage of more clearly separating the criteria for setting up phonological categories (see the quote from Sprigg in Section 2.3.2) and their exponents in the phonetics, since actual observable articulatory movements could count as criteria and the more abstract gestures could then be exponents of the phonological categories which are set up.

In one sense, my argument is simply for a redrawing of the boundaries between phonetics and phonology, with a gestural score being classed as phonetic rather than phonological. But even a simple redrawing of the boundaries between phonetics and phonology can help to relieve the confusion of analytic levels which often ensues when an attempt is made to make phonology simultaneously contrastive and intrinsically full of phonetic content.

2.3.3.3 Phonetic interpretation in government phonology

Phonetic interpretation within Government Phonology is dependent on the 'autonomous interpretation hypothesis', according to which phonological items ('elements') are interpretable at any stage in the derivation: phonological primes are 'small enough to fit inside segments, yet still big enough to remain independently interpretable' (Harris & Lindsey, 1995:34). Element theory departs from feature theory in that individual features such as [high] cannot be interpreted in isolation from other features. Elements (privative subsegmental primes), on the other hand, can be interpreted both individually and in combination.

Early versions of the theory of Government Phonology (such as Kaye *et al.*, 1985:306) in which elements were (or, at least, could be) translated into fully-specified feature matrices have been abandoned, since what might be termed sub-elemental features would not be autonomously interpretable.

Although elements are couched in acoustic terms, they are cognitive objects (encoding lexical contrasts) rather than acoustic events: elements are always interpretable rather than pronounceable. In this way, derivations involve only phonology and any part of the derivation is as interpretable as any other part. The theory aims to account for alternations and distributions as generally as possible. In this sense, it is genuinely a theory of phonology, with an associated theory of phonetic interpretation.

Phonetic interpretation in Government Phonology has an intrinsic aspect to it, in that each element has its own typical acoustic realisation, most of which are universal. However, these realisations are only gross patterns, enabling combinatory mechanisms to apply, overlaying the patterns on top of each other, while maintaining autonomous interpretation. The patterns are easiest to see in the so-called resonance elements, as in Figure 3 (adapted from Harris & Lindsey, 1995:53), in which mnemonics are given for remembering the patterns. The patterns are schematic spectra, with frequency on the abscissa and amplitude on the ordinate. The lines represent part of the spectral envelope; the region of greatest spectral energy is the frequency range that has no spectral envelope (i.e. the blank area to the right or left of each line). The pattern for [A] involves high energy at the approximation of F1 and F2 in the central region of the spectrum, the pattern for [I] has a low F1 and a high F2, and the pattern for [U] has a low-frequency concentration of energy. It is not immediately clear what constraints are placed on the fusing of these patterns, since they are only tied down to approximate quantitative values (Harris & Lindsey claim that the horizontal axes in the schematic spectra in Figure 7 are on a scale of approximately 0-3000 Hz, though this figure is revised — for male speakers — to a range of 0-2500 Hz in Harris & Lindsey, 2000).

Debate on whether there should be an [ATR] element has shown that phonetic content might be even more intrinsic in Government representations, since one argument that has been raised against the existence of [ATR] is that the vowels which some other theory might label as [-ATR] would then be less marked than the [+ATR] vowels (because, lacking [ATR], their representations would contain fewer elements). The basic vowel set would then be predicted to be [ɪ], [ɑ] and [ʊ], rather than [i], [ɑ] and [u]. However, if the phonetic interpretation is made up only of approximate patterns, then those patterns could just as easily be characterisations of [ɪ], [ɑ] and [ʊ] as of [i], [ɑ] and [u].

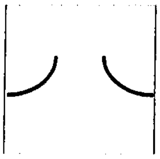
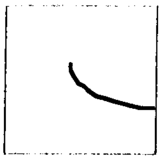
Element	**Mnemonic**	**Acoustic pattern**
[A]	*mAss*	
[I]	*dIp*	
[U]	*rUmp*	

Figure 3. Resonance elemental patterns (adapted from Harris & Lindsey, 1995:53).

There is one element whose interpretation varies cross-linguistically: the neutral element [@]. [@] is the baseline on which the [A], [I], [U] resonance patterns are superimposed. The apparent contravention of strict autonomous interpretation is eased by specifying the neutral element as 'phonologically blank'. This is fundamentally a different sort of element: it is omnipresent, but not manifest when overridden by another element. [@] only contributes to the phonetic interpretation of a segment when it is a head. It is introduced in order to account for dimensions of contrast such as centralisation of vowels in weak positions where other elements are delinked.

Government Phonology acknowledges the need for a theory of phonetic interpretation. However, the intrinsic nature of the phonetic content of most elements, in contrast to the strange interpretation (from an autonomous interpretation point of view) of the neutral element [@] once again reveals a mismatch between accounting for contrast and intrinsic phonetic interpretation.

2.3.3.4 The Firthian approach

There is clearly a tension in the generative paradigm between the linguistic significance of phonological representations and their physical manifestation in the phonic substance.

Bromberger & Halle's (1989) interpretation of feature geometries emphasises the linguistic significance of features but, in claiming intrinsic content, makes inaccurate claims about the phonetics. Browman & Goldstein's (1989, 1990, 1992) approach, on the other hand, makes great efforts to account for articulatory phonetic data, but at the expense of a clear linguistic approach to phonological contrasts.

It is possible to conceive of a third perspective on the phonetics-phonology interface. In the Firthian tradition, the tension between phonological form and phonetic substance is recognised and phonology and phonetics are set up as two quite separate domains which are nevertheless closely linked. In this tradition, the distinctiveness of features (in the manner of Bromberger & Halle) is fundamentally phonological, and the spatio-temporal driving of a task-dynamic model (in the manner of Browman & Goldstein) is fundamentally phonetic.

The Firthian approach to phonological statement is, like contemporary declarative theories, monostratal. In the words of Anderson (1985:189) it is 'entirely a theory of representation'; there are no procedural rules or operations; no intermediate representations between phonology and phonetics are admitted. Work in the Firthian Prosodic Analysis (FPA) tradition involves phonological representations which are deemed to have no intrinsic phonetic content. Observed variability is dealt with by the analytic mechanism of phonetic exponency which provides FPA with the ability to maintain single invariant phonological representations for lexical forms. Exponency is the means by which phonetic details are linked with the phonological representations, or formulae.

Firthian analyses typically contain detailed descriptions of the relationship of parts of the phonic substance to the phonological categories posited by the analyst (often laid out in tables): Henderson (1966) is a good example (she follows six pages of tables setting out the syllables she analyses with several more tables relating phonological terms to their phonetic exponents), along with the early Firth & Rogers (1937), who set out a table of tones alongside their 'correlative attributes'.

A detailed statement of exponency is what is often lacking from generative analyses, though Government Phonology's spectral patterns do constitute a serious attempt to provide a universal interpretation of elements. Articulatory Phonology provides, from a Firthian perspective, a scheme of exponency without the phonology linked to it. In devising an abstract gestural score, Articulatory Phonology can provide an abstract phonetic level of analysis, as linked by Sprigg (1957:107) to abstract phonological representations:

> '...it is clear that the phonological symbols are purely formulaic, and in themselves without precise articulatory implications. In order therefore to secure 'renewal of connection' with utterances, it becomes necessary to cite abstractions at another level of analysis, the Phonetic level: abstractions at the Phonetic level are stated as criteria for setting up the phonological categories concerned, and as exponents of phonological categories and terms.'

Sprigg (1961) is careful to define

> 'a distinction between phonetic criteria, whose function is to provide grounds for identification, and phonetic exponents, whose function is to substantiate the abstractions made at the phonological level, and to ensure "renewal of connexion."'

As outlined in Section 2.3.3.2, phonetic observations can act as criteria for setting up a phonological category. Indeed, some of the phonetics has to; otherwise there would be no link at all between phonetics and phonology. A gestural score might then form an abstract phonetic exponent of the category.

2.3.3.5 Separation of levels

The importance of there being a strict separation of phonetics and phonology and the consequential distinctions in terminology lies in the problematic nature of an approach to phonology labelled by Local (1995b) the 'intrinsic phonetic interpretation hypothesis'. The claim of this hypothesis is that the relationship between phonology and its phonetic interpretation is not arbitrary, but rather that the phonological representation somehow, in and of itself, encodes the primary information needed for phonetic interpretation to take place.

Pierrehumbert (1990) identified the phonology-phonetics relationship as a relationship of syntax and semantics: the phonetics is the semantic interpretation of the phonological syntax. Similarly, Wheeler (1981) divided the phonological component into rules of the phonological syntax and rules of phonetic interpretation in the declarative Categorial Phonology framework. Within that framework (Bach & Wheeler, 1981:35) there is an exhortation not to 'reinterpret interpretations': if phonetics and phonology are distinct levels of analysis, it makes little sense to allow phonetic elements and phonological elements to coexist within the same string.

Declarative approaches have typically asserted the need to adopt a concept of the separation of the levels of phonological representation and phonetic interpretation, and some declarative work has explored such issues (see Coleman, 1992a; Local, 1992; Local & Lodge, 1996; Ogden, 1992, 1995a, 1996; Simpson, 1992a). Simpson (1992a), for example, uses abstract phonological representations to 'generalise over certain aspects of the patterns observed' (p.542) rather than 'generating' the phonetics of conversational speech from a phonology tied to the phonetics of the citation form.

This strict demarcation between phonetics and phonology is, of course, not new: it is foreshadowed in Trubetzkoy's (1969) criticism of earlier work which failed to recognise the 'sharp division' between phonetics and phonology; witness also the Hjelmslevian (1953:§13) concept of the distinction between the expression plane and the content plane, and 'phonetic exponency' (see, for example, Firth, 1957a:VI) which plays a key role in Firthian Prosodic Analysis.

2.3.3.6 Phonology has no phonetic content

Phonology within the declarative framework used in this dissertation has no phonetic content. This assertion is not only made by researchers in the field such as Local (1995b), but also supported by comments other phoneticians have made about phonology: see Ladefoged (1977) who recognises (p.231), for example, that 'the feature Alveolar has to be given a different interpretation for fricatives and plosives', since the precise phonetic details of the articulation differ, and concludes that there is not necessarily a one-to-one mapping between phonological features and physical events. Interestingly, researchers who start from phonology and work towards phonetics tend not to come to this conclusion so easily.

[voice], for example, is the name for a phonological category whose exponents may include phonetic voicing (actual physical vibration of the vocal folds), but also others such as duration.

2.3.3.7 Some extrinsic phonetic interpretation is necessary

Let us continue the example of the relationship between [voice] and voicing. There is a long-established literature concerned with the effects of postvocalic voice contrasts in English, Heffner (1937) and Denes (1955) being early examples. It is well known that vowels preceding phonologically voiced consonants are of relatively greater duration than vowels which precede phonologically voiceless consonants. If there is a phonetic voicing contrast between the postvocalic consonants, then there is a plausible general phonetic explanation for the difference in vowel duration in terms of the air pressures and flows in the vocal tract. However, Mitleb (1984) and others have shown that this is not a universal effect: it is not found in Arabic, for example, and Arabic speakers find it a difficult aspect of English to learn.

Vowel duration effects are therefore not universally predictable, although most analyses of English treat them as secondary to a voicing contrast and therefore as (phonologically) redundant 'acoustic cues' whose purpose is to aid perception of the primary point of contrast. A neo-Firthian approach would eschew the redundancy metaphor as unhelpful to the analyst, replacing it with the concept of the informationally-rich signal. In any case, the Firthian conception of 'abstraction' did not equate with 'taking away' (which would imply some redundant phonetic information left in the signal once phonological analysis has taken place). As Firth (1957a:VI) comments:

> 'There can be no question of "residue" in the phonic material after any particular abstraction for a specific purpose has been made. All the phonic material is still available for further abstractions for a different order in separate analyses.'

Note also Henderson's (1964:416) assertion that:

> 'there must be constant reference back to and re-assessment of the phonetic material, since what may be irrelevant to one stage of the analysis may be highly relevant to another.'

There is a set of phonetic exponents, related to the phonological voice contrast, which includes nuclear durational differences and differences in formant tracks (Walsh & Parker, 1983; van Summers, 1988) as well as differences in the onset and offset of the consonant. Each of these exponents adds to the quantity of information in the signal and has the potential to cue the phonological contrast. It is an important aspect of English phonetics that it is possible for all postvocalic consonants to be phonetically voiceless. That is to say, phonological voice contrasts in English have clearly observable phonetic exponents, but these phonetic exponents do not necessarily include actual physical vocal fold vibration. Assuming the contrast is to be labelled [voice] means that this is a state of affairs which seriously challenges the intrinsic phonetic interpretation hypothesis.

2.3.3.8 Is any intrinsic interpretation necessary?

Declarative Phonology is not committed to a state of cause and effect, where some portion of phonetics serves as an acoustic cue for another. In a declarative analysis, only correlation need be expressed, leading to a less explanatory but more descriptively accurate analysis. In any case, demonstrating correlation should be a first pass in any account, before cause and effect are suggested, since a cause and effect analysis makes a claim about precisely which portion of phonetics is primary and counts as contrastive. In the case of postvocalic voicing, for example, a declarative method would be to identify the exponents of rime [voice], rather than to look for acoustic cues to voicing.

Ladefoged (1983) points out how inadequate even the standard phonetic taxonomy is for describing speech sounds from a variety of languages. In the course of discussing the cross-linguistic possibilities for marking contrasts, he states (p.181) that:

> 'if we are simply specifying contrasts ... we either have to postulate a very large number of features, or we have to admit that the terms for different features have to be interpreted in different ways in different languages.'

He then goes on to argue that, even with an extended taxonomy (to include such rare — but present — articulations as voiced labiodental flaps), the descriptions are still not precise enough to capture the fine detail of timing and coordination between articulator movements.

This is an argument based on degree rather than kind: if so much phonetic detail needs to be specified in an extrinsic fashion, is there really any point in having any intrinsic content at all?

Let us imagine that there is no phonetic content in phonological categories. What consequence might that have? The obvious result would be a lack of cross-linguistic generalisations in phonology, since there would be nothing to say that a feature in one language meant the same as a feature in another language: they would then become incomparable. But, following Ladefoged, there is already a wealth of evidence to suggest precisely that: a feature in one language cannot mean the same as a feature in another language. As Ladefoged (1983:187) goes on to say:

> 'Linguistic descriptions must be accompanied by a detailed, language-specific set of algorithms before they can be interpreted in terms of actual sounds.'

Indeed, Lindau (1985) — along the lines of Heffner (1950:146-147) — suggests that phonetic variation has the consequence that rhotics themselves must be defined in purely phonological terms rather than by any particularly phonetic property.

It is by pursuing what might be termed the extrinsic phonetic interpretation hypothesis — keeping phonetics and phonology formally distinct but associated with one another in an arbitrary but nevertheless systematic fashion — that Ladefoged's observations can be taken seriously, forcing the analyst to confront the detail of phonetic data, whilst still constructing a phonological analysis in which systems of contrast and relationship are set up.

It is here that my approach to phonology differs from the generative paradigm (and, indeed, from some declarative phonology) in that accounting for linguistic universals is not a primary goal. My aim is to account first for issues local to an individual language before attempting to identify any higher-level similarities. In fact, in accepting an abstract phonology, the set of potential phonological universals becomes limited to issues related to structure and contrast, such as the definition of syllabic or moraic structure. Any universals which involve phonetic content would be defined as phonetic rather than phonological (although, as Ladefoged, 1977, pointed out, the phonetic content does in fact differ widely from language to language).

2.3.3.9 Constraining phonetic interpretation

An important aim of theoretical linguistic work is to develop grammars which describe only the set of linguistic objects. If exponency has the potential to be relatively unconstrained, then it also has the potential to describe a set greater than that of linguistic objects. It is therefore a major challenge for contemporary Declarative Phonology to find an adequate formalism which will constrain the mechanism of phonetic interpretation. Naturally, this is also a problem for derivational phonologies, although the matter is often glossed over and left to the phoneticians.

If phonological domains cannot straightforwardly be deduced from phonetic extents, and phonological categories are not simply gross phonetic categories, how, then, might one decide what the phonological domain related to particular phonetic phenomena is? How is it possible to decide on a phonological category at all and constrain its exponents? What counts as data? As Johnson (1994:326) asks in his commentary on Coleman's paper,

> 'if phonetic implementation (and presumably the listener's knowledge of similarity relations between sounds) is to be stated in terms of hierarchical structures of features rather than stating some phonetic property which all [nasal] sounds share, how is it that [nasal] sounds in a language may group together in phonological processes?'

The answer lies in looking for systematicities. In a neo-Firthian declarative approach it is, in fact, precisely the 'grouping together' in phonological phenomena which leads the analyst to assign the same phonological feature or attribute to a set of phonetic events. It is unlikely that the phonetic phenomena associated, for example, with contrast in [voice] reported in Section 2.3.3.6 are all noted by speakers and deliberately linked to vibration of the vocal folds. It is surely more likely that what speakers notice is simply the patterning together of phonetic phenomena. In this view, speakers notice connections, relationships between events, rather than inducing a phonology directly from phonetic phenomena. The phonology would then straightforwardly record correlations between portions of phonetics, rather than selecting some exponent to be primary.

It is the relationships between phonetic phenomena, in combination with information from other grammatical levels of analysis (such as lexical sameness and contrast, or morphological sameness and contrast, alternations and distributions), which form the criteria for setting up phonological categories.

Johnson's concern for natural classes then becomes a question about exponency: what phonetic events might typically co-occur in a language? Might there be *imprecise* 'articulatory implications' (cf. Sprigg, 1957)? The body of work produced by researchers such as Ohala suggests that there might be physiological (rather than grammatical) explanations for many of the co-occurrences which are found. So a primary research question for the declarative paradigm becomes the issue of whether phonetic constraints are purely physiological, or whether there might be more deliberate control or learned patterns in action. Clearly, variability across dialects or languages speaks to this problem: if some phonetic phenomenon is not obligatory, there must be an element of learning involved.

There are three possible interpretative mechanisms abroad in the literature, the last two of which are worked out as serious contributions to the theory of Declarative Phonology. Firstly, phonological categories may have exponents in a part of the phonetic structure directly related to the phonological structure. Sproat and Fujimura's (1993) explanation of the apparent correlation between rime darkness and long duration is one which relies on a view which might be termed 'natural phonetics'. Natural phonetic explanations are often cited to account for frontness and backness (especially in terms of coarticulation or long extent frontness / backness), leaving no need for positing long domain phonological quality (since the extent of resonance would be entirely predictable), but natural phonetics is not always the most adequate way of accounting for the data. Phonetic interpretation is not simply a function of the intrinsic content of features coupled with the intrinsic content of the structure. Moreover, *post hoc* 'natural phonetic' explanations can be put forward for almost any phenomenon, but counterexamples can usually be found. Anderson (1981), for example, acknowledges that phonetic explanations might have a diachronic role to play in explaining how phonological systems came to be as they are, but points out examples such as velar fronting after back vowels in Icelandic where the naturalness has been obscured, leaving an arbitrary relationship between phonetics and phonology:

> 'when we examine practically any phonological fact in detail, we find a certain amount of significant arbitrariness that does not appear in any serious sense to be reducible to a mechanical explanation' (p.507).

This first solution (intrinsic phonetic content of phonological categories in combination with structural information) has been developed into two further interpretative mechanisms, both of which introduce the concept of headedness into the structures: head-first interpretation (Coleman, 1992a, Local, 1992, Ogden, 1992) and the head feature convention (Broe, 1991). Head-first interpretation involves the interpretation of phonological units in headed parts of structure before the interpretation of those in non-headed structure, whereas the head feature convention approach involves subdividing the 'features' themselves into head and foot features. The head feature mechanism is closely related to the mechanisms of Head-Driven Phrase Structure Grammar (Pollard & Sag, 1987, 1994), a declarative grammatical theory.

In this dissertation, I adopt the head-first approach to interpretation, although little of consequence results from this decision with reference to the data I will present.

2.4 Non-segmental phonology

Sprigg (1957: 108) points out that integrated segments which conflate phonetic parameters are too gross a concept to be useful as exponents:

> 'The Phonetic categories of abstraction differ from the *ad hoc* categories of Phonology in being a corpus of types of articulation, e.g. plosion, voicelessness, labiality. These categories are, however, thus far without a recognised symbolisation: the symbols used by Sweet for his phonetic categories, which correspond to those of the Phonetic level in the Prosodic Approach, are no longer in use; ... The I.P.A. contains no independent symbols for such categories of articulation as those referred to above (plosion, voicelessness, labiality) but only cumulate symbols for more than one articulation, e.g. friction + dentality + voicelessness [θ] ... The I.P.A. symbols are thus often more detailed than is relevant to the point at issue.'

While the Firthians were aware of the disadvantages of carving up phonetics into segments, some of their phonology (while focussed mainly on systems and structure) appears partly segmental. Phonematic units are segmental in nature and syllabic structure is often represented as strings of Cs and Vs (see, for example, Waterson, 1956). Even so, there is no level at which phonematic units and prosodies come together to form integrated segments.

Some contemporary Declarative Phonology analyses incorporate the mainstream generative phonological structure which has some sort of segmental/timing slot tier with phonology being reducible from autosegmental 'collections of strings' (Bird & Klein, 1994:6) to a single segmental string on a skeletal tier. Other analyses (for example, Local, 1992; Ogden, 1999a; Local & Ogden, 1998), by contrast, are of a non-segmental nature and employ a more explicit theory of phonetic interpretation.

The variety of Declarative Phonology found in this dissertation is nonsegmental, both in the sense of being related to parametric phonetics rather than integrated 'cross-parametric' (Kelly & Local, 1989:58) segments, and also in the sense of avoiding 'columns of features arranged like beads of indeterminate size on a string' (Ladefoged 1977: 229). I aim to avoid introducing segments into phonology if possible, since the addition of segments duplicates information (already retrievable from the structure via temporal interpretation) without further constraining the output of temporal interpretation.

In effect, Ladefoged's comment is valid also for autosegmental phonology with a skeletal tier, at which all the non-linear aspects of the formalism are collapsed into a string of timing slots which are effectively segments, despite the fact that autosegmental phonology is an attempt to account for extents both larger than and smaller than the segment, with space on the printed page as a metaphor for time in utterance. The skeletal tier is the string on which the beads are threaded. So, for example, a partial autosegmental representation for *bank* might look something like Figure 4. The features themselves are not necessarily associated with a single segment, but the melodic structure comes together in a segmental skeletal tier. Without a separate theory of phonetic implementation, such a segmental representation might raise questions such as the accuracy of predictions regarding the extent of nasality in the vowel before the velar nasal. Generative phonological formalisms, such as autosegmental phonology, can express linear precedence in their structural representations but any other temporal information is left for phonetic interpretation.

Typically, contemporary phonology is made up of two parts: a melodic component dealing with (sub)segmental information (such as distinctive features), and a prosodic component, dealing with suprasegmental information (such as syllable structure). Phonological frameworks differ in their relevance to these two aspects of phonological structure. Feature

Geometry encompasses theories of melody, Metrical Phonology encompasses theories of prosody and Government Phonology encompasses theories of both.

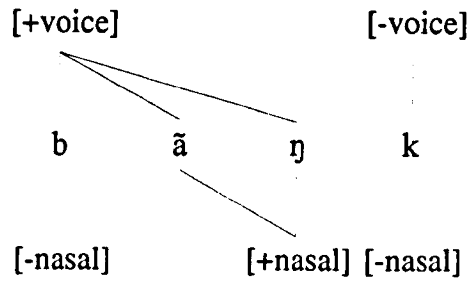


Figure 4. Possible partial autosegmental representation of <bank>.

Even within the declarative tradition, Bird (1995: 77-79) is careful to follow the generative tradition and keep these two aspects of phonology separate, with unordered hierarchies in the melodic structure (for example, place of articulation features do not precede or follow manner of articulation features: they coexist) but temporally sequenced constituents in the prosodic hierarchy (so, for example, an onset precedes a tautosyllabic coda). Once again, the prosodic structure and the melodic structure are linked on the skeletal tier.

In commenting on the use of segments, Abercrombie (1991:31) suggests that 'Firthian phonology is based on quite different fictions.' Carnochan (1957:158) asserted that:

> 'There is no time in structure, there is no sequence in structure; time and sequence are with reference to the utterance, order and place are with reference to structure.'

In this Firthian tradition, time is introduced in the exponency statements (see, for example, Ogden, 1995b).

For a phonology which incorporates prosodic structure and melodic structure to be truly non-segmental there needs to be a unified formalised prosodic and melodic (prosodo-melodic?) structure. While a traditional Firthian approach would divide phonological units into prosodies (with syntagmatic importance) and phonematic units (in paradigmatic systems) — though see Simpson (1992a), for a contemporary Firthian plea for the removal of the distinction — non-segmental Declarative Phonology unifies phonological items into a single hierarchy, expressed in directed acyclic graphs (see Coleman, 1998:193-205 for a discussion of DAGs; and Henderson, 1948, for an early example of the use of DAGs, though for classificatory purposes rather than a prosodic hierarchy). Melody and prosody are the same structure and there is then no skeletal tier at which multiplanar autosegmental representations are brought together, and no level in the hierarchy at which all the phonological information comes together as a segment. Phonology, therefore has hierarchical structure, with nodes entering into a relationship of dominance with each other. All nodes except for terminal nodes have subordinate nodes. One of these subordinate nodes is the head; all other subordinate nodes are complements. Terminal complement nodes are reentrant in order to handle ambisyllabicity (further constraints, not handled in this dissertation, are necessary to constrain reentrancy so that it occurs only in the appropriate places: a coda being linked with the onset of the syllable whose interpretation precedes it in time, for example, would clearly be inappropriate).

As an example of this hierarchical structure, the lexeme *bank*, as seen in Figure 4, may be partly described, in the style of the typed structures in Ogden (1999b) where some parts of structure are given a type such as *rime* or *onset* which defines which features they contain — see also Bird & Klein (1994) — as in Figure 5. Figure 5, while illustrating the same lexeme as Figure 4, is not equivalent to Figure 4. Fully-specified segments are included in Figure 4 alongside the values and placement of [voice] and [nasal]; no fully-specified segments are included in Figure 5.

Each level in the structure has head features and the potential for a head daughter with optional complement daughters. The precise content of the structures are defined by the types. However, for the purposes of the argument here, nothing hangs on the precise assignment of features and values in Figure 5. Note, however, that prosodic and melodic structure are integrated: typically melodic attributes (such as [VOICE]) occur within the prosodic hierarchy (as an attribute of the *rime*, for example). Ogden takes Bird & Klein's typed feature structures (which contain strings of segments) and adds a prosodo-melodic structure. Ogden includes a segmental level (the SEGS attribute) in his attribute-value matrices (AVMs) in his analysis of clitic-type structures because (pp.83, 85):

'Adjacency effects are not easily handled in AVMs incorporating exclusively hierarchical structure, and are better handled by having a flat list structure (the SEGS attribute of the AVM).'

$$
{}_{\textit{syllable}}\left[\begin{array}{ll}
\text{SEGS}: \langle 1 \wedge 2 \wedge 3 \wedge 4 \rangle & \\
\text{HEAD-FEATS}: \begin{bmatrix} 5 \\ 6 \end{bmatrix} & \\
\text{HEAD-DTR}: & {}_{\textit{rime}}\left[\begin{array}{ll}
\text{HEAD-FEATS}: \begin{bmatrix} 5\ \text{VOICE}: - \\ 6\ \text{NASAL}: + \end{bmatrix} & \\
\text{HEAD-DTR}: & {}_{\textit{nucleus}}\left[\begin{array}{l} \text{HEAD-FEATS}: \begin{bmatrix} 5 \\ 6 \end{bmatrix} \\ \text{VOWEL}: 2 \end{array}\right] \\
\text{COMP-DTRS}: & \left\langle {}_{\textit{coda}}\left[\begin{array}{l} 3\ \text{CONSONANT}: \begin{bmatrix} \text{VOICE}: + \\ 6 \end{bmatrix} \\ 4\ \text{CONSONANT}: \begin{bmatrix} 5 \\ \text{NASAL}: - \end{bmatrix} \end{array}\right] \right\rangle
\end{array}\right] \\
\text{COMP-DTRS}: & \left\langle {}_{\textit{onset}}\left[1\ \text{CONSONANT}: \begin{bmatrix} \text{VOICE}: + \\ \text{NASAL}: - \end{bmatrix} \right] \right\rangle
\end{array}\right]
$$

Figure 5. Partial description of <bank> in an attribute-value matrix, after the style of Ogden (1999b). Numbers are tags, indicating token identity (i.e. structure is shared).

However, the token-identity formalism (tagging) in AVMs (see, for example, Scobbie, 1997:33) is unconstrained with regards to which particular attributes may be tagged together. Indeed, this can be a positive advantage, as can be seen in Figure 5, with tagging throughout the heads in the structure (syllable, rime, nucleus). Despite the unconstrained nature of the formalism, it is a motivation for the use of AVMs (and their equivalent DAGs) in the first place. Token identity could then easily be expressed across different parts of the structure, even in clitics, and there would be no need to set up a different type of attribute, SEGS; different, because it contains an ordered list and therefore encodes (however crudely) some temporal information.

The unconstrainedness of such structures is a serious theoretical disadvantage, but has the practical advantage that the analyst is forced to take seriously the issues of interpretation. In fact, if all of the temporal extents of the phonetic parameters exponed by a structure such as that in Figure 5 can be constrained by a temporal interpretation model along the lines of the YorkTalk interpretation model (Coleman, 1992a; Ogden, 1992; Local, 1992), the structure in Figure 5 could then be simplified in the manner of Figure 6. Again, the precise values of the attributes do not matter for the purposes of the argument. Suffice it to note that there is no equivalent of a skeletal tier in this completely unified prosodo-melodic structure. There are no timing slots and there is nowhere in Figure 6 where the segments [bãŋk] might be placed: even the terminal nodes only carry part of the information which would be required to form one of the segments in [bãŋk].

$$\left[\text{syllable}:\left[\begin{array}{l} \text{onset}:\left[\begin{array}{l}\text{voice}:+\\ \text{nasal}:-\end{array}\right] \\ \text{rime}:\left[\begin{array}{l}\text{nasal}:+\\ \text{voice}:-\\ \text{nucleus}\\ \text{coda}\end{array}\right]\end{array}\right]\right]$$

Figure 6. Partial description of <bank> in a non-segmental attribute-value matrix without necessary terminal nodes.

The attributes [nasal] and [voice] as values of the attribute [rime] in Figure 6 form a partial description of the segment string [ãŋk], but more information is required before the description in Figure 6 is equivalent to the string-based description. At least vowel, place and manner attributes would be needed to distinguish between [ɛns], [eɪnt], [aŋk] and [ʌmp], all of which are extensions of the rime description in Figure 6. Moreover, if the description were extended to terminal node level, then the attributes found at that level would not be sufficient in themselves to describe a segment from a string. Instead, it is the complete *paths* from the root of the DAG to the terminal nodes which provide a sufficiently full description. The equivalent of the coda [ŋk] might then be described as in Figure 7. Again, the precise details of the attribute-value system are not relevant for my argument: it is enough to note that there is a path from [syllable], through [rime] and [coda], which leads eventually to terminal node level, and it is the entirety of this path which forms the phonological description, rather than any conglomeration of information at the terminal node level.

$$\begin{bmatrix} \text{syllable}: \begin{bmatrix} \text{weight}: \text{heavy} \\ \text{rime}: \begin{bmatrix} \text{voice}: - \\ \text{nasal}: + \\ \text{coda}: \begin{bmatrix} \text{consonantal}: \begin{bmatrix} \text{grave}: + \\ \text{compact}: + \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix} \end{bmatrix}$$

Figure 7. Partial description of [ŋk] in <bank>.

It must be noted that there is still a need for a temporal aspect to interpretation: this structure (with its phonological domains) still says nothing in itself about the phonetic extent of nasality in the vowel.

Phonological domain and phonetic extent have been confused in work on English liquids: West (2000:170-1) comments that:

> 'Resonance differences between dialects suggest that resonance is part of the phonology of different dialects. A Firthian prosodic analysis of these effects is, however, not wholly consistent with the data. Resonance effects are relatively large in the central portion of the domain and taper off, decreasing in size, towards the edges. Thus, although the coarticulatory effects of a liquid can be described as distributed over a domain, they are not evenly, but gradiently, distributed over that domain. Detailed phonetic exponency rules, which interact with position in the domain, would be required to explain the gradient nature of the effects. The strength of the prosodic approach is that the effects can be represented phonologically using a single label. The weakness, however, is that the phonological representation does not give any indication of the nature of the effects, and all of the phonetic detail would have to be captured in detailed exponency rules.'

Firthian prosodic analysis is relatively unconstrained in this area and it would be perfectly possible to provide appropriately detailed exponency statements. Indeed, they may be necessary in this very case, given the very wide structural range of resonance effects reported in Heid & Hawkins (2000). One of the great strengths of the Firthian approach — aside from an insistence on comparing phonological like with phonological like — is that detailed exponency statements are forced on the analyst. In less abstract phonologies, it is too easy to inadvertently gloss over such details. Nevertheless, the fact remains that the relatively unconstrained nature of exponency in cases like this means that what a Firthian approach gains in descriptive power, it loses in explanatory adequacy.

With a genuinely non-segmental phonological structure (with no skeletal tier), explicit parametric phonetic interpretation is forced on the analyst. Exponency statements (which would be necessary anyway) would then handle the precise extent of exponents, allowing for the statement of appropriate phonetic parameters for nasality in the vowel. There is no reason why the phonetic interpretation of the autosegmental representation in Figure 4 could not also handle nasality parametrically; it is just that a non-segmental (rather than non-linear) representation allows no other option.

2.5 Polysystemic phonology

An important characteristic that much Declarative Phonology has inherited from Firthian phonology is polysystematicity. Different systems are regarded as holding (or operating) at different points in the structure, so phonological categories do not carry the same value in all places, since they contrast with sets of potentially differing size and content.

A clear example of how polysystems might work (at a number of levels) in a contemporary declarative phonology inspired by Firthian tradition is to be found in Ogden (1997a,b, 1999b) — see also Simpson (1992b) on a similar topic. Ogden argues that each function word, being a member of a relatively small and closed set of items, contrasts with only a small set of other function words. Lexical content words are not in contrast with these function words since syntactic constraints prevent them from occurring at the same place in the linguistic structure. A single (monosystemic) phonological system describing English consonants would fail, for example, to account for the fact that [ð] occurs word-initially in English only in function words (*this*, *these*, etc.) and [θ] occurs word-initially only in lexical content words (*thick*, *thieves*, etc.). However, Ogden's analysis takes the implications of polysystems much further than this. Given that function words form a restricted set of items, the exponency statements linking the phonology and the phonetics can be different from those employed at other points in the phonology of the language. Ogden identifies certain articulatory and temporal constraints which hold for these words, but other constraints on exponency (which hold for lexical content words) are not present. So a wider range of variability is permitted while still maintaining as much contrast as is necessary. The legitimate limits on variability in the exponents are dependent on how many terms are in the particular system at the particular place in structure.

Sets of phonetic exponents of a particular phonological category may also vary in different structural positions. The category [voice] in English consonants, for example, has different phonetic exponents depending on whether the consonant in question is in syllable-initial or syllable-final position: the exponents of [voice] associated with syllable-final position include, among other things, durational effects in the tautosyllabic vocoid and differing transitions into the contoid, whereas the exponents of [voice] associated with syllable-initial position include voice onset time but seemingly not duration of the vocoid. See Section 2.3.3.6 on [voice] in English and Carter (1995), Nguyen & Hawkins (1999) and Hawkins & Nguyen (to appear) on the more extensive exponents of rime [voice] as found in onset laterals.

This concept of differing phonetic exponents dependent on place in structure is familiar from the language of mathematics in which, for example, the symbol '3' has differing interpretations dependent on its place in the numerical structure: in the complex symbol '32', its semantics is 'thirty', whereas in the symbol '3276', it is interpreted as 'three thousand'.

A polysystemic approach is also taken to underspecification of phonological information (see Local, 1992, in which an aspect of underspecification occurs only in codas) rather than an all-or-nothing monosystemic approach to underspecification across the board.

In a neo-Firthian polysystemic view of phonology of the sort adopted in this dissertation, there is no *a priori* need to have a coherent whole phonology, whether at the level of a single language or at the level of linguistic universals. This is a view which has come in for some criticism (not least by Langendoen, 1968) — and indeed polysystematicity risks being theoretically very unconstrained indeed in terms of the number of systems and the number of phonological primitives allowed — but a fragmented, polysystemic approach to phonological analysis forces the analyst to justify any comparisons which may be drawn between phonological atoms, rather than assuming that equivalence can be taken for granted.

It is by renewing the connection, returning to the data, that polysystematicity may be constrained. If there is such a thing as the English language, then it is that overarching system which constrains the polysystems which may be set up to describe individual parts of English. The phonological analysis of onset liquids, or of rime liquids, or of liquids in general which I will present in Chapter 8 is constrained by its being an analysis of liquids in English.

2.6 Conclusion

In this chapter I have laid out some of the arguments in favour of the sort of phonology in which this dissertation is couched: a declarative phonology which is abstract, non-segmental and polysystemic but which is ultimately accountable to patterns observed in the phonetic data.

If phonetic interpretation is not intrinsic, if phonological categories may have sets of exponents which comprise seemingly unrelated phonetic material, and if no single exponent is necessarily regarded as primary, then it follows that any statement in phonology must be abstract, since it will not represent, or be interpreted by, any single exponent. The degree of abstractness has been a point of debate within the generative tradition since its inception, with disagreement as to whether segments not found in surface structure should be licit in underlying forms. However, the nature of abstractness in a Firthian phonology finds no place in the generative continuum: it is abstractness of a different kind. None of the phonological units appear in the phonetics: indeed they cannot, for the stuff of phonology is not the stuff of phonetics.

Turning full circle or, in the Firthian parlance, 'renewing the connection' with the data, the abstract nature of the phonology requires that there be explicit statements of phonetic exponency.

The study presented here is couched in terms of a declarative, non-segmental approach to phonetics and phonology. In this framework, which derives from FPA, phonetics is the study of dynamic physical events whereas phonology is an abstract level of analysis which expresses relationships and contrasts perceived to be present in those physical events. Within this framework, neither phonetics nor phonology is described in terms of segments. The non-segmental nature of phonetics and phonology makes more explicit the need to postulate domains for phonological categories and to account for the extent of the phonetic exponents of the categories. This phonology is polysystemic, allowing for different sub-phonologies to apply at different points, constrained by 'renewal of connection', justifying the setting up of systems by testing against the phonetic data.

This is a radically different approach from many other phonologies in that it endeavours to maintain a clear distinction between phonology (and the stuff of phonology) and phonetics (and the stuff of phonetics), making explicit the conflict between the expression of contrast and phonetic accountability. It is a declarative phonology, employing a more constrained grammar than the grammar associated with derivational approaches; it simply states relationships between phonetics and phonology without the need for intervening levels of derivation. It is clearly also non-segmental: once features are given non-terminal nodes as the domain of their contrastivity, it makes no sense to segment. In my phonological approach I aim to adhere to such a phonology, to see how far it is possible to pursue the notions of abstractness, non-segmentality and polysystematicity.

After a discussion of liquids and resonance in Chapter 3 and presentation of my experimental data in Chapters 4-7 I will return, in Chapter 8, to these phonological issues and show how abstractness in the phonological representation can reduce the number of primitives in an analysis of liquids in English which depends on non-segmentality and an awareness of different systems operating at different points in structure.

3 An Overview of the Phonetics and Phonology of English Liquids

In this chapter I will present an overview of work on the phonetics and phonology of liquids in English, and on resonance qualities associated with the liquids.

In Section 3.1 I introduce liquids as a system. Given the phonological approach outlined in Chapter 2, it is important to know something of the status of liquids in the phonology in order to inform the questions which are asked about the phonetics associated with them. In particular, if liquids are in system with each other then the phonetics of one liquid cannot be fully described without reference to the phonetics of the other liquid.

In Section 3.2 I discuss the role of resonance as a distinguishing factor between [l] and [ɹ]. When data from a range of varieties of English is taken into account, the well-known pattern of syllable-initial clear [l] and syllable-final dark [l] turns out to be only a partial account. Resonance characteristics are associated with rhotics as well as with laterals, and the distribution of clear and dark is not the same for all varieties. I use the term *resonance* here in the sense relating to secondary articulation, rather than the use of the term related to formants produced in the vocal tract.

In Section 3.3 I outline some of the previous work which has examined laterals; Section 3.4, in a similar vein, examines rhotics. Liquids have often been described as instances of multiple articulations, a status which raises questions about how they might be represented in phonology.

In Section 3.5 I focus on liquids as complex segments, discussing especially their nature on the borderline between consonant and vowel. I summarise how a number of phonological frameworks have accounted for this state of affairs by including both consonantal and vocalic entities as part of the structure of liquids. I evaluate how well they succeed in accounting for the phonetic patterning and the possibilities for variation and change.

3.1 Liquids as a system

Consistent with most work within the declarative phonology paradigm which separates analysis on a phonetic level from analysis on a phonological level, the discussion of the phonology of liquids in English must involve the relationships the liquids enter into in a purely phonological realm, namely their distributions.

Any traditional treatment of English phonology (such as Gimson, 1962, or Giegerich, 1992) will mention certain aspects of the phonology of liquids in English, such as the variation between rhotic and nonrhotic varieties and the distribution of clear and dark [l]. Gimson, in particular, gives tables of distribution which demonstrate how, for example, liquids do not occur in the initial position of word-initial clusters and how liquids are the only consonants found in final clusters before non-syllabic nasals. In Section 3.1.1 I discuss the distribution of singleton liquids; in Section 3.2.2, the distribution of liquids in clusters.

3.1.1 Singleton liquids

The most salient aspect of singleton liquid distribution is the division between rhotic and nonrhotic varieties of English. Rhotic varieties have a two-term liquid system in the onset and in the rime, whereas nonrhotic varieties have a two-term liquid system in the onset, but only one liquid in the rime.

There is very little restriction on singleton onset liquids (or glides, for that matter, though there are some pansyllabic constraints such as there being no low front vowel after [w] unless a velar consonant follows (*wad* [wɒd] but *wag* [wag]). There are pansyllabic constraints (Cairns, 1988:225) which prohibit liquids in an onset cluster from also appearing in the rime, but singleton liquids may appear both in the onset and in the rime, so *lull* [lʌl] but **plull* [plʌl] and **slull* [slʌl], while *pluck* [plʌk] and *slut* [slʌt] are found; Cairns accounts for this disparity by analysing singleton onset liquids as being in a head position in the onset while liquids in clusters are in glide position, following the head (incidentally, this distinction between singleton liquids and liquids in clusters is not drawn in Adrian Simpson's analysis, reported in Coleman, 1998:225-7, in which onset liquids are also in head position in clusters).

3.1.2 Liquids in clusters

In onset clusters, liquids need to be examined in conjunction with the glides [w] and [j]. The glides in English share some of the characteristics of liquids as complex part-consonantal, part-vocalic entities (see Section 3.5). There is a diachronic link between the glides ([j] and [w]) and the vowels [i] and [u] (so, for example, the vowel [i] in niwan [niwən] became the glide [j] in new [nju]). The glides are spectrally very similar to their associated vowels, differing mainly in the temporal structure of their acoustics. However, the glides function in syllable structure as consonants, as exemplified by juncture with the definite article (with [ði] before vowels and [ðə] before consonants): the east [ði ist] but the yeast [ðə jist]; the Ouse [ði uz] but the woos [ðə wuz].

The distributional characteristics of the glides are similar to, but not identical to, those of the liquids so, for example, liquids and glides are the only possibilities between an onset plosive and a tautosyllabic vowel but glides are not found in the syllable rime.

The palatal glide [j] is found singly before a full range of vowels. However, in combination with plosives, [j] is only found before [uː]. For this reason, Coleman (1998:283, 294), following the practice in the YorkTalk synthesis system (Section 3.5.6), sets up /iw/ as a nucleus as a way of accounting for this distribution in his declarative analysis. Hammond (1999:52ff) makes the same observation with effectively the same analysis.

Onset clusters beginning in [s] or [ʃ] do not fit into the main pattern of onset clusters (indeed, Selkirk, 1982:347, suggests that such clusters are best analysed as a single obstruent). There are three reasons to support this contention. Firstly, the sibilants pattern with a wide range of consonants. Their complementary distribution ([ʃ] is found with [ɹ], [s] with other consonants) indicates that [s] and [ʃ] at this place in structure can be treated as exponents of a single phonological unit. A similar pattern, for many speakers of appropriate varieties, is found in CCC-onsets such as [stɹ] in which the sibilant is backer and more rounded than in other situations. Secondly, constraints against other homorganic clusters (e.g. *[tl]) do not apply, since [sl] is a legitimate onset. Thirdly, clusters with sibilants stand out as not conforming to the so-called sonority hierarchy as it is commonly understood, since voiceless plosives are usually taken to be the least sonorant segments (and therefore would be predicted to be found furthest from the nucleus) and [sp], [st] and [sk] are all perfectly acceptable English onsets. Moreover, there is no reversal of the order of segments between onset and coda (as would be predicted by the sonority hierarchy), so [sp], [st] and [sk] are all also perfectly acceptable English codas. It is in part for this reason that Harris (1994:54ff) — in the Government Phonology paradigm — defines the sibilants out of an onset cluster and into a preceding rime.

Factoring out these *assibilated* onsets (to use Sprigg's, ms, word), we are left with the combination constraints of two-consonant onset clusters, formed of a plosive or non-sibilant fricative followed by [l], [ɹ] or [w] laid out in Table 1.

	+l		+ɹ		+w	
labial stop	pl	bl	pɹ	bɹ	*pw	*bw
alveolar stop	*tl	*dl	tɹ	dɹ	tw	dw
velar stop	kl	gl	kɹ	gɹ	kw	?gw
labial fricative	fl	*vl	fɹ	*vɹ	*fw	*vw
dental fricative	*θl	*ðl	θɹ	*ðɹ	θw	*ðw

Table 1. Plosive or non-sibilant fricative-initial onset clusters.

There are notable distributional issues in Table 1. All the plosives and all the voiceless fricatives can combine with [ɹ], but there are intriguing patterns with those consonants which can combine with [w] and [l]. With the exception of combinations with velars (which I will discuss below), permissible clusters with [l] are in complementary distribution with clusters with [w], in that where one occurs the other does not.

The lateral is not found in combination with other coronals, [t, d, θ] and the labiovelar approximant [w] is not found in combination with other labials. However, there is one more gap in the distribution of [w]: *[gw-]. Most commentators point out that there are easily-adopted loans (mostly from Welsh) which fit this combination, such as *Gwen* and *Gwynneth.*

The *[gw-] gap can therefore be analysed as accidental rather than structural. Nevertheless, the fact remains that there are no native English *[gw-] onsets.

It could be that the absence of *[gw-] is not spurious; rather it is the presence of [kw-] which is spurious. Phonetically, [w] is more than simply labial; it is in fact a labio*velar* approximant. The coronal [l] does not combine with coronal obstruents (excepting the special case of [s], of course); similarly, the labiovelar [w] does not combine with labial or velar obstruents. Following this line of analysis would satisfy Coleman's (1998:295) wish that the appropriate constraint could be expressed simply as *[grave][grave] in his analysis (a tendency suggested as a universal for liquids by Bhat, 1974), a constraint which would then account for the non-appearance of *[tl-], *[dl-], *[θl-], *[pw-], *[bw-], and *[fw-] as well as [kw] and ?[gw]. There would then be simply a two term system in non-assibilated CC- clusters, with [w] and [l] in complementary distribution.

In order to achieve this straightforward phonological pattern out of the distribution of phonetic data which very closely relates to the pattern, it is necessary to account for [kw-] seemingly disrupting the phonetic pattern. If [kw-] were not part of the CC- systems, then the phonological analysis would easily account for such clusters. As it happens, there is evidence elsewhere that [kw-] is particular in a sense that, say, [pl-] is not. Indo-Europeanists would instantly recognise the labialised velar $[k^w]$. If English [kw-] is actually an instance of $[k^w]$, then it no longer falls within the category of CC- onsets. $[k^w]$ is now a singleton C- onset. This is in fact the argument given by Cairns (1988:225) who supports it with pansyllabic constraints. There is some possible support from the distribution with following vowels, though the evidence is not conclusive: *won* [wʌn], *wool* [wʊl], *woo* [wuː], *wow* [waʊ] and *where* [wɛə] are possible in the one hand (where those vowels do not occur after [kw]), and *qualm* [kwɑːm] is possible (although there is an alternative [kwɔːm]) where [ɑː] does not occur after [w].

Turning to CCC- onsets, we find the following possibilities: [spl-], ?[skl-], [spɹ-], [stɹ-], [skɹ-], [skw-]. The symbol *?* before [skl-] indicates that it has very low lexical frequency, and then only in unstressed syllables (primarily in lexemes related to *sclerosis*). Once again, coronal laterals do not combine with the coronal obstruent [t], [ɹ] patterns with all possible preceding consonants but [w] has one odd case: its combination with the velar plosive. If we postulate [kʷ] as a singleton C, then [skw-] onsets are in fact instances of [skʷ-]. Such onsets would then fall within the CC- set, unproblematically becoming part of the assibilated set, with [skʷ] as assibilated [kʷ], just as [sk] is assibilated [k].

However, a drawback of this analysis is that a new gap is introduced in the set of singleton onsets: there is no *[gʷ], or indeed any other consonant which may be described as labiovelarised. Simplifying cooccurrence constraints introduces gaps in the inventory.

3.2 Resonance

The complex nature of liquids both in terms of their articulation and their phonology is associated with resonance in the sense related to secondary articulation. However, resonance can be more than a secondary articulation local to the liquid itself.

In contrast to earlier observations on resonance in English liquids, Kelly & Local (1989: 212ff) discuss the relevance of observing and analysing the resonance characteristics of a wider set of consonantal articulations. For example, they comment (p.213) that

> '... velarisation of **r**, **m** or **z**, half-clearness of **t** or **p**, centrality of **ʃ** or **f** would all be resonance features. The set of resonance features that we recognise is fixed partly by the limitations of our skill, partly by the pragmatics of the language-describing situation.'

It is important to note that resonance as a phenomenon is not limited to [l] or even to liquids. The literature on articulatory setting (such as Honikman, 1964; Laver, 1980) bears witness to the fact that resonance may also be an important characteristic of dialects or languages in general, although articulatory setting relates to some sort of long-term average of resonance characteristics (or secondary articulations) rather than resonance as it operates dynamically in individual speakers' productions.

Kelly & Local (1986, 1989), combine resonance in laterals and resonance in rhotics into an analysis of resonance in the English liquid system as a whole. They reported on long-domain effects of secondary articulations in laterals and rhotics. They examined (acoustically and impressionistically) two varieties of British English, focusing on the clearness or darkness of liquids and also the relative clearness or darkness of vocoids in the vicinity of liquids. They found the following polarities: speakers with a clear initial lateral had a dark initial rhotic; speakers with a dark initial lateral had a clear initial rhotic. These patterns were also evident in nearby vocoids. They set up a single phonematic unit C_L, with two prosodies related to resonance, ^{y} and ^{w} (simplifying the symbols Kelly & Local used), so for speakers from Haltwhistle and Stockport, they suggest an analysis such as is provided for two sample lexemes in Table 2.

Variety	partial analysis for *Telly*	partial analysis for *Terry*
Haltwhistle	$CVC_L{}^yV$	$CVC_L{}^wV$
Stockport	$CVC_L{}^wV$	$CVC_L{}^yV$

Table 2. Resonance polarities in Kelly & Local (1989).

Kelly & Local make no explicit predictions regarding relationships between liquids in syllable final position (although, in examining vocalised [r] in nonrhotic varieties they do note that resonance polarities may be different in different structural positions), since the varieties they examined are nonrhotic and hence have no contrast between the liquids in syllable-final position. They do not make predictions about what patterns may be present in rhotic varieties of English.

Kelly & Local's framework is broadly that of Firthian prosodic analysis, and their interest in observing and notating various consonantal resonance categories is, in part, motivated by the kinds of non-segmental prosodic phonological analyses they undertake. Resonance in their approach has the potential to have much wider effect in speech than has previously been identified except, perhaps, by the Firthians themselves. Henderson (1964:419-420) is an example of how *resonance* is used in linguistic description and of how it is a more abstract term than particular descriptive articulatory terms such as *velarisation*:

> 'Before a close front vowel the Siamese unaspirated plosive [t] and the labiodental fricative [f] are frequently "dark" in quality, with an [ɯ]-like off-glide which suggests that there is raising of the back of the tongue. There is probably a similar modification of the sound before other vowels, but it is before the close front vowel that it is most readily perceived. The secondary articulation feature may perhaps best be referred to for the present as "velarization", but I am not satisfied that this is all that is involved. The flat, spread position of the tongue appears to be important, and there may be some such articulatory mechanism as that of the so-called emphatic consonants of Arabic. Once again, phonetic details which are perhaps "irrelevant" to the phonemicist may be highly relevant to the dialectologist and historian. There are, for example, in certain Tai dialects and languages, words in which there is fluctuation between initial [khw] and [f]. Compare, for example, Sui [_fa] *right (side)* with Siamese [ˎkhwa:], and Songkhla [ˎkhwai], and [ˎfai] *fire*, which are in free variation. When it is seen that these consonantal initials can be regarded quite similarly as two different arrangements of features common to them both which may be termed velarity, labiality, and breathy onset, their equation for philological purposes becomes much more plausible.'

Tunley (1999) compares [l] and [ɹ] to a baseline of [h], finding a lower F2 associated with [l] and a much lower F2 associated with [ɹ]. While phonetic effects are brought into relief by this methodology, [h] is not in system with [l] and [ɹ]. Phonologically, then, [h] is irrelevant and Tunley's important result (from the phonological perspective adopted in this dissertation) then becomes the fact that F2 in [l] is higher than F2 in [ɹ].

Perhaps the most striking finding in the recent literature on resonance quality associated with liquids is that of Heid & Hawkins (2000) who examined the speech of a single speaker of southern British English. They found resonance effects (which they attribute to the presence of a lateral or a rhotic) in F2, F3 and F4 up to five syllables and up to one second before the conditioning onset [ɹ] or [l]. These effects were similar to, but considerably more extensive than, those reported by Tunley (1999). These effects appeared to 'pass through' stressed syllables. However, the direction of change in F2 was not always in the predicted direction.

Heid & Hawkins present a two-component hypothesis, that liquid resonance has a large short-term effect which interacts with segmental context, and a smaller long-term effect which is less affected by segmental context. They argue that, despite the lack of an obvious lexical reason why [l] and [ɹ] should be so prominent, these effects would add to the perceptual coherence (a revision of the earlier term — acoustic coherence — in Hawkins, 1995) of the stretches of speech. These findings are supported to an extent by an observation made by Stevens (1998:535) that higher-frequency spectral effects related to liquids are found over a wider extent than the relatively low frequency patterns found in F1.

Heid & Hawkins (2000) is part of a body of recent work on liquids in British English which has taken seriously Kelly & Local's observations and has attempted to investigate the extent of the resonance effects they noted and formalise the phonetic exponents of the contrasts within the liquid system of different varieties.

The resonance quality reported by West (2000) mostly involves the more general acoustic difference between laterals and rhotics, namely F3, although she does find (p.32) that long-domain effects involve F2 and (to a lesser extent) F1. However, these effects are not always in a consistent direction for her RP speakers.

She reports a perception experiment to investigate phoneme restoration (see also West, 1999) with RP and Manchester speakers and stimuli which showed that speakers from both dialect groups have better recognition of the dark liquid ([l] for Manchester English and [ɹ] for RP) than the clear one. This is perhaps no coincidence: it could be that both varieties employ resonance quality to enhance the contrast between [l] and [ɹ]. If darkness involves relatively slow dorsal gestures (as opposed to relatively fast apical gestures); perhaps it is no surprise that the resonance effects West identifies are able to spread further and increase the possibility for correct perception in her gating experiments. In order to confirm such a prediction, though, there would need to be some method of factoring out the effect of F3 in a perceptual experiment — clearly not a straightforward matter in perceptual tasks involving real (as opposed to synthetic) speech.

West demonstrates that local anticipatory resonance distinctions appear to be stronger for [ɹ] than for [l] in both varieties: perhaps the effect of F3 is more notable locally (presumably due to the complex rhotic articulation) and that of F2 at a distance (an analysis which is not inconsistent with Heid & Hawkins's, 2000, two-component hypothesis). However, overall, she finds few F2 effects and those that there are vary with the speaker.

It is still not clear precisely what the mechanism is that may be controlling these resonance differences, although there may be a consensus emerging that salient coarticulatory effects occur locally in combination with some longer-domain resonance effects.

3.3 Laterals

3.3.1 Articulation of laterals

Lateral articulations are formed with a mid-sagittal closure which is usually coronal but velar laterals have also been reported in some languages (for example, by Ladefoged *et al.*, 1977; see also Ladefoged & Maddieson, 1996:190). To my knowledge, laterals with primary velar constriction do not occur in English, although vocalised forms such as are common in many southern English varieties have open approximations in the velar area which have a lateral tongue shape. Lateral cavities are formed on one or both sides of the constriction, allowing air to flow past the constriction. The primary coronal constriction in English is usually alveolar but can be dental in combination with dental articulations as, for example, in *health* [hɛl̪θ]. The rest of the tongue is relatively free to take up a variety of configurations, resulting in a range of possible resonance qualities.

Direct articulatory investigation of the tongue shape in American English [l] (Stone, 1990; Stone *et al.*, 1992; Stone & Lundberg, 1996; Narayanan *et al.*, 1997) has shown that the tongue has lingual contact along the mid-sagittal line, either apical or laminal. Stone & Lundberg reported a groove immediately posterior in the middle segment, but this configuration was not consistently found by Narayanan *et al.* The tongue is laterally compressed with a raised, convex posterior segment. Additionally, Narayanan *et al.* found pharyngeal constrictions in dark [l] due to retraction of the tongue root and/or raising of the posterior tongue body.

Sproat & Fujimura's (1993) articulatory analysis of laterals in English puts forward an explanation for the allophony associated with the secondary articulation of laterals which, while not actually universalist, nevertheless claims to set out natural phonetic tendencies with which languages are predicted to comply. Their analysis is a development of that of Giles & Moll (1975), who looked at the articulatory aspects of English [l] , finding that postvocalic [l] had slower tongue movement, often with undershoot. For this reason and also because postvocalic [l] often involved less constriction in the vocal tract, Giles & Moll suggest that prevocalic [l] is consonantal in nature whereas postvocalic [l] is vocalic in nature (this is the analysis adopted by Espy-Wilson, 1992). Undershoot in English postvocalic dark [l] is consistent with Leidner's (1976) finding that a velarising gesture in [l] is antagonistic to tongue tip raising and forward movement of the tongue body.

Sproat & Fujimura claim that, for relevant accents (that is, those with a clear [l] - dark [l] distinction), quality of [l] can be predicted on the basis of its position in the syllable and on the prosodic context of the syllable in the utterance. On this evidence, they discount the notion that /l/ is divisible into two categorically distinct allophones [l] and [ɫ], and agree with Giles & Moll that 'postvocalic' [l] is in fact itself predominantly vocalic in nature.

Sproat & Fujimura divide the lateral articulation into two gestures: a consonantal apical gesture and a vocalic dorsal gesture. This is compatible with Coleman's (1992a) phonological analysis. The consonantal gesture/vocalic gesture terminology is based on the premise that vocalic gestures have greater affinity for the syllable nucleus whereas consonantal gestures have greater affinity for syllable margins; this accounts for the relative timing of the gestures. Consonantal gestures are assumed to be weaker in syllable final position than they are in syllable initial position; vocalic gestures are assumed to be weaker in syllable initial position than they are in syllable final position (pp.305-6); this accounts for the relative prominence of the gestures. This latter phenomenon is taken to be a reflection of the maximal onset principle, by which the unmarked syllable is taken to be of the form CV, with consonantal material in syllable-initial position and vocalic material in syllable-final position. Sproat & Fujimura reach this conclusion from articulatory data which show syllable-initial (relatively clear) laterals having a prominent apical gesture timed before a less prominent dorsal gesture whereas syllable-final (relatively dark) laterals have a prominent dorsal gesture timed before a weaker apical gesture which may undershoot. This analysis accounts for laterals being darker in syllable-final position than they are in syllable-initial position and for an apparent correlation between darkness and relatively long duration (see Newton, 1993, for supporting data from perception experiments).

Figure 8 gives a schematised overview of such an analysis (with syllable structure superimposed), with vocalic gestures associated with the syllable nucleus and consonantal gestures associated with the syllable margins.

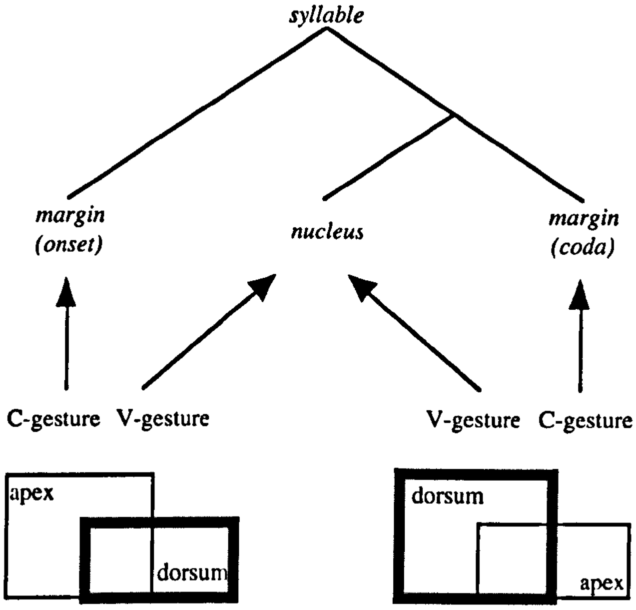


Figure 8. Schematic view of Sproat & Fujimura's (1993) gestural account of laterals in English. Consonantal gestures are attracted to syllable margins; vocalic gestures are attracted to syllable nuclei. Taller boxes represent more prominent gestures.

Ladefoged & Maddieson (1996: 361) dispute part of Sproat & Fujimura's analysis, giving the example of many speakers of American English who have dark laterals in all positions. Slow F2 transitions are identified as being indicative of the relatively slow dorsal gesture involved in "velarisation". A low F2 in the lateral indicates velarisation. By Sproat & Fujimura's predictions, the gradual F2 transition into a final velarised lateral should be mirrored by a gradual F2 transition out of an initial velarised lateral. Spectrographic evidence shows this not to be the case.

3.3.2 Resonance in laterals

There is a long tradition of examining resonance in English [l]. Jones (1972:§665) — a later edition of Jones (1918) — recognises that a wide variety of resonance qualities is theoretically possible with the English lateral, commenting that

> 'Many varieties of **l**-sounds may be formed with the tip of the tongue in the lateral position against the teeth-ridge or teeth. These varieties depend on the position of the *main part of the tongue* and not on the position of the tip; this is a point of considerable importance. While the tip is touching the teeth-ridge or teeth, the main part is free to take up any position, and in particular it may take up any vowel-position. The **l**-sound produced with a given vowel-position of the main part of the tongue always has a noticeable acoustic resemblance to that vowel; it may be said to have the 'resonance' of that vowel. It is not difficult to pronounce a whole series of **l**-sounds having the resonance of all the principal vowels, **i**, **e**, **ɑ**, **ɔ**, **u**, **ə**, etc.' (original emphasis).

Jones also refers to the effect dark [l] in London English has on adjacent vowels (§847v).

Ward (1939:140-147), in the Jonesian tradition, refers explicitly to the presence of clear [l] in prevocalic position and dark [l] syllable-finally and preconsonantally and explains the difference in terms of palatalisation and velarisation:

> 'palatalised means that the front of the tongue is raised towards the hard palate, velarised the back of the tongue raised towards the soft palate; in both cases this modification is a secondary articulation, the primary one being the tip of the tongue against the teeth ridge.' (§263).

Abercrombie (1967:63) also comments on differences in clearness and darkness in laterals in varieties of English:

> 'the adjectives *clear* and *dark* are often used to refer to a not very marked degree of palatalization and of pharyngalization respectively ... the adjective *dark* is used of segments with a not very marked degree of velarization also'.

It is worth emphasising Abercrombie's point that a clear lateral in English shows only a 'not very marked' degree of palatalisation. Indeed, Jones (1972:§676) comments that

> 'Russians have difficulty in making the English clear **l**. Before sounds of the **i** and **e** type they substitute a "palatalized" **l** which is followed by a distinct **j**-glide'.

English clear [l] is not to be equated precisely with palatalised laterals in other languages.

The structurally conditioned distinction between dark and clear [l] in English is well known (Sweet, 1908; Jones, 1956, 1972; Gimson, 1962; Giegerich, 1992; Ladefoged, 1993). These standard accounts of RP refer to [l] as being clear before vowels and [j] (as in [ljuːd]), and dark postvocalically. Nevertheless, Jones (1956: 90) points out (as do others) that 'the degree of clearness of the /l/ varies to some extent with the following vowel; it is less clear when the following vowel is a back one.' The terms *clear* (*light* is sometimes found in the literature as an alternative term) and *dark* refer to the particular (acoustic) resonances an articulation may have. As Jones and Ward reported, in [l] (aside from the — usually alveolar — lateral constriction) the tongue body is relatively free to alter its configuration. A clear [l] is said to have a front vowel resonance (such as [ɪ], as identified in Heffner, 1950:144) due to its relatively front tongue back configuration, whereas a dark [l] has back vowel resonances (identified as [ʊ] — 'slightly velarized' — in Heffner, 1950:144) since the tongue body moves back and / or down, as suggested, for example, by Sproat and Fujimura (1993) and Narayanan *et al.* (1997). The clear / dark [l] distinction is comparable to the distinction between palatalised and non-palatalised liquids in Russian which Fant (1960:162) identified as having articulations related to [i] and [u].

Much of the previous investigative instrumental work on liquids has been carried out on American English (with typically dark prevocalic [l] and very dark postvocalic [l], as in Lehiste, 1964), and so is rather different from the British data of the present study (although Lehiste, 1964, does appear to suggest patterns in American English which are similar to those reported later in this dissertation). Borden & Harris (1980: 110-1), attempting to explain the fact that American postvocalic [l] is very dark, suggest that

> 'Initial /l/ is produced as the speaker releases the tongue-alveolar contact; it cannot be held or it becomes a 'dark' [ɫ], the sound in 'full' ... No wonder the two sounds differ, when one releases the vowel and the other arrests it'.

Their equation of darkness with long (syllable-final) laterals may be a result of American English having initial laterals which, while clearer than final laterals, are still phonetically dark.

Bladon & Al-Bamerni (1976) investigated in some detail the variation in /l/ quality attributable to an adjacent vowel. Their argument was in favour of the traditional clear [l] / dark [l] allophonic distinction in English, with clear [l] showing a lesser degree of 'coarticulatory resistance' than dark [l], and dark [l] showing a lesser degree than syllabic [l]. Coarticulatory resistance in this context is a measure of the (lack of) susceptibility of [l] to coarticulation with the acoustic resonances of adjacent vowels: coarticulation was more likely to occur with clear [l] than with dark [l]. In contrast, Sproat & Fujimura (1993) propose that there is no categorical distinction between clear and dark [l] in English; rather, there is a continuum of articulations accounting for the observable facts by natural phonetic processes (viewed in terms of apical and dorsal gestures) affected by duration of the [l]. This comment applies to their American speakers; it is claimed that their British speaker showed effects related to syllable affiliation but this point is less extensively discussed in their paper.

Most traditional work on laterals in English refers only to varieties which have a relatively clear initial lateral and a relatively dark final lateral: usually RP / southern British English. This is the case, for instance, in Bladon & Al-Bamerni (1976), Sproat & Fujimura (1993) and Huffman (1997). However, it is well known (Wells, 1982) that there are varieties of English with noticeably clear laterals in all positions and, conversely, varieties with noticeably dark laterals in all positions. As Wells (1982:370-371) comments:

> 'Northern [i.e. in the north of England] pronunciation often lacks the sharp clear/dark allophony of /l/ found in the south and RP. A middle kind of [l] in all environments can, however, give the impression of being dark when it occurs in surroundings in which other accents would have a clear /l/ ... but of being clear when it occurs in surroundings where other accents would have dark /l/ ... The far

> north [i.e. roughly corresponding with the historical borders of Northumberland and Durham] tends to have a rather clear variety of /l/ in all environments.'

Ward (1939) notes a certain amount of dialectal variation in the resonance of [l] (§267), although more detail than she gives is necessary for a comprehensive account:

> 'in Ireland and some parts of the North of England, a *clear l* is used in all positions, **teɪbl^{i}, piːpl^{i}, bɛl^{i}z**. In Scotland and in some types of American and West Country speech, *dark l* is often found initially **ɫeɪt, ɫɒŋ**.'

Clear [l] in all environments in the north-east of England was compared to RP [l] as far back as Orton (1933:7):

> 'In Byers Green [County Durham] [l] is always 'thin', that is, in forming the sound, the back of the tongue is not raised towards the soft palate. Thus dialectal [l] is like RS [=RP] [l] in *lip*, *lit*, etc., rather than in *tall* and *cold*. However, it is not so thin as in present-day Northumbrian vernacular speech or in Swedish.'

Nevertheless, it is true to say that postvocalic [l] in the north-east of England may be phonetically darker than prevocalic [l] in the north-east of England. Even accents described as having clear [l] in all positions do seem to have different phonetic resonances at different points in the syllable: see, for example Newton (1996). The important aspect here is that postvocalic north-eastern [l] is clearer than postvocalic RP [l].

There is also, of course, evidence that the distribution of resonance in [l] is not intrinsically associated with syllable structure from other languages such as German (Viëtor, 1913:51-52) and French (Passy, 1913:76) — see also Viëtor (1910:77-81) and Delattre (1965:88ff) — which have syllable-final clear [l] and no dark [l]. However, the claim that postvocalic [l] and long-duration [l] are naturally dark does find some support in the work of Sproat & Fujimura (1993) and Newton (1993, 1996).

In summary, although there does seem to be a continuum of articulations, rather than a discrete differentiation, in English laterals (and some differences of opinion as to how to interpret the continuum), it is still generally true that [l] is relatively clear prevocalically and darker postvocalically. However, there are varieties of English in which [l] is either typically very clear or typically very dark.

3.3.3 Acoustics of laterals

There are a variety of acoustic properties which result from a lateral articulation. These properties are much more salient for a clear [l] than for a dark [l]. It is often observed that a clear [l] is easier to segment than is a dark [l], simply because the boundaries are so abrupt. Umeda (1977:846), for example, reports that word-final [l] (and also [ɹ]) were 'totally impossible to measure.' Stevens & Blumstein (1994) — discussed also in Stevens (1998:553) — report that postvocalic (dark) [l] resembles the offglide of a diphthong and formant frequencies are variable.

Investigation of the acoustic correlates of the variety of [l] articulations dates back some considerable time. Tarnóczy (1948: 75) notes that

> 'the darker colour of the back [ɫ] depends not only on a slight displacement of the lower formant, but also on the upper formants' changing position.'

Table 3 gives average formant frequencies from one British (Nolan, 1983) and one American (Lehiste, 1964) study of [l]. A comparable table for [ɹ] in these two studies is given at Table 4 (p.90).

Study	**F1**	**F2**	**F3**
Nolan (1983)	360	1350	3050
Lehiste (1964)	295	980	2600

Table 3. Mean formant frequencies for [l] from two studies.

Lehiste (1964) examined the acoustics of liquids in American English. She reported that F3 in [l] is higher than average, and Kent & Read (1992) report an F3 considerably higher (by approximately 1 kHz) than that of the rhotic. although Borden & Harris (1980) report that F3 in [l] rises mainly in the context of a front high vowel. The expected spectral discontinuities resulting from zeros were quite variable in Lehiste's study. Fant (1960; 1962:13, 1968: 236) suggested that the formant in question might actually be F4, with F3 obliterated by a spectral zero.

Note that Lehiste (1964) — following Fant (1960) — identifies the high F3 in laterals as F4, with F3 being masked by a spectral zero. This is similar to Stevens's (1998:535) use of F_R in place of F3 in rhotics, and is merely a discrepancy in the definition of a formant, with the more basic definition of a vocal tract resonance conflicting in these cases with the frequent use of the term to refer to the counting of bands of energy in spectra. Indeed, Stevens (1998:546) agrees that the acoustic side-branch in laterals would result in a zero within the range 2200-4400 Hz, the precise value depending on the length of the side-branch. F3 is a back cavity resonance and is variable but can indeed often be higher than the average F3 in vowels (Stevens, 1998:547). Stevens (1998) models F3 in [r] at 2800 Hz.

Stevens & Blumstein (1994) mention a high F3 and F4, general high frequency prominence and abrupt spectral change upon release of the apical occlusion. This lack of lower frequency energy results from zeros set up by the interaction of the sound waves in the two lateral cavities which are of approximately the same length and cross-sectional area and have resonances of very similar frequencies (Kent & Read, 1992). High frequency prominence may be due to a resonance set up in a short front cavity forward of the alveolar constriction.

F2 in [l] may be similar in frequency to F2 in [ɹ] (Kent & Read, 1992) with a large bandwidth (Stevens & Blumstein, 1994; Stevens, 1998).

The noticeably lower mean F2 frequency in Lehiste (1964) as compared to Nolan (1983) would appear to correlate with Lehiste's data being American English. (Stevens (1998:546) models F2 in American English laterals at around 1100 Hz). However, at least for Lehiste (1964)'s speaker from whom there is the most extensive data, a syllable-final [l] seems to have a smaller F2-F1 space than a syllable-initial [l] (despite the fact that initial [l] in American English is not as clear as in many varieties of British English).

Stevens & Blumstein (1994) report that F1 and F2 frequencies in prestressed laterals vary depending on the formant frequencies in the following vowel, so F2 in [l] is higher before a front vowel and F1 in [l] is higher before a low vowel.

F1 in [l] may also be close to the F1 frequency in [ɹ] (Kent & Read, 1992). Although the F1 of a syllable-initial [l] is generally quite low in Lehiste's (1964) study, the F1 of a following vocoid is usually higher than average, resulting in a rapid rise in F1 which is a strong cue for [l]. The presence of a lateral interacts with the formant structure of an adjacent vocoid:

> 'It appears that the second formant of the initial allophone of /l/ anticipates to a certain degree the second formant position of the following vowel, but that the first and third formant of the vowel are in turn influenced by the preceding /l/. The final allophone of /l/ shows a much smaller range of variations and is essentially independent of the preceding vowel, but it exerts a strong influence on the second formant of the preceding syllable nucleus.' (p.10)

Stevens (1998:546) models F1 in American English laterals at around 360 Hz. F1 is usually taken to correlate with openness of the vocal tract in vocoidal articulations (e.g. Stevens, 1998:268), although Stevens (p.515) points out that in glides a constriction which is further forward in its place of articulation results in a lower F1 and (p.533) the shorter constriction in liquids compared with glides raises F1. In liquids, F1 could therefore also be an indication of change in the front/back dimension.

Overall amplitude in liquids is relatively low in liquids due to a wide bandwidth in F1 (Stevens, 1998:534). Zue (1989) points out that laterals involve an 'energy dip' in comparison with adjacent vowels because of a relatively greater constriction, and that the offset of prevocalic [l] shows the sharp spectral discontinuity mentioned above. This abrupt acoustic discontinuity is presumably due to the abrupt movement of the tongue tip as it leaves the alveolar ridge, thereby producing a single central cavity rather than two lateral ones.

> A vocalic variant of [l] would have no contact between the tongue tip and the alveolar ridge, and thus would not show such abrupt spectral discontinuity. Dark (non-vocalised) [l], as well as vocalised [l], has slower tongue movement than does clear [l] (as a result of tongue back, as opposed to tongue tip, articulation), as outlined in Giles & Moll (1975).

The observed formant frequencies in these studies are consistent with formant patterns in vowels, with a high, front constriction showing an [i]- or [y]-like resonance pattern and a back constriction showing a more [ɯ]- or [u]-like resonance (for [lˠ]) or even [ɒ] (for [lˤ]) as pointed out, for example, by Fry (1979: 120-1).

As mentioned above, secondary articulations have an effect on the formant structure of laterals. Fant (1960:164-167), for example, identifies a lower F2 in the Russian non-palatal [l] than in its palatalised counterpart, due to a pharyngeal constriction. In this dissertation, both F2 (Delattre, 1951:872; Gimson, 1962:201; Recasens *et al.*, 1995; Ladefoged & Maddieson, 1996:361, West, 2000) and F2-F1 (Lehiste, 1964) will be used as correlates of darkness.

Zue (1989) states that:

> 'Postvocalic /l/ is not characterised by a spectral discontinuity as much as by a gradual movement of the formants. Typically, F1 and F2 drift downward in frequency whereas F3 drifts upward. When the preceding vowel is low and back, the rising F3 often is accompanied by a decrease in spectral amplitude. In this latter environment, /l/ is often very difficult to recognise [in reading a spectrogram], except for the changes in F3 and the long duration of the vocalic segment.'

Note that Zue's account equates postvocalic [l] with dark [l]; in accents with phonetically clear postvocalic [l], spectral discontinuity from the preceding vowel can often be observed. Moreover, accents with prevocalic dark [l] can show a lack of spectral discontinuity in prevocalic laterals. Spectral discontinuities appear to be typical of clear (rather than necessarily prevocalic) laterals.

Dalston (1975) suggests that the fact that tongue contact is involved in the articulation of [l] might account for F1 and F2 steady states being longer in [l] than in [ɹ], and that the rapid movement of the tongue tip is the cause of short F1 transitions and rapid F1 transition rate in [l]. [l] also was found to have shorter F2 transitions than [ɹ].

The acoustics of laterals, then, involve high F3 (with spectral zeroes and widened bandwidths in the F2-F4 region), with more variable lower formants. Most studies have examined American (rather than British) English and have reported a fairly low F2. Dark [l] has a particularly low F2 and acoustically resembles vowels much more than does clear [l].

3.4 Rhotics

3.4.1 Articulation of rhotics

There is a great variety of articulations which pattern as rhotics (Lindau, 1985). Many leading texts which give a treatment of rhotics rely on data from articulations not found in the dialects investigated in this study, an example being Fant (1960) on trilled [r]. Since the cross-linguistic connections between rhotics are sometimes articulatory and sometimes acoustic (Lindau, 1985), it is unclear to what extent work on rhotics in languages other than English is relevant to the present study.

However, there is a reasonable body of work on English [ɹ], particularly in American varieties of English. There is also a variety of possible articulations which can vary across dialects and between speakers. Work on American English has identified two major variations: a retroflexed [ɹ] or [ɻ] and a bunched [ɹ] (Uldall, 1958; Hockett, 1958; Delattre & Freeman, 1968; Lindau, 1985). Rounding of the lips also has a role to play (Delattre & Freeman, 1968; Zawadzki & Kuehn, 1980; Espy-Wilson, 1992). These varieties of [ɹ] may also vary with syllable position or consonantal context (Espy-Wilson & Boyce, 1994; Boyce & Espy-Wilson, 1997). Zawadzki & Kuehn (1980) studied three speakers of American English and identify two basic types of [ɹ] in their speech: prevocalic and postvocalic. The prevocalic rhotic exhibits relatively greater lip rounding, a more advanced tongue position with less tongue dorsum grooving.

In British English too, [ɹ] is often accompanied by an element of lip rounding. Brown (1981) not only claims that rounding is more typical of consonants than of vowels in RP English, but also that [ɹ] is among the set of RP consonants — [ʃ ʒ tʃ dʒ ɹ] — which most readily exhibit lip rounding. A labiodental production [ʋ] appears to be on the increase (see, for example, Foulkes & Docherty, 2000) in British English.

Westbury *et al.* (1995, 1998) argue that the whole vocal tract area function is important for modelling [ɹ] (tongue shapes in their study did not distribute well into discrete articulatory categories such as 'retroflexed' or 'bunched'), and that constrictions in the pharynx and at the lips may be especially important in producing the low F3 typical of [ɹ]. They found no evidence (such as the morphology of the vocal tract or other factors such as gender) to suggest why some speakers might use one articulation while others use another.

Alwan *et al.* (1997) investigated rhotics using EPG and MRI with speakers of American English. The productions were sustained instances (necessarily so, as in Narayanan *et al.*, 1997, on laterals) of word-initial and syllabic [ɹ] produced by non-naive speakers. They found evidence of two constrictions: a primary one in the oral cavity and a secondary one in the pharyngeal cavity. The anterior tongue body was characterised by convex cross sections, leaving a large cavity further forward. Further back, the tongue had a concave shape. The finer details of the articulation varied between the speakers, but they report no evidence of systematic differences between word-initial and syllabic instances of [ɹ]. Of course, the practicalities of MRI imposed their methodology, but it is not clear that sustained productions would reveal any differences between rhotics in different syllable positions that there might be in normal speech (it is possible, for example, that lip rounding might be relaxed in sustained productions). However, Guenther *et al.* (1999) report that cross-speaker variability in the articulation of [ɹ] might reflect trading relations in articulatory strategy which produce similar acoustic effects.

It appears, therefore, that there may be a considerable amount of variation in the articulation of [ɹ] in English. Much of this variation appears to be idiolectal in nature, although there is some evidence that variation in rhotic articulations may be associated with different prosodic positions.

3.4.2 Resonance in rhotics

Jones (1972) does not discuss resonance in the context of rhotic articulations as he does in the context of lateral articulations. Again, although Ward (1939) discusses differing types of rhotic (trilled, tapped and fricative), there is no mention of vowel resonance in rhotics to parallel her description of [l].

Typically the only secondary articulation characteristics of rhotics which are mentioned in descriptions of English are labial articulations such as lip rounding or protrusion (Jones 1972:§749):

> 'Many English people pronounce **r** with a certain amount of lip-protrusion, especially in stressed position.'

Sweet (1908:§133) agrees that 'lip modified **r**' is a common individual characteristic. As outlined in Section 3.4.1, it may also be dependent on prosodic position.

Kelly & Local (1989) are unusual in mentioning clearness and darkness in the context of [ɹ] as well as [l]. Most recent work on [ɹ], such as Alwan *et al.* (1997) or Westbury *et al.* (1995), makes no reference to such patternings. A noticeable exception is Harris (1994:259), who discusses clear and dark [ɹ] cross-dialectally, although Harris makes no connection with resonance quality in [l].

Another recent study which reports on resonance in rhotics as well as in laterals is Olive *et al.* (1993:204, 216). In their discussion of liquids in American English (their informant was a male speaker from Pittsburgh), they describe a pattern which tallies with Lehiste's (1964) American data: laterals are relatively clear syllable-initially (though, with an F2 of around 1000 Hz, darker than is typical for the British English varieties examined in this dissertation) and relatively dark syllable-finally, while rhotics are relatively dark syllable-initially (perhaps because of the lip-rounding discussed by Delattre & Freeman, 1968, Zawadzki & Kuehn, 1980, and Espy-Wilson, 1992) and relatively clear syllable-finally.

3.4.3 Acoustics of rhotics

Table 4 gives average formant frequencies from one British (Nolan, 1983) and one American (Lehiste, 1964) study of [ɹ]. A comparable table for [l] in these two studies was given at Table 3 (p.83).

Nolan's British speakers have higher formant frequencies than Lehiste's American speakers. However, both show the same pattern between [ɹ] and [l]: [ɹ] has a lower F1, lower F2 and lower F3 than [l].

Study	F1	F2	F3
Nolan (1983)	320	1090	1670
Lehiste (1964)	280	930	1360

Table 4. Mean formant frequencies for [ɹ] from two studies.

Zawadzki & Kuehn (1980) suggest that the lower formant frequencies for prevocalic [ɹ] reported by Lehiste (1964) were due to increased lip rounding. Westbury *et al.* (1995, 1998) found no reliable correlation between articulation types for [ɹ] and the resulting formant structure; they too suspect that labial activity (along with a pharyngeal constriction which they could not measure by x-ray microbeam) may be important in producing the typical acoustic results of [ɹ]. It is particularly relevant to note that here the acoustics of darkness in prevocalic [ɹ] seem to be related to lip activity rather than to the tongue position which can be relatively front. Westbury *et al.* also report less coarticulatory variation in prevocalic [ɹ] than in postvocalic [ɹ] (steady state formant frequencies of prevocalic [ɹ] are relatively invariant) and agree with Lehiste that greater articulatory speeds are demonstrated in prevocalic [ɹ]: [ɹV] transitions are much shorter than [Vɹ] transitions (these are similar results to those reported by Giles & Moll, 1975, for [l]). Espy-Wilson (1991) argues that [ɹ] requires a relatively long minimum time of execution, perhaps due to the relatively slow movement of the tongue body, but that F3 trajectory shapes and the precise timing of the trajectories was subject to cross-speaker variation and variation in speech rate and segmental context.

The most noticeable aspect of the acoustics of rhotics is a low F3. Lindau (1985) notes that uvular rhotics do not show a low F3, though rhotics of this sort are not found in many varieties of English (nevertheless, Foulkes & Docherty, 2000, identify a relatively high F3 as being typical of the [ʋ] production increasingly found in British English). Stevens (1998:535) identifies the low F3 in English rhotics as an extra front cavity resonance (created on the underside of the tongue and with lip rounding) which he labels F_R. This is close to the back cavity resonance, F2, which is also relatively low because of the backing of the tongue. The sublingual cavity which produces F_R functions effectively as a side branch to the pathway between glottis and lips, and so also introduces a zero into the spectrum (pp.537-538) which attenuates the energy above the prominence formed by F2 and F_R (including the F3 from an adjacent vowel). Stevens therefore models the acoustics of [ɹ] as an all-pole spectrum (F1, F2, F3) modified by a pole-zero pair (F_R and the zero, which he labels Z_R).

Lehiste (1964) identified — at least for the speaker from whom there is the most extensive data — that a syllable-final [ɹ] (in Midwestern American English) seems to have a greater F2-F1 space than a syllable-initial [ɹ] (in which the F3-F2 space was noticeably small). All of her speakers displayed lower formants in syllable-initial [ɹ] than for [ɹ] in other positions. The identity of the following vocoid had little effect on the formant structure of the rhotic. Transitions between a rhotic and a tautosyllabic vocoid were more rapid for syllable-initial [ɹ] than for syllable-final [ɹ]. Syllable-final [ɹ] had higher formants than syllable-initial [ɹ] and was influenced to a considerable extent by the preceding vocoid. However, the preceding vocoid often had lower F2 and F3 than corresponding vocoids not before [ɹ].

Alwan *et al.* (1997) conclude that F2 corresponds to either a half-wavelength resonance of the cavity behind the primary constriction (where the secondary pharyngeal constriction was not narrow), or a Helmholtz resonance between the pharyngeal constriction and the cavity below it (where the secondary pharyngeal constriction was narrow). Espy-Wilson *et al.* (2000) worked from MRI images of productions of [ɹ] and calculated tube models. They argue that F3 in [ɹ] is a front cavity resonance, and F1, F2 and F4 are mid and back cavity resonances. It may be, then, that darkness in [ɹ] (reflecting a low F2 and/or a small F2-F1 space) is not straightforwardly related to lip rounding as could be surmised by an analysis of Zawadzki & Kuehn (1980).

The acoustics of [ɹ] have often been examined in contrast to the acoustics of [l]. Polka & Strange (1985) carried out perceptual experiments with American English prevocalic liquids (the *rock / lock* pair: broadly [ɹɑk] and [lɑk] in American English) in terms of the frequency of onset and transition of F2 and F3, and the relative duration of the initial steady state of F1 and its transition (where a short steady state followed by a gradual transition cued [ɹ] and inappropriate F1 material even disrupted the F3 cue for [ɹ]). They report that although previous work had claimed that F3 was a sufficient cue for [ɹ], there exists context-specific and language-specific variation. In opposition to the results reported by O'Connor *et al.* (1957) and Dalston (1975), they found an asymmetry in the trading relations between acoustic cues for [ɹ] and [l]. Instead of temporal cues being more important for specifying [l] than [ɹ], they report (p.1194)

> 'increased temporal bias towards /l/ prevented reasonable "R" percepts while acceptable "L" percepts were obtained even with temporal bias toward /r/.'

More recently, Iverson & Kuhl (1996) synthesised [ɹa] and [la] tokens by varying frequencies of F2 as well as F3, keeping the vowel formants static. Bond's (1976) results show that this might not be an altogether valid approach to take, given that the formant patterns in the vocalic portion Bond investigated varied with the identity of an adjacent liquid. It would seem that the interpretation of 'being an l' or 'being an r' involves formant trajectories through a greater extent than what might as a first approximation be termed the consonantal or sonorant portion. Nevertheless, Iverson & Kuhl's results show some relevant patterns, not least that a short F1 transition length leads some subjects to identify most tokens as [la], demonstrating the dominance of this cue.

In summary, [ɹ] has a noticeably low F3, and lower formants in general than [l] in the varieties of English examined in the literature. Syllable position has an influence on the acoustics of [ɹ], and temporal information is also important in distinguishing [ɹ] from [l].

3.5 Complex segments

In this section I will discuss the nature of liquids as complex segments, going on to outline how consonant-like and vowel-like phonological atoms are used in liquids in a cross-section of theoretical approaches. Then I will discuss in more detail the phonological representations of liquids.

3.5.1 Liquids as complex segments

The fact that liquids appear to be complex articulations raises questions about what sort of entities liquids are and how they fit into a phonological analysis. Many theoretical approaches to phonology have as part of their armoury of machinery a division of segments either into consonants and vowels or into two categories that are closely related to the traditional notion of consonant and vowel. However, it would appear that there are certain segments which seem to blur the boundary between the two categories. Such segments may be similar in some respects to both consonant and vowel; in other respects, they may be dissimilar to both.

Liquids typically are members of this set of segments, and so the appropriate treatment of liquids has been a long-standing issue in phonology.

The common occurrence of secondary articulation with liquids leads them to be classified as multiple articulations, but even liquids without what is traditionally termed secondary articulation can be modelled as complex articulations (Recasens *et al.*, 1995, 1998; though see also Recasens *et al.*, 1996).

Multiple articulations such as liquids are complex not only in a featural sense, but also temporally: there are often constraints on the relative timing of articulations which must be accounted for either in phonological representation or in phonetic implementation. Ladefoged & Maddieson (1996:334ff, 355) suggest this may be perceptually motivated, at least for double stops: perception may be aided by the phasing of gestures so that the transitions typical of one are found coming into an occlusion while transitions typical of another appear out of an occlusion.

Walsh Dickey (1997) identifies a cross-linguistic tendency for liquids to be excluded from word-initial position which parallels a tendency for complex articulations to be excluded word-initially; indeed, languages with no word-initial liquids do not have other segments with multiple Place nodes in that position. However, she does not discuss any connection with Ladefoged & Maddieson's possible phonetic explanation, namely that segments at edges of prosodic units such as the word might not give the opportunity for formant transitions on both sides to cue the segment, as multiple articulations tend to be timed slightly asynchronously. Nevertheless, in fluent speech, there is still the opportunity to perceive formant transitions into the start of a segment which is initial in a prosodic unit such as the word.

3.5.2 C and V in phonological representations of liquids

Early writers on liquids in English (on laterals in particular) often note that they sometimes function as consonants and sometimes as vowels (when [l] is 'syllabic'). Ellis (1877) refers to [l] in English as 'the most vocal of the English consonants', which 'may itself form a syllable'. In a similar vein, Sweet (1892) calls [l] 'a vowellike consonant'. In more recent times, Espy-Wilson (1992) also suggests that postvocalic liquids are part of the syllable nucleus. Experimental evidence has also produced evidence that liquids are different from both consonants and vowels. Stemberger (1983) is an example. Based on investigation of speech errors, Stemberger concludes (p.141) that

> '/r/ and /l/ are not parallel to either [diphthong off-]glides or consonants. They are not as integrally associated with the vowel as [diphthong off-]glides are, but nor are they as loosely associated with it as consonants are.'

Pike's (1943) terminology which was intended to clarify the C/V boundary also bears witness to the difficulty of assigning liquids to consonant or vowel categories. Since laterals, by definition, do not have central air flow past their primary constriction, they are classed in Pike's system as contoids, while rhotics are classed as vocoids.

In this section I will sketch how a number of prominent recent phonological approaches have handled the case of the overlap between consonantal and vocalic material, which is clearly particularly pertinent in the case of liquids. I will use the terms *C-like* and *V-like* phonological entities to refer, across phonological theories and frameworks, to approximately comparable constructs which are in some sense related to the traditional terms *consonant* and *vowel.*

3.5.2.1 C and V in feature systems

Whether Jakobson *et al.*'s (1952) acoustics-based scheme or the articulatory-based revision by Chomsky & Halle (1968:302) is used, liquids have both C-like ([+consonantal]) and V-like ([+vocalic]) features. However, a later revision of Chomsky & Halle's feature system (1968:354) replaces [vocalic] with [syllabic]. In this scheme, liquids continue to be [+consonantal] but vary in their value of [syllabic].

Espy-Wilson (1992), in investigating the acoustic correlates of feature sets for glides and liquids, incorporates syllable position into the relationship between feature structure and the traditional segmental representations [l] and [ɹ]. She classifies [l] and [ɹ] as [-syllabic], with initial [l] as [+consonantal]. Final [l] and all instances of [ɹ] are [-consonantal].

The Feature Geometry approach shares Chomsky & Halle's articulatory feature definitions, but the featural content of liquids is somewhat different in Feature Geometric approaches to phonology (Clements, 1985; for an overview see, for example, Clements & Hume, 1995), which have mainly attached the major class features [sonorant], [approximant] and [vocoid] to the root tier. These features are not entirely independent of each other (so, for example, [-sonorant] implies [-approximant] and [-vocoid]). Liquids are represented as [+sonorant], [+approximant], [-vocoid], as in Figure 9.

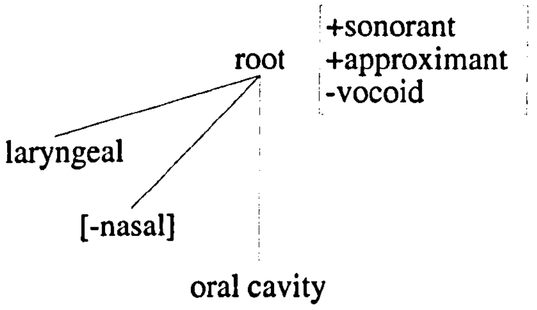


Figure 9. A Feature Geometric representation of liquids.

Unlike the Jakobsonian feature set, Clements's scheme has no C-like feature to parallel the V-like [vocoid] at the root node. Moreover, in the particular case of liquids, [vocoid] is specified as [-vocoid], rather than the [[+vocalic], [+consonantal]] representation of liquids in the Jakobsonian set. However, within a consonant, there may be a [vocalic] node below the C-place node (below the oral cavity node) to allow for secondary articulations (see Section 3.5.4) and, in particular, to allow secondary articulations to persist in cases of change in the primary articulation.

In a recent application of Feature Geometry to the phonology of liquids, Walsh Dickey (1997) argues for the existence of a feature [liquid], but claims that the distinguishing feature between laterals and rhotics is the structure and content of the two Place nodes (as in Figure 10) which she identifies as typical of liquids.

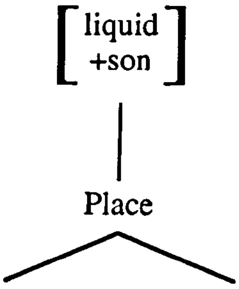


Figure 10. Walsh Dickey's (1997) Liquid branching Place node constraint.

Consequently, there is no need for a separate feature [lateral]. Rather than using C-place and V-place nodes, she performs her analysis with direct node dependencies, allowing for secondary Place nodes without having the separately labelled V-place node.

3.5.2.2 C and V with unary phonological atoms

Unlike the binary features found in most systems, the phonological atoms of Dependency Phonology, Radical CV Phonology and Government Phonology are unary and enter into relationships of simple combination and dependency.

In Dependency Phonology (see, for example, Anderson & Durand, 1986), the V-like component |V| relates to relatively periodic segments, while the C-like component |C| relates to periodic energy reduction. These components are similar to the Jakobsonian feature set in that they are defined in acoustic terms.

Liquids are represented with a |V| component which governs a |V| and a |C| which are in a relationship of simple combination. This can be symbolised in any of the three equivalent ways in Figure 11.

Of course, many other combinations of |V| and |C| are possible, constrained only by the stipulation that there may be a maximum of two of any component in a particular representation. So, for example, nasals are represented as {|V;C|} and voiced plosives as

{|C;V|}. In Dependency Phonology, then, the set of items described by combinations of C and V (as opposed to singleton C or V) is much wider than in many other theories.

{|V;V,C|} {|V→V,C|}

Figure 11. Equivalent Dependency Phonology representations of the set of liquids.

In one subsequent development of Dependency Phonology, Radical CV Phonology (van der Hulst, 1995), C-like and V-like phonological entities are used even more extensively. In order to produce representations with a drastically reduced set of components, the dependency/government relations are allowed to be more complex. The distinction between lateral liquids and rhotic liquids is handled with instances of C and V in the stricture sub-gesture, rather than with elements or components associated with place.

These dependency-based approaches to phonology go beyond the concept of a C-like phonological entity and a V-like phonological entity combining in the representation of liquids. Instead, there are multiple instances of |C| and |V|, and the definitions of |C| and |V| are therefore necessarily more distant from the traditional notions of consonant and vowel.

Government Phonology is an approach in which licensing constraints are placed on the internal structure of segments (in particular, on the number of elements which may occur at a particular place in structure) based on the structure above the segmental level. The Government approach aims to account for as many phonological phenomena as possible by general universal mechanisms such as licensing constraints and governing relations.

In the melodic structure, the small set of vocalic elements ([A], [I], [U], [@]) are used not only to represent vocoids, but also to represent place of articulation information in consonants: so, for example, [?, U̲, H] represents [p] (with [U] contributing labiality). Government Phonology segments of many kinds therefore include both a vocalic and a consonantal portion: the structural difference between vowels and consonants is handled by the prosodic structure rather than by the presence of C-like or V-like phonological entities.

Harris (1994) represents rhotics in English with a consonantal element, [R], and a vocalic element, [I] or [@], which varies between dialects. Laterals, on the other hand, have two consonantal elements: [R, $\underline{?}$]. Potentially, however, vocalic elements could also be added to the lateral structure to represent resonance quality.

3.5.2.3 C and V in Constraint-Based Phonologies: Optimality and Declarative Phonology

Optimality and Declarative Phonology differ from the other approaches outlined so far in this section, in that they are not in themselves theories of the atoms of phonology; rather they are theories of how phonology is organised and how it works. Typically, Optimality is used within a generative framework and therefore will be combined with an approach similar to one of those outlined in the preceding sections. Walsh Dickey's (1997) work on the phonology of liquids, for example, is set in a feature geometric approach within an Optimality framework.

Declarative Phonology, as it is usually practised, allows for constraints which are more *ad hoc* than universal in nature to be set up as part of descriptions of linguistic objects. However, varieties of a scheme to describe the phonology of English syllables (Coleman, 1991, 1992a, 1992b, 1994, 1998; Local, 1992; Ogden, 1992; Ogden *et al.*, 1999; Ogden *et al.*, 2000) include parts of the representation which are labelled as consonantal and vocalic fields. Both pieces of structure which relate to the traditional concept of *consonant* and pieces of structure which relate to the traditional concept of *vowel* have consonantal and vocalic fields. Pieces of structure which have specified consonantal fields but unspecified vocalic fields relate to the set of most traditional consonants (whose vocalic fields are used to account for what might traditionally be referred to as coarticulation with the tautosyllabic vowel); pieces of structure which have unspecified consonantal fields but specified vocalic fields relate to the set of traditional vowels; liquids and glides are unusual in that they have both a specified consonantal field and a specified vocalic field.

3.5.2.4 Summary

In general, then, the early insights of writers on the phonology of English such as Ellis (1877) and Sweet (1892), referred to above, have been incorporated into modern frameworks and theories which separate C-like and V-like phonological entities. Liquids tend to be members of the set of phonological entities which straddle the dividing line between consonant and vowel.

3.5.3 Gestures

In Section 3.3.1, I outlined Sproat & Fujimura's (1993) analysis of laterals in terms of a gestural score. Gick (to appear), in a similar vein, examines a wider range of data, including (diphthong off-) glides in American English. He reports no evidence of more than one gesture in [j], but in [w] he notes a parallel to Sproat & Fujimura's data for [l] (which Gick also replicates), finding similar support for consonantal and vocalic gestures. A phonetic assignment of consonantal and vocalic labels to gestures as had been done previously in Articulatory Phonology (vocalic gestures produce no extreme obstruction in the vocal tract) would fail to differentiate the two gestures in [w], which would both be classified as vocalic. Instead, Gick uses the terms C-gesture and V-gesture as more abstract labels. He finds evidence of the labial gesture in [w] behaving like the apical (consonantal) gesture in [l], while the dorsal gesture in [w] behaves like the dorsal (vocalic) gesture in [l]. The apical gesture in [l] and the labial gesture in [w] are both then classified as C-gestures, while the dorsal gesture in [l] and the dorsal gesture in [w] are both classified as V-gestures.

Work on liquids within the framework of Articulatory Phonology has enriched the data base with useful articulatory phonetic information regarding the nature and phasing of gestures in liquids.

3.5.4 Features

Early work in feature theory (such as Jakobson *et al.*, 1952, who aimed for a minimal set of acoustically-defined features) emphasised the contrastive phonological nature of the feature set.

Chomsky & Halle's (1968:177) feature structure for liquids in English has the lateral as [+anterior] while the rhotic is [-anterior]. The feature [lateral] is also included in their universal set, so [l] is [+lateral] and [ɹ] is [-lateral]. Dark [ɫ] is not explicitly handled by Chomsky & Halle, but it could be represented within their system by changing certain features to [+high, -low, +back], which represents velarisation, or to [-high, +low, +back], which represents pharyngealisation.

Later in the development of feature theory, Clements (1985), within a feature geometry system, treated secondary articulations in laterals with non-contrastive features which would otherwise be 'uncharacterised', as in Figure 12.

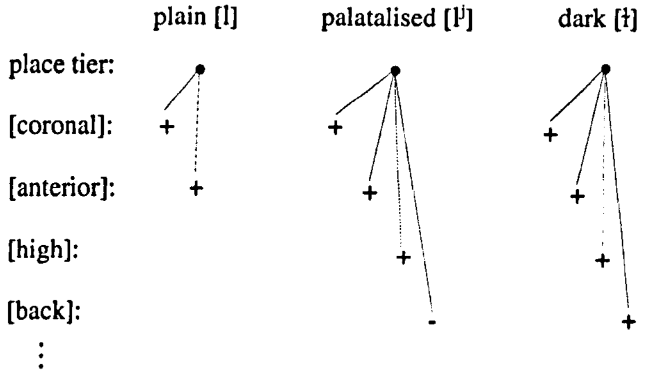


Figure 12. Clements's (1985) representation of secondary articulation in laterals.

Some writers have claimed that such non-contrastive features may sometimes be present in the capacity of enhancement features (Stevens *et al.*, 1986). Stevens *et al.* argue that redundant features may be used to enhance the primary distinctions marked by distinctive features. Sometimes these are part of the phonological feature set (they suggest that [round] can enhance [back] in nonlow vowels) and sometimes they are phonetic effects (phonetic duration can be an enhancement of phonological [voice]). Stevens & Keyser (1989:101), in their search for universally optimal feature combinations, suggest that darkness may be an enhancement in laterals:

> '[+lateral] is enhanced if F2 is positioned relatively close to F1. The combination of these two formants produces a perceptual centre of gravity that is raised relative to F1, thereby enhancing the contrast with sonorant consonants that have a low F1. The decreased value of F2 is achieved with the feature [+back].'

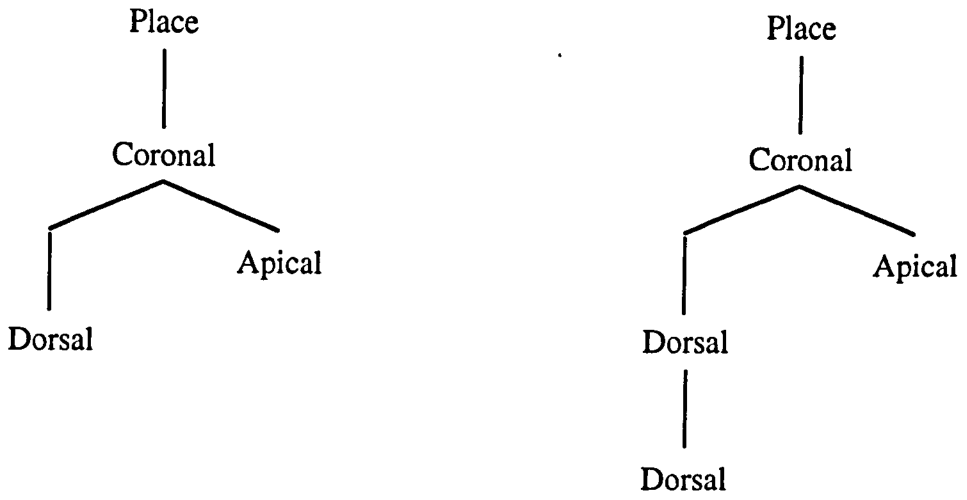
The feature enhancement approach, however, fails to account for instances in which the enhancing feature ([+back] in this case) does not occur even when it is apparently redundant, such as in laterals in syllable initial position in varieties which have clear [l] in that position.

Walsh Dickey (1997) offers a cross-linguistic view of the phonology of liquids, using a feature geometry framework. Her interest is to demonstrate what phonological resources languages have to produce their own phonology. She makes the strong claim that, although there is phonological evidence to support a liquid class (encompassing rhotics and sonorant — but not obstruent — laterals, echoing Chomsky & Halle's, 1968:317, analysis of non-sonorant laterals as [+lateral] but [-vocalic] while other liquids are [+vocalic] and [+consonantal]), there is no need to set up a [±lateral] feature in order to differentiate between [l] and [r]. Instead, she concludes that the structure and content of the primary and secondary Place nodes are sufficient to define and differentiate laterals and rhotics (which do form natural classes). For alveolar laterals at least, the Coronal node is primary and the Dorsal node is secondary.

In a feature geometry in which features are defined in terms of their phonetic content, it is uncontroversial, at least for alveolar or dental laterals, that laterals should include a Coronal node. Distributions in English provide an example, where laterals do not occur in clusters with coronals. Walsh Dickey expresses this in a less convincing fashion (p.21), claiming that monomorphemic words in English cannot contain more than one non-coronal in a cluster, and therefore the patterning of laterals in words such as *elk* demonstrates that they are coronals. Despite counter-examples such as *ink*, however, it is not controversial to class laterals in English as (at least partially) coronal.

Walsh Dickey's (p.67) geometries for the laterals typically found in English (alveolar and velarised alveolar) are reproduced in Figure 13. A velarised alveolar lateral differs from a plain alveolar lateral only by the presence of an additional Dorsal node. This would neatly account for the extra (phonetic) dorsal prominence in dark laterals but, although these representations show some similarities to Sproat & Fujimura's (1993) consonantal and vocalic gestures, they make no predictions about the relative timing of gestures which are predicted by an articulatory theory such as presented by Sproat & Fujimura or a temporal interpretation theory such as that expounded by Coleman (1992a, 1994), Local (1992) and Ogden (1992, 1999b).

Some of Walsh Dickey's argumentation in favour of the presence of a Dorsal node in laterals comes from varieties of English such as Jamaican English which has <little> [lɪkl] and <handle> [hæŋgl]. This she interprets as laterals having dorsal features which spread on to an adjacent consonant, causing a coronal stop to become a velar stop.



Alveolar lateral

Velarised Alveolar lateral

Figure 13. Walsh Dickey's (1997:67) partial feature geometries for alveolar and velarised alveolar laterals.

There is distributional evidence for laterals patterning with dorsals in Pittsburgh English, where non-low vowels are (variably — see McElhinny, 1999) realised as laxer when they precede [l] or [g], with some neutralisation among the back vowels, so <teal> [tɪl], <league> [lɪg], <ale> [ɛl], <Hague> [hɛg], <tool> [tʰʊl], <frugal> [frʊgəl], <toll> [tʰʊl], rogue [ɹʊg] (I have altered Walsh Dickey's own transcriptions only to update the IPA [ʊ] symbol).

Much of Walsh Dickey's cross-linguistic evidence focuses on [l] patterning with [w] or [u], both of which are labio-dorsal articulations. This raises the question of why labial features are not included in her representations if dorsal features are included. However, Walsh Dickey does present evidence of laterals patterning with plain velars, such as is seen indirectly in Jamaican English, but also more directly in Pittsburgh English, in which laterals pattern with [g] in terms of the vowel qualities which can precede them. There is no corresponding evidence of laterals patterning with plain labials.

Some of Walsh Dickey's argumentation for the Coronal node being primary and the Dorsal node being secondary in laterals does not stand up to closer examination, unless phonological constraints apply differently to primary and secondary nodes. For instance, she suggests (p.64) that the constraint against *[tl] in English onsets (where, for example, [kl] is found) is an OCP constraint against two primary coronal nodes, an argument she specifically excludes in the case of Jamaican English outlined above. Moreover, patterning with coronals here is put forward as evidence of the primary nature of the coronal node in laterals, whereas patterning with dorsals was only evidence for the existence (rather than the primary nature) of a dorsal node.

There is also evidence of what happens where laterals appear to be weakened. Where laterals lose coronal features, the resulting dorsal segment is almost always a vocoid (though Walsh Dickey gives the example of Jibbali in which [ɮ] alternates with the stop [g]). She claims (p.64) that where a lateral loses dorsal features, the resulting coronal is always a consonant, though she does give a counter-example of first language acquisition in English in which 'the lateral becomes a vocalic [j]' (p.66). A possible explanation offered is that coronals are preferred in onsets and dorsals in codas. While this ceases to motivate the analysis of coronal as primary and dorsal as secondary aspects of the phonological representation, it does tie in with Sproat & Fujimura's (1993) analysis of laterals with consonantal coronal gestures and vocalic dorsal gestures, with consonantal gestures being preferred syllable-initially and vocalic gestures being preferred syllable-finally, as in the supposedly unmarked CV syllable structure.

Walsh Dickey proposes, along the lines of Lindau (1985) that the category of rhotics is a polymorphous category, with overlapping sets of physical properties and no single defining feature. Even so, rhotics are even more polymorphous than her intrinsically-interpreted structures will allow, since she admits to not being able to account for uvular rhotics. Evidence of non-palatalisation of rhotics leads to all rhotics in her scheme having a non-primary Laminal node, for which there is no phonetic evidence in uvular rhotics. A weaker option is also put forward: that rhotics simply have the feature [liquid] and have a branching non-Corono-Dorsal Place node. Effectively, this defines them simply as non-lateral liquids. Laminal presence in rhotics hints at the analyses offered by Sledd (1966) and Harris (1994), though Walsh Dickey's claims are for the universal structure of rhotics, rather than any language- or dialect-specific forms.

On the Laminal node in rhotics, Walsh Dickey (p.105) suggests a reason for the non-primary Laminal node in rhotics, acting much like an enhancement feature (Stevens *et al.*, 1986; Stevens & Keyser, 1989):

> 'Under this analysis, rhotics are intrinsically palatalized phonologically. This structure for rhotics parallels very closely the complex Corono-Dorsal place structure argued for laterals ... It is indeed possible that the contrast between laterals and rhotics motivates the secondary laminal specification in rhotics. A lateral's articulation is defined by a Corono-Dorsal complex place structure. The secondary Laminal of a rhotic is like an enhancing feature which further distinguishes it from the other liquid, the lateral. This is analogous to the case in Russian, where coronals have either a secondary Coronal or a secondary Dorsal to make the distinction between the two sets greater. This notion of enhancement also leaves open the possibility that the secondary place specification of liquids is only crucial to a language when the phoneme inventory provides at least two liquids. When there is only one liquid in the language, it is conceivable that such extra structure is not required.'

The force of Walsh Dickey's (1997:105) argument for a non-primary Laminal node in rhotics acting as an enhancement feature is that the secondary node may only be needed in a particular language's phonology where there is more than one liquid in that language; the secondary articulation would then serve to enhance the contrast between the liquids. The detail of the structure of the liquids is then dependent on how many liquids there are in the liquid system.

Normally within the theory of feature geometry, a non-primary Laminal node would have the phonetic effect of palatalisation, though Laminal does not have this intrinsic content in the case of rhotics: it is included purely for cross-linguistic distributional reasons, namely that palatal rhotics and rhotics with underlying secondary palatalisation are significantly less frequent in the languages of the world than might be expected by chance, given the frequencies of palatal segments and rhotics. Walsh Dickey also points out that rhotics seem to alternate with high front vowels and resist secondary/derived palatalisation. The presence of an extrinsically-interpreted Laminal node in the geometry for a plain rhotic relegates the avoidance of palatalisation in rhotics to a general constraint (read: tendency) against quaternary place structure, derived from markedness principles which favour less embedded structure. The place node of a coronal rhotic would therefore be the same as the place node of a palatalised alveolar, as in Figure 14.

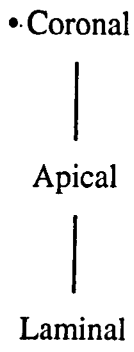


Figure 14. The geometry of the Place node in coronal rhotics and palatalised alveolars.

A palatalised rhotic would have quaternary place structure as in Figure 15. There is a problem with a general tendency against quaternary place structure in Figure 15, in that — unless the features in Figure 15 are all primary nodes as opposed to the existence of primary and secondary nodes in the velarised lateral in Figure 13 — such a constraint would also bar velarised laterals, which are relatively common (and indeed ubiquitous in some varieties of English, such as the Manchester variety discussed in the following chapters).

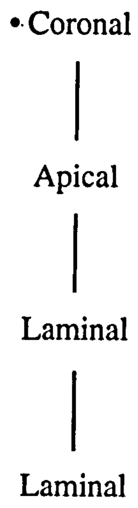


Figure 15. The geometry of the Place node in palatalised coronal rhotics.

Given the admission that there is no phonetic or phonological evidence for a Laminal node in uvular rhotics, 'consistency in ... representations' (p.138) ranks higher in Walsh Dickey's theory even than consistent phonological evidence (though not as high as a dispreference for having more features than are strictly necessary). This is evident from the whole thrust of her dissertation, which is that the feature [liquid] is justified (with a slightly modified definition) but that there is no phonological need for an extra feature [±lateral]. There is phonological support for a liquid class. Laterals are, in fact, a phonetic grouping of items articulated with a narrowed tongue which of necessity makes the tongue longer and therefore more likely to approximate the upper side of the vocal tract at more than one place. Phonologically, in some languages they pattern with coronals and in some with dorsals. Often there are signs of both, as in English where laterals pattern as coronals in the phonotactics of the onset but pattern with back vowels in vocalisation in the rime.

A number of important issues arise from the geometries proposed for liquids by Walsh Dickey. Firstly, there is an accepted need for some language-specific interpretation of universal structures. Since languages which contrast rhotic trills and approximants also distinguish them in place of articulation (enhancement?) with trills typically being alveolar and approximants retroflex, there is no need in the phonology to distinguish [r] and [ɹ] as languages do not use both, preferring instead [r] and [ɻ]. This shared geometry for [r] and [ɹ] is shown in Figure 16.

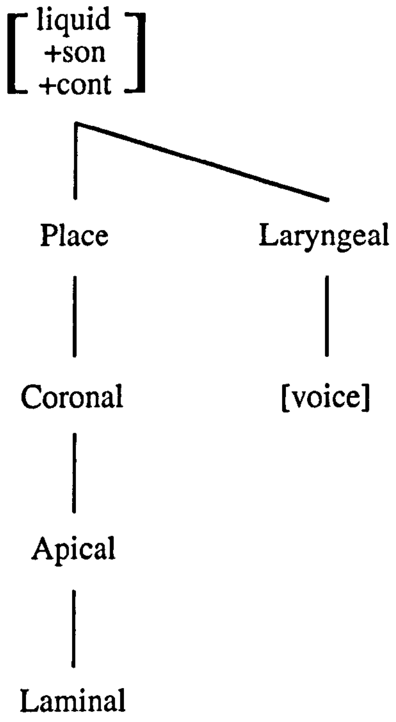


Figure 16. Walsh Dickey's geometry for [r] and [ɹ].

Of course, the intrinsic content of the features in the structure in Figure 16 could not be used to represent the [ɹ]/[ʋ] variation in British English, since the labiodental [ʋ] would presumably be Labial rather than Coronal.

3.5.5 Elements

Harris (1994) explicitly sets out to provide an account of dialectal variation in English within a well-defined theoretical framework: Government Phonology. He is notable among phonologists working on English in that he discusses resonance quality as being associated with rhotics rather than laterals.

Harris (1994:259) discusses the existence of a variety of rhotics as cross-dialectal alternatives, with a tap [ɾ] having the simplest elemental structure among them, [R] ([R], when in combination with other elements, contributes coronality to the interpretation). Thus far, the analysis is similar to the Dependency Phonology approach (Anderson & Durand, 1986) which has {|l|} (the lingual component) as a representation of a non-lateral alveolar liquid and {|l,λ|} (lingual and laterality) as a lateral alveolar liquid. However, Harris goes on to add more elements in his analysis. Harris identifies a typical approximant rhotic as having dark resonance [R, @] and clear rhotics found in some varieties as [R, I]. His source for a clear rhotic variety (Sledd, 1966) refers only to palatalisation of rhotics in certain pre-consonantal environments in some southern American varieties and its reflexes in some nonrhotic varieties such as the Brooklynese *bird* [bəɪd]. This is not, therefore, simple variation between dialects, but structurally-conditioned variation within a single dialect. Given the concerns of this dissertation, that there is indeed variation cross-dialectally in the resonance quality of liquids, it is pertinent to note that Harris's static (within a dialect) analysis may have the potential to account better for the data presented here than for the southern American data. However, I will also argue that some of the variation in resonance in British English [ɹ] is also structurally conditioned.

Laterals are represented as [R, ?̲] — underlining of an element indicates that it is the head of a structure — (Kaye *et al.*, 1989, reported in Harris & Lindsey, 1995: 73). Laterals are closely related to coronal stops, [R̲, ?] on distributional grounds such as Sesotho *bal-a – bad-ile* 'read/count'. Harris & Lindsey also argue on phonetic grounds for the distinction in headedness between the representation of laterals and the representation of coronal stops, but this is a less convincing argument than their primary distributional motivation. They suggest that the headedness of [R̲] in coronal stops results in a greater "degree of lingual contact associated with the closure contributed by [?]" (p.73). The lower status of the dependent [R] in laterals results in a less complete closure. However, it is equally plausible that a headed [?̲] would produce greater closure (whether lingual or otherwise) and a dependent [?] a lesser degree of closure, since [?] represents a sudden and sustained drop in amplitude brought on by closure somewhere in the vocal tract. It is clear, therefore, that arguments on the basis of phonetic plausibility could be used either to support the structure [R̲, ?] or the structure [R, ?̲] as representations for laterals.

Harris avoids discussion of resonance as such in laterals (despite a comment in the paper he refers to with regard to a clear rhotic variety, Sledd 1966:29, 'Just as it is necessary to establish a palatal and a velar !r!, so clear !l! and dark !l! must be distinguished'), and leaves vocalisation of laterals as an exercise for the reader (pp.266-268), although he does provide (p.220) a partial analysis of vocalised [l] (in the course of an exposition of lenition in [t]) which consists of loss of both the elements associated with the lateral, [R, ?̲], and their replacement with [U], 'a reflex of the lateral's originally secondary gesture', suggesting that Harris's own analysis of dark laterals would be [R, ?̲, U]. Presumably, clearness and darkness in laterals could be represented in Government Phonology by the addition of the elements [I] and [@] to the basic lateral scheme, as for rhotics, giving [R, ?̲, I] for a clear lateral and [R, ?̲, @] for a dark lateral. The (supposed) absence of front rounded vowels in English leads to an analysis in which the elements [I] and [U] are found on the same autosegmental tier (as in Kaye *et al.*, 1985), so these two elements (being in some sense in system with each other) are also candidates for representing resonance, as they provide an effective binary opposition. Clear laterals would then be represented as [R, ?̲, I] and dark laterals as [R, ?̲, U]. Either way, a vocalic element would be introduced to accompany the consonantal elements already present.

Clear laterals would then have the elements [R, ?̲, I], with dark laterals having [R, ?̲, @] or possibly [R, ?̲, U]. Dark laterals, however, have noticeably less abrupt spectral transitions than do clear laterals. For elements which are defined primarily in acoustic terms (although [R] is 'coronal'), it is not immediately obvious how a [?̲]-headed segment could fail to show a 'stop' or 'edge' (p.122) with sudden decrease in amplitude. In interpretation of vowels, headedness indicates greater presence of the head element as compared to non-head elements, so [A, I] is interpreted as [ɛ], whereas [A, I] is [e]. A change in a dependent element leaving the head alone (the dark [R, ?, @] as opposed to the clear [R, ?, I]) would presumably not predict an effect on the degree of amplitude fall.

Tollfree (1996) provides a critique of a Government approach to variation in selected consonants of English. One of her concerns is vocalisation in laterals, though much of her discussion is relevant to a discussion of darkness in laterals. Tollfree (1996:170) points out that [U] might not be the most appropriate element to contribute sonorancy to laterals, since vocalised reflexes of laterals do not always display lip rounding and [U] is usually described as representing labiality or labiovelarity. Perhaps a more appropriate formulation would therefore be [R, ?, @] for dark laterals and [R, ?, I] for clear laterals, although this would have to be used only to account for dialect variation (that is, one combination of elements in one dialect and the other in another) since this sort of element change would not be allowed within a single phonology. Phonologically, this would introduce a parallel with rhotics but the phonetic predictions for vocalisation would be inappropriate. The element [@] could contribute velarisation to a consonant but its independent vocalic interpretation would be more central ([ə] or [ɨ]) than is in fact the case, with backer vocoids turning up in vocalised forms, in the region of [ʊ] or [ɤ]. Moreover, clear and dark laterals within the same variety could only be related to each other by change in their elemental makeup, which is inadmissible in the Government theoretical approach.

Tollfree (1996:171) suggests the following possibilities for putative Government representations for laterals: [R, ?, @ *or* U] for clear [l], [R, ?, @ *or* U] for dark [l] and [@ *or* U] for vocalised [l]. She raises the theoretical difficulty of change in the identity of the element which is the head in these representations during the derivation if these variants are indeed to be related.

Tollfree points out that if dark and vocalised laterals have a vocalic element [U] as their head, they should appear in nuclear position rather than onset. Harris (1994:104-105) accounts for [j] and [w] in word juncture by spreading of [I] or [U] to a following onset, so it is possible to express a vocalised lateral in this way in Government Phonology. However, problems occur when a vocalised lateral follows a heavy nucleus, as in <pile> [pɑɪʊ]. The nucleus (which can maximally bifurcate) would be filled by the diphthong, leaving a vocalised lateral in postnuclear rimal position. There would then be even less well-motivated alternations between laterals in the rime (both nuclear and postnuclear) and laterals in the onset.

Tollfree's major objection to the Government analysis is that it is troubled by the variation she found in vocalisation of laterals (and in other examples of consonantal phenomena in English traditionally referred to as weakening or loss). In fact, this is more an objection to the universalist intrinsic interpretation which is part of GP than to the melodic or prosodic structures set up in the theory. The discrete nature of representations in Government Phonology does not seem able easily to account for synchronic variation (particularly within a single variety of the language), and hence for diachronic change. Governing domains are defined at the level of lexical representation and do not change through the derivation. This situation militates against variation, though some dialect differences (such as the clear and dark rhotics in different dialects identified by Harris) could be accounted for by differences in the grammar between one variety (or speaker) and another.

3.5.6 Attributes

There are three extant relatively well-articulated attribute sets in declarative phonology for liquids and glides. These analyses are not historically independent, since they all stem from the structures developed for the YorkTalk speech synthesis system (Coleman, 1992a,b, 1994; Local, 1992; Ogden, 1992), intended for use as a computational testing ground for declarative theories of English phonology interpreted with explicit phonetic exponency functions.

The other two analyses I discuss are Coleman's (1998, based on Coleman, 1991) and that used for the ProSynth speech synthesis system (Ogden et al., 1999, Ogden et al., 2000), both produced by researchers who worked on YorkTalk. Of these, Coleman (1998) is the most explicit in terms of discussion of the substructure of the feature specifications.

3.5.6.1 Coleman's (1998) liquid attributes

In contrast to many other phonological approaches which have C-like and V-like units for only some of their inventory, within the attribute sets deriving from YorkTalk, all consonants are treated as having both consonantal ([cns]) and vocalic ([voc]) fields made up of attributes.

Most consonants have unspecified [voc] fields which are specified in unification with other syllabic constituents; specifically, they share values of the [voc] field with the tautosyllabic vowel. By this method, coarticulation between a consonant and a tautosyllabic vowel can be modelled (Coleman, 1992a:16), although coarticulation is also handled independently by the coproduction approach to exponency, in which the exponents of one category overlap the exponents of another (Coleman, 1992a:36), so the exponents of a vowel will necessarily overlay the exponents of tautosyllabic consonants (since the nucleus is a head while the onset and coda are dependents).

Liquids and glides are the only consonants which have vocalic fields which are (at least partly) specified, allowing for an account of secondary articulation (Coleman, 1992a:14, compares the vocalic field with the Dorsal node in Feature Geometry). Glides (subsuming the category of liquids in this case) are defined by Coleman (1998:290, constraint 7.73) as those entities which have non-empty consonantal ([cns]) and vocalic ([voc]) fields. Coleman's constraint is reproduced here as (3.1).

(3.1)

$$\text{Glide} = \overset{\text{C}}{\begin{bmatrix}\text{consonantal}: & \text{ANY}\\ \text{vocalic}: & \text{ANY}\end{bmatrix}}$$

The consonantal field is associated with place of articulation in such a way that it is possible to set up category templates such as Table 5 (adapted from Coleman 1998:289).

place of articulation	**structure**
alveolar	[cns:[grave:-, compact:-]]
labiovelar	[cns:[grave:+]]
palatal	[cns:[grave:-, compact:+], strident:+] ([strident] is unspecified in the palatal template in Coleman, 1991).

Table 5. Place of articulation category templates from Coleman (1998).

Vocalic fields are associated with secondary resonance aspects of the glides. Coleman accommodates the cross-dialectal resonance polarities by suggesting (p.291):

> 'according to Kelly and Local 1986, the values of [grave] in /l/ and /r/ might be reversed in other dialects, but would nevertheless be opposite to each other in all the dialects of English they have examined.'

Coleman's constraints (7.74) and (7.75) do not have opposite values for [grave] in /l/ and /r/ (they are both [voc:[grave:+]]). However, it is evident from discussion in the text (p.291: 'Observe that [grave] distinguishes palatal /y/ [=/j/] and clear /r/ from labiovelar /w/ and dark /l/') and comparison with Coleman's (1991) dissertation (on which Coleman, 1998, is based) that the attribute structure given for /r/ includes a typographical error and /r/ should have the value [voc:[grave:-]]. There would then indeed be opposite values for [voc:[grave]] in /l/ and /r/, so (assuming the presence of an error in the text of Coleman, 1998) Coleman's features are as in Table 6 (I have altered Coleman's /y/ to /j/).

phonemic equivalent	unification of templates and structures
/l/	alveolar ∪ glide ∪ [voc:[grave:+, height:close, round:-]]
/r/	alveolar ∪ glide ∪ [voc:[grave:-, height:mid, round:+]]
/w/	labiovelar ∪ glide ∪ [voc:[grave:+, height:close, round:+]]
/j/	palatal ∪ glide ∪ [voc:[grave:-, height:close, round:-]]

Table 6. Unification of templates for liquids and glides in Coleman (1998).

The unification of [voc] fields brings to light an apparent problem with the interpretation of declarative structures of this sort. When constraints are unified to form larger pieces of structure (as discussed in Section 2.3.1), it is not immediately obvious how a constraint such as (3.1) can be expressed in a declarative sense, given that phonetic exponency would operate on the unified structure, in which the [voc] field in any consonant would be filled by unification with attributes in the ([voc] field of the) tautosyllabic vowel. At the time of interpretation, then, all consonants (and not just glides) would seem to satisfy the right hand side of the equation in (3.1). This problem can be exemplified in a pair of words such as *booth/boule*. In *booth*, the structure associated with the final [ð] is specified as voiced ∪ mellow ∪ alveolar ∪ fricative, which expands to [nasal:-, voice:+, strident:-, continuant:+, cns:[grave:-, compact:-]]. In unification with the vowel (since the consonant does not exist independently of the syllable), the coda consonant would then be represented as [nasal:-, voice:+, strident:-, continuant:+, cns:[grave:-, compact:-], voc:[grave:+, height:close, round:_]] (the underscore symbol in [round:_] represents an unspecified value). In *boule*, the final [l] is specified as alveolar ∪ glide ∪ [voc:[grave:+, height:close, round:-]] which expands to [cns:[grave:-, compact:-], voc:[grave:+, height:close, round:-]]. Informally, it is not hard to see that the lateral would also have the values [nasal:-, voice:+, strident:-, continuant:+]. Compare the two representations at this stage:

(3.2) *booth* [nas:-, voi:+, str:-, cnt:+, cns:[grv:-, cmp:-], voc:[grv:+, height:close, rnd:_]]

(3.3) *boule* [nas:-, voi:+, str:-, cnt:+, cns:[grv:-, cmp:-], voc:[grv:+, height:close, rnd:-]]

Clearly, (3.3) describes a subset of the objects described by (3.2). In phonetic interpretation, the two could easily turn out identical, since (3.3) is a possible fully-specified version of (3.2). It might therefore seem that constraint (3.1) needs to be satisfied before unification. Such a stipulation is clearly not possible because it would make the phonology procedural and, by definition, no longer declarative. There needs to be a way of expressing constraint (3.1) without the interpretation mechanism needing to interpret this constraint before unification.

The problem, however, is more apparent than real. The solution is to be found when these attribute-value matrices are expanded into the directed acyclic graphs for which they are shorthand. In the case of the non-glide, a [voc] field is shared with the vowel: the [voc] field in question is dominated by two nodes (nucleus and coda) and there is token identity (see, for example, Scobbie, 1997:33). In the case of the lateral, however, two separate [voc] fields accidentally look similar: the nucleus dominates one [voc] field and the coda dominates another; there is merely type identity.

Coleman (1998:198-202) also presents an alternative analysis for [voc] fields in laterals, giving the example of English dark /l/ as [consonantal:[compact:-, grave:-], vocalic:[grave:+, compact:+], source:[nasal:-]] (also found in Coleman, 1992a:14). In this scheme, [cns] and [voc] fields have similar attributes but [voc] fields which unify with [voc] fields dominated by nuclei would then have a different set of attributes to specified [voc] fields as in liquids and glides. In this scheme (Coleman chapter 5), unlike the previously discussed scheme (Coleman chapter 7), [round] is specifically excluded from the attribute set in the [voc] field on the grounds that it is ‘not distinctive in the structural positions in which this category may occur (in English)' (p.199). In the chapter 7 scheme, [round] is included specifically to distinguish /l/ from /w/.

These two schemes do not conflict (as might at first appear), since 'the structural positions in which [dark l] may occur' are not the same as those in which /w/ occurs: dark [l] is found in the rime while [w] is found in the onset.

Nevertheless, this does not sit easily with Coleman's chapter 7 scheme, since the chapter 7 scheme allows for the sort of cross-dialectal variation (at least in nonrhotic varieties) expounded in this dissertation in which dark laterals can be found in onset position where [w] is also found. Indeed, not only is this variation permissible but the working out of the (chapter 7) scheme Coleman gives does in fact model a dark [l] variety which would have dark [l] and [w] in opposition in onset position. In further discussion, then, I will limit myself to Coleman's chapter 7 scheme, which is closer to the YorkTalk and ProSynth schemes.

3.5.6.2 YorkTalk liquid attributes

The attribute set used in YorkTalk is similar to Coleman's chapter 7 scheme (with [voc:[grv, height, rnd]]), though the palatal glide shares the value [str:-] with the other glides. In this way, [strident] is maintained as a purely [source] attribute, rather than as a [source] attribute which combines with [consonantal] attributes to form a place of articulation template. Moreover, the values of [voc:[grave]] in /l/ and [voc:[round]] in /r/ are unspecified in YorkTalk, as opposed to having the values [voc:[grave:+]] and [voc:[round:+]] respectively in Coleman's analysis. The YorkTalk [voc] fields are presented in Table 7.

phonemic equivalent	**[voc] field**
/l/	[voc:[grave:_, height:close, round:-]]
/r/	[voc:[grave:+, height:mid, round:_]]
/w/	[voc:[grave:+, height:close, round:+]]
/j/	[voc:[grave:-, height:close, round:-]]

Table 7. YorkTalk [voc] fields for liquids and glides.

At first glance, the unspecified value for [voc:[grv]] in the YorkTalk equivalent of /l/ would appear to allow an identical structure to the equivalent of /j/. However, this is an instance of the same issue as was discussed in Section 3.5.6.1, namely that where the unspecified value of [voc:[grv]] receives a value, it is through sharing a [voc] field with a tautosyllabic vowel, whereas the specified value of [voc:[grv]] has its own [voc] field which may, coincidentally, be identical to that of a tautosyllabic vowel.

3.5.6.3 ProSynth liquid attributes

The ProSynth project adopted the YorkTalk attribute set, with two attributes added to the scheme solely for ease of processing (with the aim of writing scripts to interrogate an XML-encoded database and produce novel structures for synthesis): [son] (with the value [son:+] for all liquids and glides) and [rho], with the value [rho:+] for /r/ and [rho:-] for all other liquids and glides. This difference, then, has a practical rather than theoretic phonological origin, since the values of [son] and [rho] are entirely predictable from the values of other attributes in the ProSynth scheme.

One major difference between ProSynth and its predecessor YorkTalk is that unspecified boolean attributes in ProSynth do not remain unspecified; rather they default to a value of "N" (rather than "Y" or the unspecified value "_"). Translating the XML structures of ProSynth into a similar representation to the YorkTalk system therefore gives the structures in Table 8.

phonemic equivalent	**[voc] field**
/l/	[voc:[grave:-, height:close, round:-]]
/r/	[voc:[grave:+, height:mid, round:-]]
/w/	[voc:[grave:+, height:close, round:+]]
/j/	[voc:[grave:-, height:close, round:-]]

Table 8. ProSynth [voc] fields for liquids and glides.

ProSynth and Coleman (1998) therefore display the variation in the value of [voc:[grave]] associated with the traditional phonemes /l/ and /r/ that Coleman suggested could describe the cross-dialectal resonance polarity effects. ProSynth would be modelling a variety such as Sunderland English, with a clear initial lateral (it is, in fact, a model of southern British English), while Coleman is modelling a variety, such as Manchester English, with a dark initial lateral. YorkTalk, however, has an unspecified value of [voc:[grv]] for /l/, allowing for coarticulatory effects. Interestingly, the YorkTalk analysis might support Bladon & Al-

Bamerni's (1976) observations presented in Section 3.3.2 in which onset laterals appear to coarticulate more than onset rhotics, since, in the case of the lateral, the value for [grv] in the syllabic nucleus would be shared by the vocalic field in the onset (and could therefore be either [grv:+] or [grv:-], allowing for relatively great variability in the interpretation), while in the case of the rhotic, the value for [grv] in the onset vocalic field is set at [grv:+]. The variation possible in the interpretation of the unspecified [rnd:_] in the vocalic field of rhotics in YorkTalk might allow for coarticulation but would be less likely to influence resonance effects since, in Coleman's analysis, [grv] is recognised as the attribute which carries the resonance effect information.

3.5.6.4 Motivation of liquid attributes

Consonantal and vocalic fields are both specified in liquids and glides in YorkTalk and its developments because liquids and glides pattern in some respects with consonants and in others with vowels, but there is some mixing of phonetic motivation and phonological motivation.

Coleman's (1998) attributes themselves are justified mainly on phonetic grounds: /l/ has a value [voc:[height:close]] on the basis of the vowel in a vocalised form such as *milk* [mɪɤk]. The values of [voc:[rnd]] are assigned 'according to simple phonetic observation' (p.291). However, there is often (though not always — see Tollfree, 1999:174) some degree of rounding in vocalised forms such as *milk* [mɪʊk]. If the phonetics of vocalised forms can motivate the value of [voc:[height]], there is no reason for the phonetics of vocalised forms not to motivate the value of [voc:[rnd]] in a similar fashion. It is not therefore necessarily obvious what value of [voc:[rnd]] should be assigned on the basis of phonetic observation.

The extra feature [voc:[rnd]] is included because the logically necessary feature set (two binary features to distinguish four items) is not sufficient since /l/ and /w/ share the same values of [voc:[grv]] and [voc:[height]]. Additionally, of course, [voc:[height]] is a ternary feature (the value [voc:[height:open]] is also possible), so logically twelve items could be distinguished, as in Table 9. Not taking into account, for example, differing constraints at different points in syllable structure, the [cns]/[voc] field analysis generates four values for [cns] (two binary attributes) and twelve values for [voc] (two binary attributes and one ternary attribute), allowing for a total of 48 structures. The feature system therefore overgenerates unless negative constraints (or the absence of positive constraints) are stipulated.

attribute			phonemic equivalents		
voc:			Coleman (1998), corrected	YorkTalk	ProSynth
grave:	height:	round:			
-	close	-	/j/	/l/, /j/	/l/, /j/
-	close	+			
-	mid	-			
-	mid	+	/r/		
-	open	-			
-	open	+			
+	close	-	/l/	/l/	
+	close	+	/w/	/w/	/w/
+	mid	-		/r/	/r/
+	mid	+		/r/	
+	open	-			
+	open	+			

Table 9. Potential overgeneration in the liquid and glide attribute sets.

3.6 Conclusion

In this chapter I have discussed how laterals and rhotics form a system in the phonology of English and how resonance is an important aspect of their phonetic shape. I have detailed previous work on the phonetics of liquids and discussed how their complex nature relates to phonological analyses. In common with a variety of phonological approaches which identify consonantal and vocalic material in liquids, Sproat & Fujimura's (1993) division of laterals into two gestures (a consonantal apical gesture and a vocalic dorsal gesture) is compatible with the analysis I will present.

Kelly & Local's (1986, 1989) work, amongst others, shows that there is a spread of dialectal variation within the liquid system of English. The most well known liquid system shibboleth for dialects of English is rhoticity, but I will argue, along with Kelly & Local, that clearness and darkness also appear to play an important part in dialectal differences. I will support this claim not only with evidence from nonrhotic varieties comparable with those Kelly & Local investigated, but also from rhotic varieties.

In the following chapters I will argue that liquids are best accounted for by a unified scheme of clearness and darkness. Clearness and darkness are not intrinsically linked to a particular articulation: in laterals, darkness may be produced by tongue backing, whereas in rhotics darkness may be produced by lip rounding or a combination of lip rounding and tongue position.

The acoustics of clearness and darkness involves F2 and the F2-F1 space. I will argue that, although F3 is indeed the major acoustic cue for the distinction between [l] and [ɹ], F2 in particular is also crucially important for a coherent account of liquids in English. I will outline how F2 shows consistent patterns not only at a distance such as West (2000) reported, but at the point of the lateral or rhotic articulations themselves. I will show how the opposite patterns Lehiste (1964) found for laterals (large F2-F1 space in syllable-initial position and small F2-F1 space in syllable-final position) and rhotics (small F2-F1 space in syllable-initial position and large F2-F1 space in syllable-final position) are crucially important for the operating of the liquid system in varieties of English. I will demonstrate that clearness and darkness are indeed important enhancements of the distinction between laterals and rhotics, but that the distinction is not automatically in favour of darkness in laterals (as Stevens & Keyser, 1989, suggested); it varies cross-dialectally.

I will present evidence to support the argument that natural phonetic processes implemented as an intrinsic part of phonological structure are not sufficient to account for cross-dialectal variation. Sproat & Fujimura's (1993) paper is far from unusual in accounting for a well-known phonetic pattern in terms of a natural articulatory explanation. In the presentation of my data in the following chapters of this dissertation, I aim to extend Sproat & Fujimura's work beyond articulatory phonetics and beyond laterals by concentrating on acoustics and by including also a comparison with the closest phonological relation of laterals in English, rhotics, in an attempt to see if a natural articulatory explanation is adequate to explain data which are phonologically similar but which come from a wider range of varieties of English.

Sproat & Fujimura's instrumental investigation has provided valuable data on the gestural phasing of laterals. However, I will argue that their phonological speculations make too many assumptions: gestural alignment is less strictly associated with syllable structure than they suggest, and clearness and darkness are less of an epiphenomenon than they suggest. In fact, even within a similar phonological framework, Huffman (1997) points out that the situation is somewhat more complicated than Sproat & Fujimura suggested.

A gestural model relies on intrinsic interpretation of phonological units with reference to limited structural information; the data I will present in subsequent chapters support the need for structural information but challenge the validity of intrinsic interpretation.

Walsh Dickey (1997) argues that the secondary node in rhotics may only be needed when there is more than one liquid in the language under investigation, with secondary articulations enhancing the contrast between liquids. The detail of the structure of the liquids is then dependent on how many liquids there are in the liquid system. Such a systems-driven phonology (or phonetic exponency, in a neo-Firthian framework) is, unfortunately, not used to its full potential in a universalist exploration of cross-linguistic phonological structure of liquids such as Walsh Dickey's. In a polysystemic approach within an individual language, English, this is the argument that can be used to account for differing phonetic patterns at different points in syllable structure, dependent on what systems of contrast obtain at the point in question. This is precisely the line of argumentation which will be taken up in later chapters of this dissertation.

I will present a phonological analysis, informed by the neo-Firthian declarative tradition, which will tackle the issues I have raised here, such as how an abstract phonology relates to phonetic justification of attributes and variation between dialects, and how such a phonology might reduce the overgeneration present in previous declarative analyses.

4 Introduction to experiments

4.1 Introduction

4.1.1 Resonance quality

The purpose of this study was to search for patterns of resonance quality involving clearness or darkness in liquids. Since previous work on resonance qualities associated with liquids has tended to concentrate on laterals, the dialects under examination here will be defined in terms of the clearness or darkness of their laterals, in particular, in terms of the clearness or darkness of their syllable-initial laterals. In defining this variable in terms of syllable-initial laterals, no claim is being made regarding any putative theoretical prominence of laterals over rhotics or of syllable-initial position over syllable-final position: defining dialects in this way serves only as a convenient expository tool, since previous work on resonance qualities associated with liquids has tended to concentrate on laterals.

4.1.2 A note on the bark scale

For some of the analysis to be presented, it is essential for the difference between any one pair of formants to be comparable to the difference between any other pair of formants. Without the use of a perceptual scale, it is impossible to tell whether a difference of, say, 200 Hz is as important when that 200 Hz represents the F3-F2 space as it would be when it represents the F2-F1 space. The perceptual inadequacy of the frequencies measured in Hertz for each formant would necessarily skew the results of any statistical analysis. The bark scale, being perceptually-based, avoids such difficulties.

Formant frequencies measured in Hertz were bark-scaled using Traunmüller's (1983, 1988, 1990) approximation formulae (see Appendix 1 for a discussion of why this group of formulae was chosen rather than a more common alternative, such as Zwicker & Terhardt, 1980).

The bark scale was chosen over the ERB for the principled reason that much of the analysis is dynamic (see Appendix 1 for more details). However, above about 500 Hz, the two scales are proportional to one another and, indeed only minimal differences were found when the formant data were transformed into an ERB scale as opposed to a bark scale. I will therefore present only bark-transformed data.

4.1.3 Note on phonetic transcription

Since most of the discussion of the experimental investigation of liquids in this and subsequent chapters centres on the one hand around acoustic details too fine to be easily captured in a transcription system and, on the other hand, differences between the realisations of two categories, I will follow the International Phonetic Association's (1999:159) principle 4(a), namely to employ plain Roman characters where possible for clarity and simplicity.

Laterals and rhotics will therefore in general be transcribed straightforwardly as [l] or [r]. Where narrower, more precise, transcriptions are necessary, their use will be made clear in the surrounding text. In particular, the transcription symbol [r] should not be taken to represent an alveolar trill. Instead, it is used with the status of a generalised, broad transcription, as a representation of English rhotics in general.

I avoid the use of the phonemic slash-bracket representation (such as /r/), preferring to use instead the square bracket notation (such as [r]) for both narrow and broad phonetic transcriptions. No commitment is being made at this stage to a phonological analysis, which is implicit in the slash-bracket notation. I will argue (in Chapter 8) for a non-segmental phonology with phonological attributes distributed across the prosodic hierarchy, leaving no unitary composite phonological segment (which might be represented as /r/) in the conventional sense.

4.2 Research questions

In this section I will outline the two acoustic experiments which were carried out. Section 4.2.1 introduces an investigation into liquids in syllable-initial and syllable-final position. Section 4.2.2 introduces an investigation into liquids in syllable-initial position in greater detail for a subset of the varieties examined.

4.2.1 Experiment 1: liquids and syllable position

Experiment 1 was designed to study liquids in initial and final syllable positions, controlled for the context of the vowel in the syllable.

Initial hypotheses for this study followed the findings of Kelly & Local (1986, 1989), in which varieties of English which have typically clear initial [l] have dark initial [r] and varieties of English which have typically dark initial [l] have clear initial [r].

Kelly & Local's observations relate only to nonrhotic varieties of English, in which there is no contrast in the liquid system syllable-finally since rhotic articulations are only present as markers of juncture (as 'linking' or 'intrusive' r). In order to extend Kelly & Local's analysis so that it is appropriate also for rhotic varieties of English, syllable position must be taken into account.

Sproat & Fujimura (1993) support traditional claims that there is a phonetic tendency (at least in English) for [l] in syllable-final position to be darker than [l] in syllable-initial position. Given this observed relationship between syllable position and the resonance quality of laterals, and the existence of the polarities identified by Kelly & Local, and also following preliminary auditory impressions, the hypothesis was extended to predict that opposite resonance quality would be found in certain pairs of liquids, as in Table 10. As a corollary, certain other pairs of liquids will share the same resonance quality.

Opposite resonance quality	**Shared resonance quality**
syllable-initial [l] & syllable-final [l] (following Sproat & Fujimura)	syllable-initial [l] & syllable-final [r]
syllable-initial [l] & syllable-initial [r] (following Kelly & Local)	
syllable-initial [r] & syllable-final [r]	syllable-initial [r] & syllable-final [l]
syllable-final [l] & syllable-final [r]	

Table 10. Full set of predictions of resonance qualities in liquids.

The experiments will also test the hypothesis that long duration equates with darkness. Sproat & Fujimura (1993) predict that laterals (particularly in rimes) should be darker if they are of greater duration, since the dorsal gesture has more time to become prominent. This prediction was supported by Newton (1993, 1996) and in part by Huffman (1997).

Bladon & Al-Bamerni (1976) suggested that coarticulation was more prevalent with clear (syllable-initial) laterals than with dark (syllable-final) laterals. Two possible extensions of Bladon & Al-Bamerni's analysis to an analysis of liquids in general are examined here: firstly a prosodic structure-based hypothesis, that syllable-initial liquids (whether [l] or [r]) coarticulate more than syllable-final liquids (whether [l] or [r]); or, secondly, a resonance-based hypothesis that clear liquids (whether syllable-initial [l] or syllable-final [r]) coarticulate more than dark liquids (whether syllable-initial [r] or syllable-final [l]). This second possibility might be suggested by Nolan's (1983) analysis of standard southern British English, which reported (p.91) a considerably greater effect of following vocoid quality on initial laterals than on initial rhotics, although there was still some evidence of coarticulation in the rhotics.

4.2.2 Experiment 2: liquids in onsets

Experiment 2 includes more detailed investigations into the cross-dialectal variability which is permitted in onset liquids in the nonrhotic varieties, in particular the claims that onset laterals have the opposite resonance quality from onset rhotics and that articulatory information about these differences can be indirectly extracted from formant transition spectro-temporal detail. Experiment 2 has a greater number of tokens than Experiment 1 and increases the reliability of statistical results with the consequent increase in degrees of freedom.

Sproat & Fujimura predict that clear laterals are intrinsically associated with syllable-initial position, an analysis which has the potential to conflict with Kelly & Local's observations about dark syllable-initial laterals in certain varieties of English. The case which speaks most clearly to these previous studies of liquids in English is the onset lateral in Manchester English, which is dark.

Since the most notable variation is found in syllable-initial position, the metrical position of the liquids in Experiment 2 was restricted to the syllable onset.

A variety of acoustic measures are used to investigate effects in the data. Classification and regression trees are used as a knowledge-driven technique of data exploration. Detailed traditional formant measures are supplemented with a number of spectral moments analyses.

4.3 Materials

There is evidence, at least from French (Marchal *et al.*, 1995), that the distinction between nonsense and real words can affect liquids. Marchal *et al.* compared the production of [ulu] in nonsense data, in citation form and in fluent sentence form. The duration of [l] was greater in the nonsense word than in the citation form, and greater in the citation form than in the sentential context.

There is also similar work which gives cause for caution regarding the investigation of liquids in laboratory speech. Chafcouloff & Marchal (1995) examined variation between data gathered under laboratory conditions and data gathered as spontaneous speech. Although their data were French tokens (with liquid articulations different from those found in English), it is likely that their findings are also relevant to English language data. They found that the steady state duration of sonorants was significantly shorter in spontaneous speech than in laboratory-controlled speech, but that the duration of formant transitions was less affected. This state of affairs was particularly prevalent with [l], which was found to have the longest steady-state portion and the shortest transitions. They found no significant difference in F2 frequencies between the two registers of speech.

Despite these drawbacks, however, the use of read laboratory speech is necessary in order to achieve adequate experimental control.

Each lexeme used in word lists in this study is an actually-occurring English monosyllable. For details of the experimental materials themselves, see Chapter 5.

4.4 Techniques

A variety of techniques will be used to investigate the role of resonance.

4.4.1 Cluster analysis

Cluster analysis provides a principled method of sorting data where variables are not entirely independent (as is the case with formant frequencies). In an attempt to provide a more objective comparison of the spectral characteristics of the liquids in the varieties reported (for example, without necessarily prejudging which formant might be most relevant for the analysis), a cluster analysis was performed in order to identify groups of cases within the data which have some internal similarity.

The bark scale, being perceptually-based, is particularly suited to the requirement for a distance metric, since distances at one part of the scale are equivalent to distances at another part of the scale.

Given the large acoustic difference between laterals and rhotics found in F3, then the output of a cluster analysis (even with data from other formants included) would be expected to show a predominant clustering of cases of [l] as opposed to cases of [r].

If resonance quality has a noticeable effect on these data, the anticipated straightforward division between laterals and rhotics will be disrupted. The hypothesis is, then, that cluster analysis will result in more complex clusters than a simple [l]/[r] split.

4.4.2 Classification and regression trees

Classification and regression tree building (Breiman *et al.*, 1984) is an information theoretic exploratory approach which has been used for training models from labelled data sets in speech synthesis systems such as Festival (Black & Taylor, 1997) and ProSynth (Ogden *et al.*, 2000). As a technique it has the advantage of combining statistical information from databases with the specified linguistic knowledge expressed in the labelling system of attributes and values. The output is a series of binary decisions based on the values of attributes which predicts the value of a discrete variable (a classification tree) or of a continuous variable (a regression tree).

For the purposes of the analysis presented in this dissertation, classification and regression trees can be thought of as knowledge-based clustering. They are easier than clusters to interpret in a larger data set and can incorporate a range of different variables with non-uniform dimensions. Both discrete and continuous variables can be used as predictors.

4.4.3 Formant space

It has been suggested (for example by Syrdal & Gopal, 1986) that the bark scale provides a useful tool for comparison across speakers and across sexes when measurements are given in bark differences. At the very least, analysis of formants in terms of bark differences provides a fairly crude first pass at a normalisation for the differing sizes of vocal tracts between speakers which lead to differing acoustic natural resonance characteristics and hence differences in the absolute placement of formants in speech.

The present work uses all male speakers so the issue of cross-sex comparison does not arise (except in using the results of these experiments to make predictions about the varieties in general, beyond the particular data from the speakers in this study), but in order to present what may be a slightly more robust comparison of the speakers, plots and statistical test results will also be presented in bark difference terms. F2 is generally identified as the main correlate of clearness or darkness in liquids (see, for example, Gimson, 1962: §8.24), though F2-F1 has also occasionally been used as an indicator of frontness and backness (for example Ladefoged, 1993, and Butcher, 1974, who correlates 'brightness' with a greater frequency difference between F1 and F2). Note also that Stevens (1998:515) computes that F1 frequencies are lower in glide-like articulations when the constriction is further forward in the vocal tract. It is therefore quite likely that both a high F2 and a low F1 contribute to a large F2-F1 space in liquids with clear resonance quality.

Syrdal & Gopal (1986) suggest that high vowels have an F1-F0 space of less than 3 bark, while front vowels have an F3-F2 space of less than 3 bark. If clear resonance corresponds especially to front vocoid quality but perhaps also to high vocoid quality, then a bark-transformed F2-F1 space is an appropriate measure for clearness and darkness since a large F2-F1 space (representing maximal clearness) could be associated with a small F3-F2 space (due to a relatively high F2, and indicating front vocoid quality) and/or a small F1-F0 space (due to a relatively low F1, and indicating high vocoid quality).

4.4.4 Spectral moments

A traditional analysis of formant peaks does not give the full picture of spectral detail available to the analyst or the hearer. Chistovich (for example in Chistovich, 1985) has reported that formant peaks closer to each other than 3.0-3.5 bark produce a perceptual centre of gravity effect in which the relative amplitudes of the formants are used in perception, alongside the frequencies of the peaks.

It is possible to produce an integrated peaks model which would combine formant peaks with centre of gravity information by replacing a close (within 3 or 3.5 bark of each other) pair of formant peaks at any given sample point with a measure of the centre of spectral gravity between those two formants. A model of this kind is exemplified by the single token of the word <lag> taken from the data set for Experiment 2, in Figure 17. Time is normalised, so that sample points 0-10 represent a transition into [l], 10-20 represent the steady state of [l], 30-40 represent a transition out of [l] and 30-40 represent the vocoid [a].

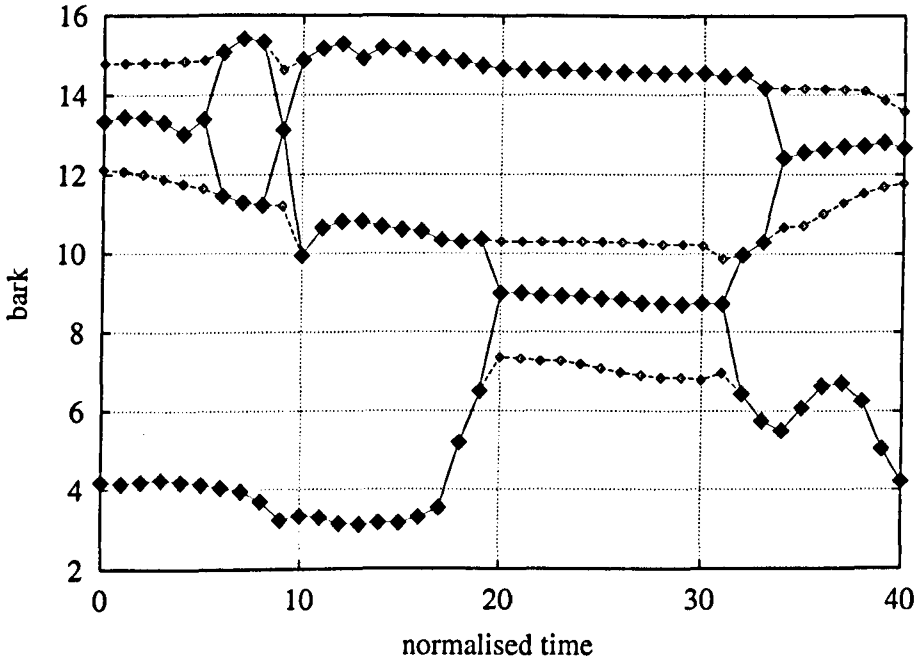


Figure 17. Formant tracks and integrated peaks model plot in normalised time of a token of <lag> by the Sunderland speaker. Filled diamonds represent points in the integrated peaks model; open diamonds represent formant tracks, where the formant tracks do not coincide with the integrated peaks model.

At sample point 0, there are two peaks (represented by the filled diamonds in the plot). The lower peak equates to a single formant peak (F1 in this case), but the upper peak corresponds to a centre of gravity (weighted average) of F2 and F3. The unmerged formant peaks are represented by open diamonds in the plot. At sample point 6, F2 and F3 are separated by more than 3.5 bark, and the single peak of the model bifurcates into the two formant curves. Further along the normalised time axis, at sample point 20, F2 has separated from F3 and approached F1 to such an extent that the centre of gravity effect applies and the two formant curves (F1 and F2) coalesce into a single curve. Once again, there are only two peaks in the model. However, unlike at the beginning of the normalised time period, here it is F1 and F2 which are (in a sense) 'averaged', rather than F2 and F3. By the second half of the vocoid portion, though, the two peaks correspond again to F1 on the one hand and a weighted average of F2 and F3 on the other.

An integrated peaks model can shed light on the observation that F1 may enhance the darkness of an extremely low F2 (as for the Manchester speaker: see, for example, Section 6.1.2.1). If the perceptual mechanism is tracking an F2 as it approaches its minimum, then a high F1 could come within the 3.5 bark cut-off point and effectively lower the percept of the trajectory still further since F1 and F2 peaks would no longer be resolved but would be perceived as a single weighted average.

Plots such as Figure 17 give an intriguing view of each individual token but it is not straightforwardly possible to draw statistical generalisations over the whole dataset since not all tokens have the same number of peaks at any given sample point: at some sample points there are three peaks, corresponding to the three formant peaks; at other sample points, pairs of formant peaks are merged into a single centre-of-gravity peak.

The possibility of making statistical generalisations means that a simple spectral moments analysis (Forrest *et al.*, 1988) is worth carrying out in conjunction with the formant analysis. The detail of the spectral envelope which is missing from the formant analysis can then be supplied by the moments analysis and the precise location of the formant peaks — missing from a moments analysis — can be provided by the formant analysis.

Since a spectral moments analysis can be supported (at least in part) by a perceptual model (see, for example, Zahorian & Jaghargh, 1993, on information from whole spectra improving on formant peak information, and Ito *et al.*, 2001, on how the amplitude ratio of high to low frequency components can be a cue for vowel perception even where formant separation is greater than 3.5 bark), it can lead to a more integrated understanding of the acoustic detail than can a traditional formant peak analysis on its own.

There are four spectral moments.

The first moment is the mean, often referred to as the centre of gravity. It is an amplitude-weighted average frequency.

The second moment is the variance around the mean.

The third moment, skew, corresponds roughly to the acoustic notion of spectral tilt.

The fourth moment, kurtosis, is a measure of how much data is found in the tails of a distribution: a flatter than normal distribution has negative kurtosis whereas a distribution with a sharper peak than normal has a positive kurtosis. Since acoustic spectra from speech are not simply made up of one large resonance with varying bandwidths, this definition will not quite hold for a spectral moments analysis; however, it can still be a useful measure of overall spectral envelope.

While skew and kurtosis are less easy to interpret with speech data than are the centre of gravity and the variance, these moments provide a more abstract spectral representation which has been used in speech applications such as the classification of fricatives (Forrest *et al.*, 1988).

Details of the algorithm used for calculating the moments are given in Section 5.3.6.

5 Experimental method

5.1 Materials

The materials for the experiments comprised read lists of words in a frame (“Say ... again”). The word lists included pairs of words which differed only in whether they contained a lateral or a rhotic.

5.1.1 Experiment 1: liquids and syllable structure

Sixteen phonologically representative lexemes (Table 11) were selected for Experiment 1.

	front vowel context		**back vowel context**	
high vowel context	lead	reed	loot	root
	deal	deer	tool	tour
low vowel context	lap	rap	law	raw
	pal	par	all	oar

Table 11. Lexemes investigated in Experiment 1, arranged by phonological structure.

Each lexeme includes one liquid in either initial or final position in the syllable. The lexemes are arranged so that there are a set of minimal contrasts which (at least for the speakers of rhotic varieties) have lateral versus rhotic articulations as their phonetic exponents.

The vocalic contexts in which the liquids were placed vary along the dimensions of phonological height and frontness versus backness. The vocoids [a] and [ɑ] can be treated as contextually-conditioned exponents of the same category since in rhotic dialects they are in complementary distribution. It is therefore legitimate to treat the [l] in *pal* and the [r] in *par* as being in the same vocalic context. For this reason [a] and [ɑ] are conflated and counted as “front.” These contrasts represent, as far as is allowable within the constraints of the English lexicon, extremes of the vocoid quality continua.

For comparison, additional data were also examined from a published source: Lehiste (1964) investigated in some detail the spectral properties of syllables containing liquids in American English. In the present study, the results Lehiste gives for one speaker ('GEP', whose data are more extensive than Lehiste's other speakers) are included. Lehiste used different lexemes, but an appropriate subset of her data was arranged by syllable position and vocalic context so as to resemble the data set outlined in Table 11. The subset of Lehiste's word list is given in Table 12.

	front vowel context		**back vowel context**	
high vowel context	lee	read	lose, lure	rue
	feel	here, steer	fool	cure, lure, sure
low vowel context	lamb	ram	law, lore	raw
	shall	bar	ball	lore, pour, war, wore, yore, your

Table 12. Subset of Lehiste's (1964) data for comparison.

5.1.2 Experiment 2: liquids in onsets

The word list for Experiment 2 (designed for the investigation of liquids in syllable onsets in nonrhotic varieties of English) was less well balanced (in terms of phonological oppositions) than the restricted word list used in Experiment 1, but includes a considerably larger number of lexical items (146 in total, with 73 instances of onset [l] and 73 instances of onset [r]). The word list is set out in Table 13.

5.2 Speakers

The speech of four speakers was examined. All speakers were males, aged between twenty and thirty years old at the time of recording, with no speech or hearing impediment and educated to university level. The speakers spoke with British regional varieties chosen to be representative of wider dialect groups within the language. They differed in rhoticity and the typical resonance qualities of syllable-initial liquids in their variety of English. Data were gathered from a number of other speakers but excessive errors in recording or variability in rhoticity meant that their data were disregarded.

	front vowel context				back vowel context			
high vowel context	lee leap lead leek leech leaf leave Leith lease leash leam	lip lib lit lid lick lift limb ling link lynx	re reap reed reek reach reef Reeve wreath Rees ream	rip rib writ rid rick rift rim ring rink rinks	loot lose loon	look	root ruse rune rule Ruhr	rook
mid vowel context	led Len lent lend	lay late laid lake lace lave lane	red wren rent rend	ray rate raid rake race rave rain	lug luff lush lum lung lob lot lock loss long	low lope lobe load loach loam loan	rug rough rush rum rung rob rot rock Ross wrong	roe rope robe road roach roam Rhone
low vowel context	lap lad lack lacks lax lag lags lash lamb lang	lie light lied life lithe lice lies lime line	rap rad rack racks rag rags rash ram rang	rye right ride rife writhe rice rise rhyme Rhine	law		raw	

Table 13. Lexemes investigated in the second data set, arranged by phonological structure.

Table 14 shows the varieties of English examined. Sunderland (north-east England) English is a clear initial [l] nonrhotic variety; County Tyrone (Northern Ireland) English is a clear initial [l] rhotic variety; Manchester (north-west England) English is a dark initial [l] nonrhotic variety; Fife (east Scotland) English is a dark initial [l] rhotic variety. All speakers used approximant productions of [r].

	Nonrhotic	Rhotic
Clear initial lateral	Sunderland (NE England)	Co. Tyrone (Northern Ireland)
Dark initial lateral	Manchester (NW England)	Fife (E Scotland)

Table 14. Varieties of English examined.

For Experiment 2, the same two nonrhotic speakers were recorded (the speakers from Sunderland and Manchester).

5.3 Procedure

5.3.1 Data acquisition

All the lexemes in both data sets were embedded in the frame "Say ... again" and randomised into blocks of ten sentences in combination with several dummy filler lexemes (see Appendix 2) included in an attempt to avoid any effect of list prosody.

Two tokens of each lexeme (in the frame) were elicited from each speaker, who read from a printed list of sentences.

Both the data sets were recorded in the sound studio of the Department of Language and Linguistic Science at the University of York. Recordings took place over a period of several months, though the acquisition of the data sets for each speaker was achieved in a single recording session.

Recordings were made via a Brüel & Kjær 4004 microphone (positioned approximately 30cm from the speaker) on to a Sony TCD-D10 PRO II two-head portable DAT recorder. These recordings were then resampled at 11025 Hz into an SGI computer running Entropic's ESPS and `xwaves` speech analysis package.

Two repetitions of each item were recorded, although errors made during recording meant that several items were repeated (and therefore have three repetitions); in 8 cases there were 4 repetitions, and in 1 case only one. The total number of utterances was 676, broken down as in Table 15. The complete data set is not entirely balanced since it was designed to investigate a number of different issues (such as the effect of [s] and [ʃ] in *lease* versus *leash*). However, the small number of tokens gathered compromised the validity of analyses with such a fine level of detail and so the data are presented here as a single unified set.

Variety	**l**	**r**
Sunderland	170	163
Manchester	177	166

Table 15. Distribution of onset tokens by variety and liquid identity.

5.3.2 Labelling

Both data sets were labelled by hand using the `xlabel` attachment to the ESPS/`xwaves` signal processing package.

5.3.2.1 Experiment 1: liquids and syllable position

The data set for Experiment 1 was labelled using an unsophisticated system, labelling only the duration of the liquid, the vocoid and the other consonant in the word, if one existed. Segmentation decisions were based on combinations of spectral events; specifically, portions of lower amplitude (particularly above F2) in the liquid, general instances of spectral discontinuity such as the presence of noticeable spikes in the spectrogram at the onset and offset of the liquid and, to a lesser extent, formant transitions. Figure 18 is an example of a waveform and spectrogram labelled according to this scheme.

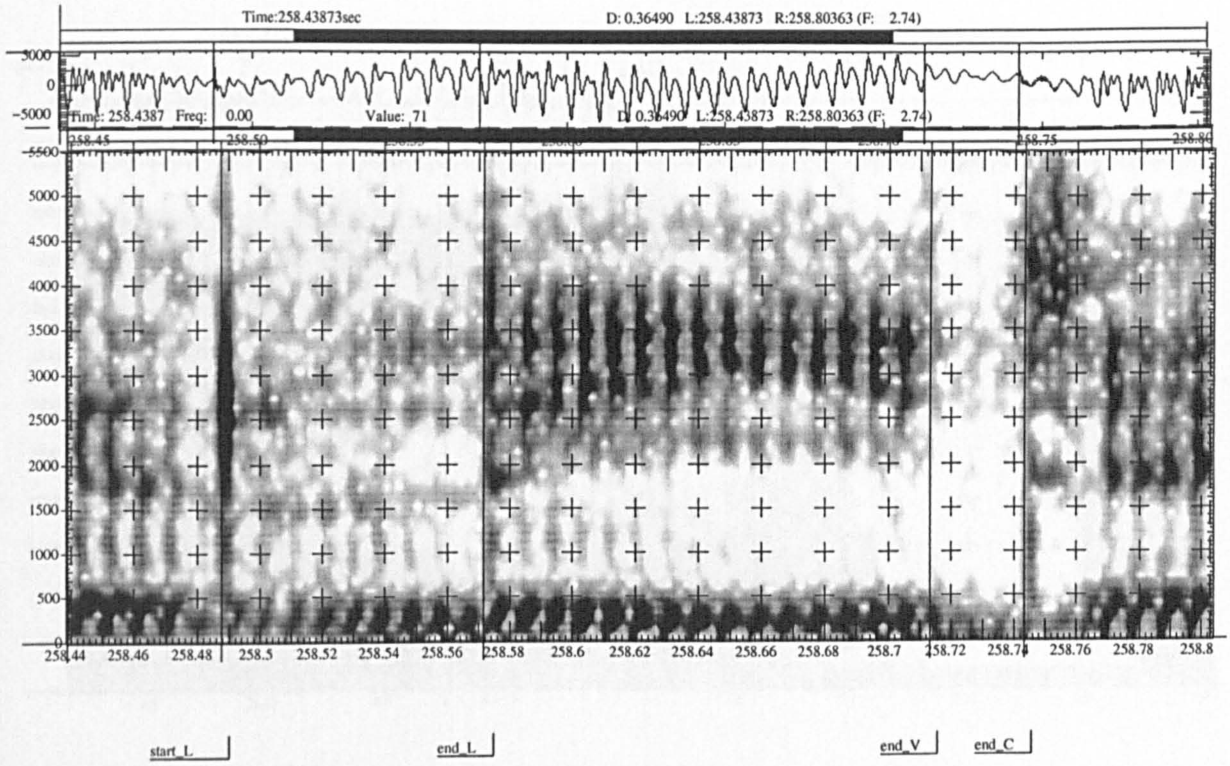


Figure 18. An example of a simply labelled waveform and spectrogram (an instance of <lead>, Sunderland speaker).

Not all of the tokens presented such obvious energy spikes around the lateral as are found in the example in Figure 18. For instance, clear instances of [l] were much easier to segment than dark instances of [l], since spikes on the spectrogram were more evident and were often accompanied by rapid changes in overall amplitude.

For some of the temporal analysis, the focus was on the course of the F2 transition, with the start and end points of the F2 transition both into and out of the liquid labelled. This is exemplified in Figure 19.

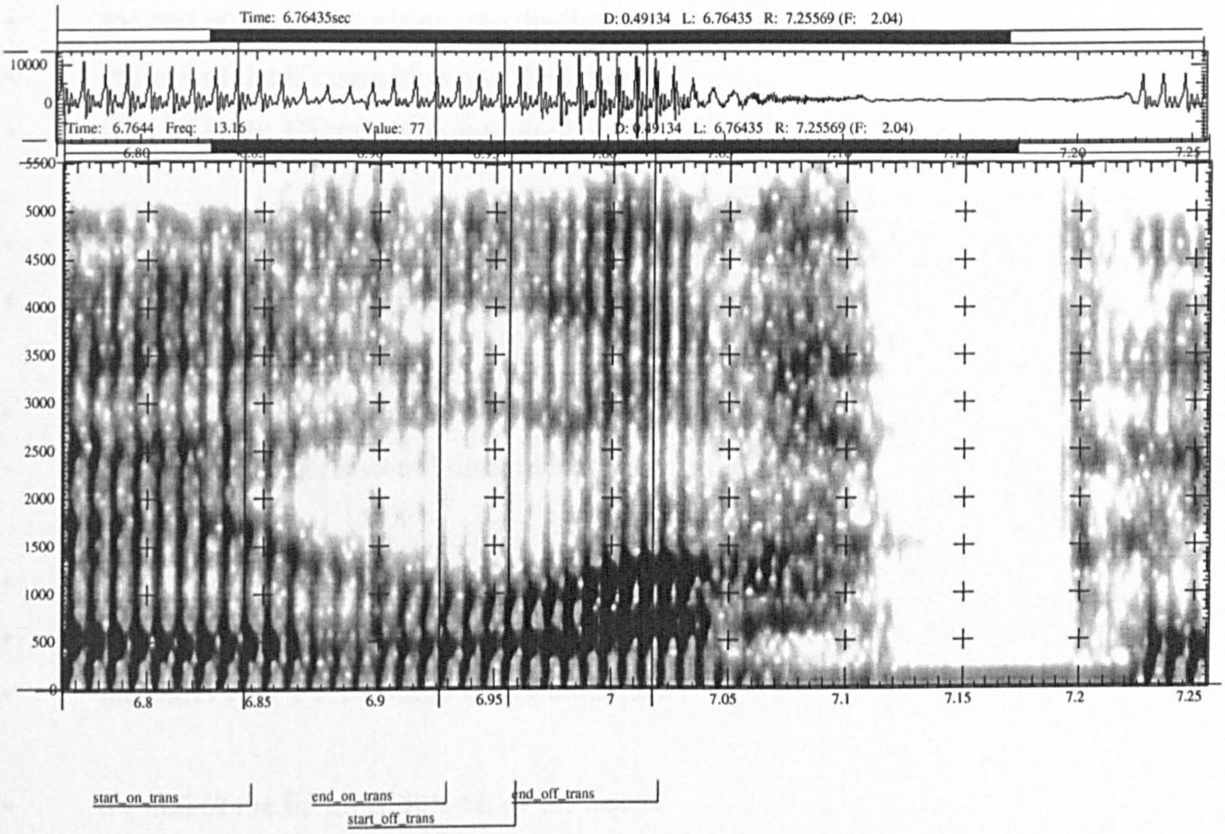


Figure 19. An example of a waveform labelled with the course of the F2 transition (an instance of <lap>, Manchester speaker).

5.3.2.2 Experiment 2: liquids in onsets

The data set for Experiment 2 was labelled with a much more sophisticated system in which no *a priori* decision was taken regarding segmental boundaries. Instead, the spectral events themselves were labelled, giving the possibility of a variety of definitions of duration of any given (so-called) segment.

Each token was then labelled by hand at the following points:

- the start of the F1 transition into the liquid
- the start of the F2 transition into the liquid
- the start of the F3 transition into the liquid

- the end of the F1 transition into the liquid
- the end of the F2 transition into the liquid
- the end of the F3 transition into the liquid

- the point of major spectral discontinuity into the liquid
- the point of a fall in overall RMS amplitude into the liquid

- the point of a rise in overall RMS amplitude out of the liquid
- the point of major spectral discontinuity out of the liquid

- the start of the F1 transition out of the liquid
- the start of the F2 transition out of the liquid
- the start of the F3 transition out of the liquid

- the end of the F1 transition out of the liquid
- the end of the F2 transition out of the liquid
- the end of the F3 transition out of the liquid

- the end of the vocoid portion
- the end of the target syllable

The end of the vocoid portion was located at the end of voicing in the target syllable, except where the syllable ended with a voiced obstruent, in which case the label was placed at the onset of the obstruent. In open syllables, the end of the syllable was located at the same place as the end of the vocoid. In syllables which ended in a plosive, the end of the syllable was defined as the point of release of closure. For syllables which ended in other consonants, the end of the consonant was taken as the end of the syllable.

An example of a waveform labelled according to this scheme is given in Figure 20.

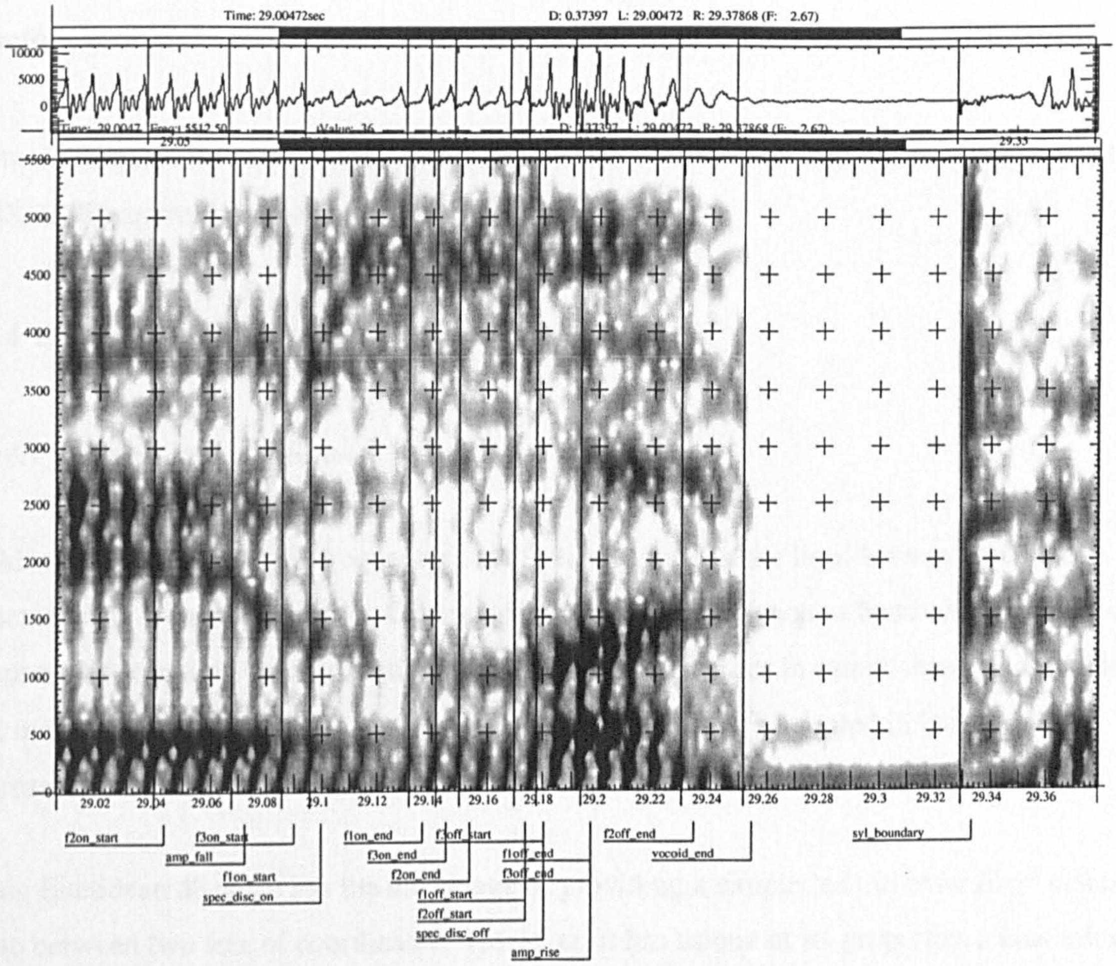


Figure 20. An example of a fully labelled waveform and spectrogram (an instance of <lip>, Manchester speaker).

5.3.3 Spectral information: formant frequencies

The ESPS formant tracker, `formant`, was run over each file, tracking every millisecond with a 25 ms hamming window, a preemphasis of 0.96 and an order 14 autocorrelation LPC and an expected f0 range of 60-200 Hz. Other settings (such as an order 12 autocorrelation LPC) were also used to compute formant tracks but the settings outlined above produced the fewest errors in the track as judged by a visual inspection of the formant trajectories overlaid on a wideband spectrogram. However, each token was inspected in this way and all errors in the formant tracking were corrected by hand using wideband spectrograms and DFT spectra. Thus, reliable estimations of formant frequencies at intervals of one millisecond through each of the 676 tokens were obtained. Subsequent analysis of formants at any given point in the waveform simply extracted the nearest appropriate values from this LPC analysis and is therefore accurate in the temporal dimension to ±0.5 ms.

Formant frequencies were then transformed into the bark scale using Traunmüller's (1983, 1988, 1990) approximation formulae.

5.3.4 Spectral information: clustering

5.3.4.1 Cluster analysis distance metrics

In this study, F1, F2 and F3 frequencies at the steady state in the liquids were used as the dimensions in a cluster analysis. Other pertinent dimensions (such as bandwidth, amplitude or temporal information) were excluded because of the difficulties in establishing an equivalent unit measure in all dimensions. Distance between formants represented in bark can be expressed in terms of simple Euclidean distance.

Using Euclidean distance has the advantage of providing a simple 'as the crow flies' distance value between two sets of coordinates. However, it has as one of its properties a bias towards showing a greater distance between two points when their separation is primarily along one dimension. For example, two points which differ by one unit on each of two dimensions will be deemed closer together by the Euclidean metric (the Euclidean distance between such points is $\sqrt{2}$) than two points which differ by two units on only one dimension (the Euclidean distance between the points in this case is 2).

An alternative to Euclidean distance is Manhattan distance. Manhattan distance is so called because it resembles travel around a city in that the steps taken in measurement (which parallel movement within the city) are effectively only permitted in one dimension at a time. Manhattan distance counts the examples given in the preceding paragraph as being of equal distance apart (a distance of 2 units in these cases), thereby overcoming one of the shortcomings of Euclidean distance. However, Manhattan distance is equivalent to a measure of direct distance in the Euclidean space only in the case where the two points in question differ in no more than one dimension.

It is not immediately clear which of these two measures of similarity is more appropriate in the analysis of spectral data from speech such as is found in this study. In terms of the data examined here, the large and well-established F3 difference between tokens of [l] and tokens of [r] could skew a distance matrix devised using Euclidean distance and dominate the results since the F3 dimension would have a relatively great influence on the outcome of the similarity calculations: the primary difference would be in one dimension. On the other hand, Euclidean distance should pick up those cases for which the primary difference between two tokens is found in the F2 dimension. Any deviation from a straightforward [l] versus [r] split would therefore be potentially meaningful. If there are important differences along the single F2 dimension, a Euclidean distance metric would also be suitable for detecting them.

In practice, however, both distance metrics were used with little effective difference in the results. The results reported in this dissertation were produced using Euclidean distance as a metric, but the clusters described turn up with such stability that the use of different difference metrics has negligible effect. Such robustness across methods serves to confirm the reliability of the results.

5.3.4.2 Clustering Algorithm

Cluster analysis was performed using Ward's method (Ward, 1963). Ward's clustering algorithm is an agglomerative hierarchical clustering method. In common with other agglomerative methods, it begins by effectively assuming each data point to be a cluster of size one and then proceeds stepwise merging the most similar clusters until all data points together form a single cluster. Once clusters are formed, they are never unmerged. Ward's method defines proximity between clusters by their error sum of squares. At any step in the algorithm, the two clusters which are merged are those which would result in the minimum increase in the sum of the squares of the distances from each data point to the centroid (mean) of the new cluster.

Ward's method, though useful for a variety of applications, is not without its problems (Mojena 1988, Everitt 1993). Some of these drawbacks are particularly pertinent to the present study. Firstly, the method is not particularly robust in its treatment of outliers in the data. This data set includes a certain number of outliers, and is not large enough for them to be sufficiently disguised amongst the more regular data, and so clusters may be skewed. The second difficulty is that the total sum of errors increases as the number of clusters decreases. Finally, and perhaps most importantly, data points once merged into the same cluster are never unmerged. If early clusters turn out to be spurious, then there is a risk that more significant clusters later on will fail to be identified. This last problem is a property of agglomerative methods in general rather than of Ward's method in particular. Nevertheless, cluster analysis can show up patterns present in the data, as long as the drawbacks are borne in mind.

5.3.4.3 Dendrograms

Dendrograms are graphs constructed from the output of a cluster analysis algorithm. Data points or clusters which are merged into larger clusters are represented in the dendrogram by points or groups of points joined by a line. Greater dissimilarity between clusters is represented in the graph by the lines from each cluster projecting for a longer distance before being joined.

5.3.5 Spectral information: classification and regression trees

For the trees presented in Chapter 7, the data set was coded for variety (Manchester or Sunderland), liquid ([l] or [r]), height of following vowel (high, mid or low), backness of following vowel (front or back), length of following vowel (long or short) and type of following vowel (monophthong or diphthong).

5.3.6 Spectral moments

A spectral moments analysis was carried out using the following algorithm on each power spectrum.

The spectrum is represented in the normal fashion as a set of (frequency, amplitude) pairs and the pair corresponding to a frequency of 0 Hz is deleted. Amplitude values are adjusted to a baseline of 0dB by finding the minimum dB level and subtracting it from all the amplitude values. This amplitude distribution is then converted into a form which resembles a probability density function by ensuring that all the amplitude values sum to 1. This is achieved by dividing each amplitude value by the cumulative total of all the amplitude values.

The set of pairs is now effectively of the form (frequency, *p*) and a standard statistical moments analysis can be performed.

In spectral analyses the first moment, the mean, is often referred to as the centre of gravity. It is calculated by summing the products of each probability, *p*, with its associated frequency value.

The second moment, the variance, is defined as the sum of the products of each *p* value with the square of the difference between the *p* value's associated frequency value and the mean. It is then normalised by taking the square root. Normalisation is carried out in order to counteract the effects of centre frequency and frequency scale shifts between subjects (Newell & Hancock, 1984; Forrest *et al.*, 1988).

The third moment, skew, is defined as the sum of the products of each *p* value with the cube of the difference between the *p* value's associated frequency value and the mean. It is then normalised by dividing by the square root of the cube of the unnormalised variance.

The fourth moment, kurtosis, is defined as the sum of the products of each *p* value with the fourth power of the difference between the *p* value's associated frequency value and the mean. It is then normalised by dividing by the square of the unnormalised variance and subtracting 3.

Details of the filter applied to the spectrum matter. Small changes in the region of the spectrum used to calculate spectral moments can lead to large changes in the outcome of the analysis. This is particularly true in the case of liquids. Stevens (1998:547) points out, for example, that

> 'Small changes in the frequency of the zero [produced as a result of a lateral articulation] can give rise to large changes in the amplitudes of the spectral peaks corresponding to the poles in this [1500 to 4000 Hz] higher-frequency region. Consequently, when the vocal tract is in the lateral configuration, considerable variability can be expected in the spectral shape in the frequency range of 2500 to 4000 Hz.'

There is no generally accepted standard for selecting regions of spectra. Indeed, some analysts select more than one fixed window to act as a passband filter on the spectrum before a centre of gravity analysis is performed. Beddor and Hawkins (1990), for example, in part of their study on synthetic speech select a range (100-1100 Hz) which included the low frequency formant peaks and skirts they were investigating. However, they extend the upper limit of the range to 1400 Hz for low back vowels. This method has the advantage that, for the most part, the same region of the spectrum is being used in each case, but the disadvantage that it is highly unlikely that identical portions of the formant structure of the spectrum are being included in each case.

A static filter of this sort will include some formants (up to F3, for example) by definition of the upper limit, but some tokens may also include higher formants (F4 in this case) which could affect the results of a spectral moments analysis by introducing an amount of higher frequency energy.

Indeed, Beddor & Hawkins develop an alternative technique with two-formant synthetic vowels, specifying limits on the skirts of the formants they investigated at 5dB below the trough between the two formant peaks and at 15dB below the peak formant amplitude.

A further technique which incorporates the spirit of Beddor & Hawkins's approach while allowing for greater automation with natural speech is an attempt at relating the spectral moments analysis more closely to the formant peak analysis by tracking the formant space to provide dynamically changing limits on the spectra to be subjected to spectral moments analysis. The frequency limits imposed on the spectral moments analysis vary depending on the formant structure of each individual time-normalised sample. In this way, the advantages and disadvantages of the analysis are reversed with respect to a static filter, namely that the analyses are performed over a consistent portion of the spectral structure (the same formants are included at each sample point) but not over a consistent portion of the frequency domain.

The precise formant space which is appropriate to track for the dynamically changing spectral moments analysis is an issue: whether to track the F3-F1 space, which would give a fuller picture of the spectra involved at the risk of being overpowered by the predominant effect of F3 in distinguishing liquids, or the F2-F1 space which might be more appropriate to compare with the major formant data presented earlier, such as the F2-F1 difference itself.

The tracking algorithm was applied both to the F3-F1 space and to the F2-F1 space. For each time-normalised sample in each token, formant data were taken from a hand-corrected version of the results of an autocorrelation formant tracker. Due to inaccuracies in formant tracking with autocorrelation spectra, it is not feasible straightforwardly to include only the peaks and skirts of the relevant formants by detecting maxima and minima in the autocorrelation spectra. The algorithm implemented in this analysis is a compromise position using the notion of the critical bandwidth used in calculating the bark scale.

The critical bandwidth (Zwicker *et al.*, 1957), *CB*, increases monotonically but in a non-linear fashion as frequency increases. *CB* is calculated for any bark-transformed frequency, *z*, by Traunmüller's (1990) approximation:

$$CB = \frac{52548}{z^2 + 52 \cdot 56z + 690 \cdot 39}$$

In order to account for some of the skirt of the formants, half a critical bandwidth was added to the upper skirt of the higher formant and subtracted from the lower skirt of the lower formant. The limits on the filter applied to the spectra in this analysis are therefore defined as

$$\left(F_i - \frac{CB(F_i)}{2}\right), \left(F_j + \frac{CB(F_j)}{2}\right)$$

where i=1 and j=3 in the case of F3-F1 tracking (j=2 in the case of F2-F1 tracking).

5.3.7 Analysis of variance

Factorial ANOVAs were carried out on the data in Experiment 2. The three factors entered into the analysis were variety (Manchester or Sunderland), liquid ([l] or [r]) and backness of the following vowel (front or back). Lexical constraints meant that there was too great an interaction between backness and height of the following vowel for both categories to be entered as factors. Backness was chosen over height as it more typically has an effect on F2 (which was identified as the formant of primary interest). Repetitions were not included as a factor since they were not of primary interest. A repeated measures design was not used because there was only one subject per variety, meaning that variation of subjects within groups could not be analysed.

6 Experiment 1 (liquids and syllable structure): results and discussion

6.1 Experiment 1: results

6.1.1 Cluster analysis

The sets in Figures 21 to 23 present in stylised Venn diagram form the dendrograms produced by the application of Ward's clustering method to Euclidean distance dissimilarity matrices based on bark transformations of the frequencies of F1, F2 and F3 for each token for each speaker. Complete dendrograms are given in Appendix 3. The sets in the Venn diagrams are based on inspection of the dendrograms, identifying as far as possible high level splits which categorise tokens which share similar linguistic structure.

Figure 21 shows that in the clear initial [l] nonrhotic variety (Sunderland), the {F1, F2, F3} formant space is split into two, with initial laterals separated from other liquids. Final [l] clusters with [r].

The {F1, F2, F3} cluster analysis of the dark initial [l] variety (Manchester) produces a simple [l]/[r] split (though within the [l] group, there is a split with initial [l] followed by a high vowel being separated from other instances of [l]).

In the lower panels of Figure 21, F3 is excluded from the analysis in order to factor out the main effect which differentiates [l] and [r]. In the clear initial [l] variety (Sunderland), the pattern is the same as when F3 is present as an additional dimension in the difference matrix, confirming that F1 and/or F2 are playing an important part in the clustering of liquids in this variety. In the dark initial [l] variety (Manchester), the pattern is also very similar to that where F3 is included. In this case, however, initial [l] when followed by a high vowel clusters with initial [r] (the clear liquid).

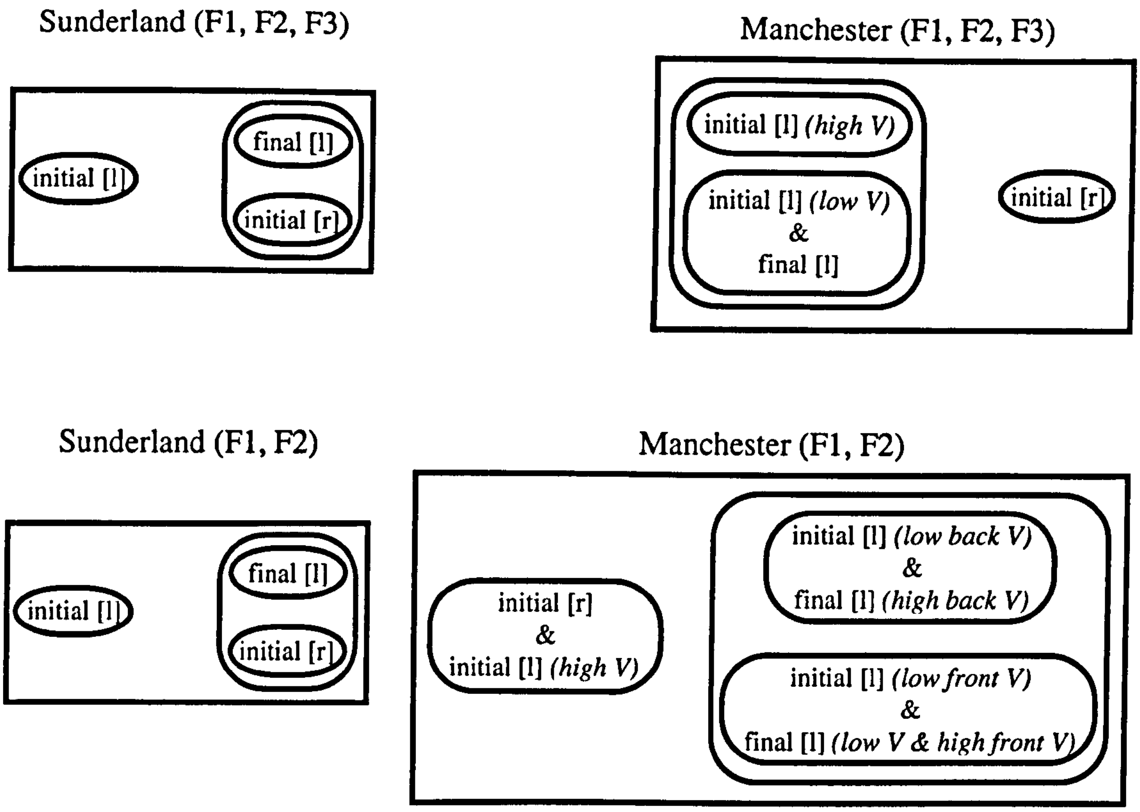


Figure 21. Summary of cluster analysis of liquids in nonrhotic varieties. Upper panels: F1, F2, F3 frequencies as dimensions; lower panels: F1, F2 frequencies as dimensions. Left panels: clear initial [l] variety (Sunderland); right panels: dark initial [l] variety (Manchester).

Figure 22 shows that the clear initial [l] rhotic variety (Tyrone) has more complex splits than the clear initial [l] nonrhotic variety (Sunderland), although the picture is similar to that found for the Sunderland speaker. Initial (clear) laterals are separated from other liquids, though some final laterals found after high vocoids cluster with the initial laterals. Within the set containing the rest of the liquids, initial [r], final [l] and [r] after back vowels cluster together. A simple [l]/[r] split (which is what would be expected if resonance does not play a part in distinguishing the liquids, leaving F3 as the predominant factor) is what is found in the dark initial [l] rhotic variety (Fife).

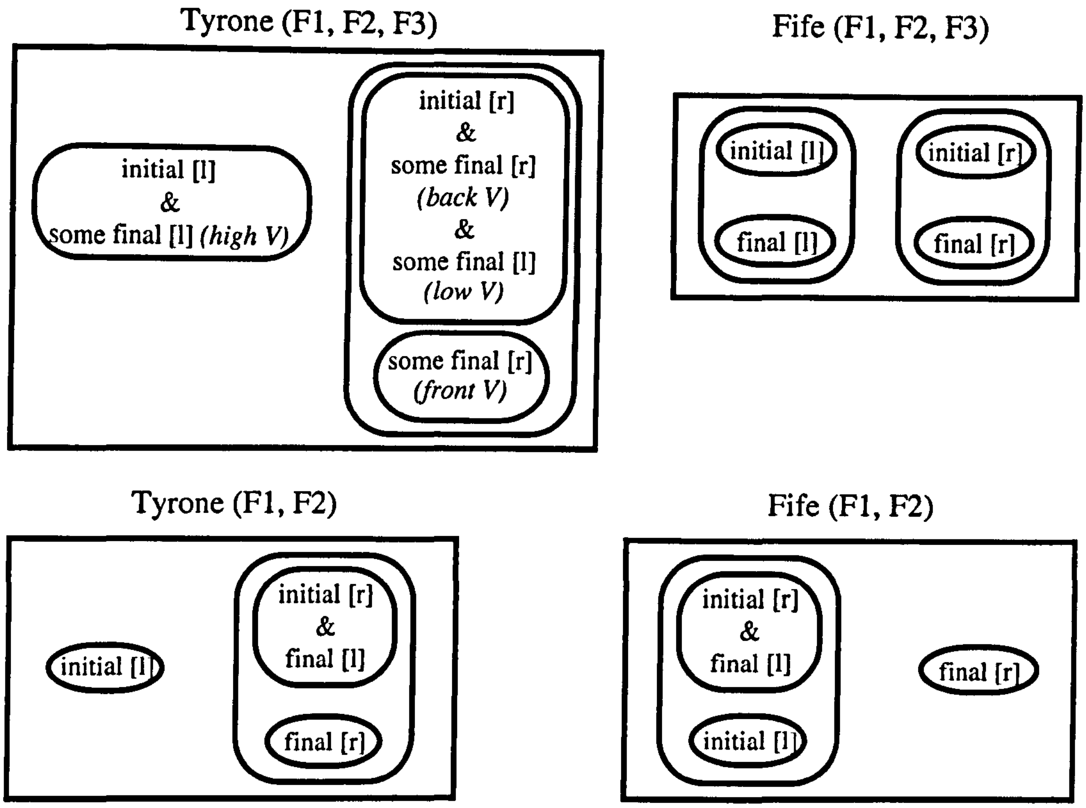


Figure 22. Summary of cluster analysis of liquids in rhotic varieties. Upper panels: F1, F2, F3 frequencies as dimensions; lower panels: F1, F2 frequencies as dimensions. Left panels: clear initial [l] variety (Tyrone); right panels: dark initial [l] variety (Fife).

When F3 is taken out of the reckoning, in the Tyrone clear initial [l] variety, initial [l] is completely separated from the other liquids; among the other liquids, final [r] is separated from initial [r] and final [l]. In the dark initial [l] rhotic variety (Fife), the patterns are the same, with only slight differences in the detail: it is final [r] (rather than initial [l] in the Tyrone case) which is separated from the remainder of the liquids.

In order to investigate the impact liquids have on the clustering of vocoids, dendrograms are presented which derive from measurements at the mid-point/steady state of the vocoid. The dendrograms produced for the vocoid {F1, F2, F3} matrices in nonrhotic varieties (summarised in the upper panels of Figure 23) show splits predominantly based on vowel quality, as would be expected if the liquids had little effect. However, in the clear initial [l] nonrhotic (Sunderland) variety, initial [r] and final [l] seem to influence the formant matrix of high back vowels so that they cluster with the low vowels. In the dark initial [l] nonrhotic

(Manchester) variety, it is only final [l] which causes high back vowels to cluster with the low vowels.

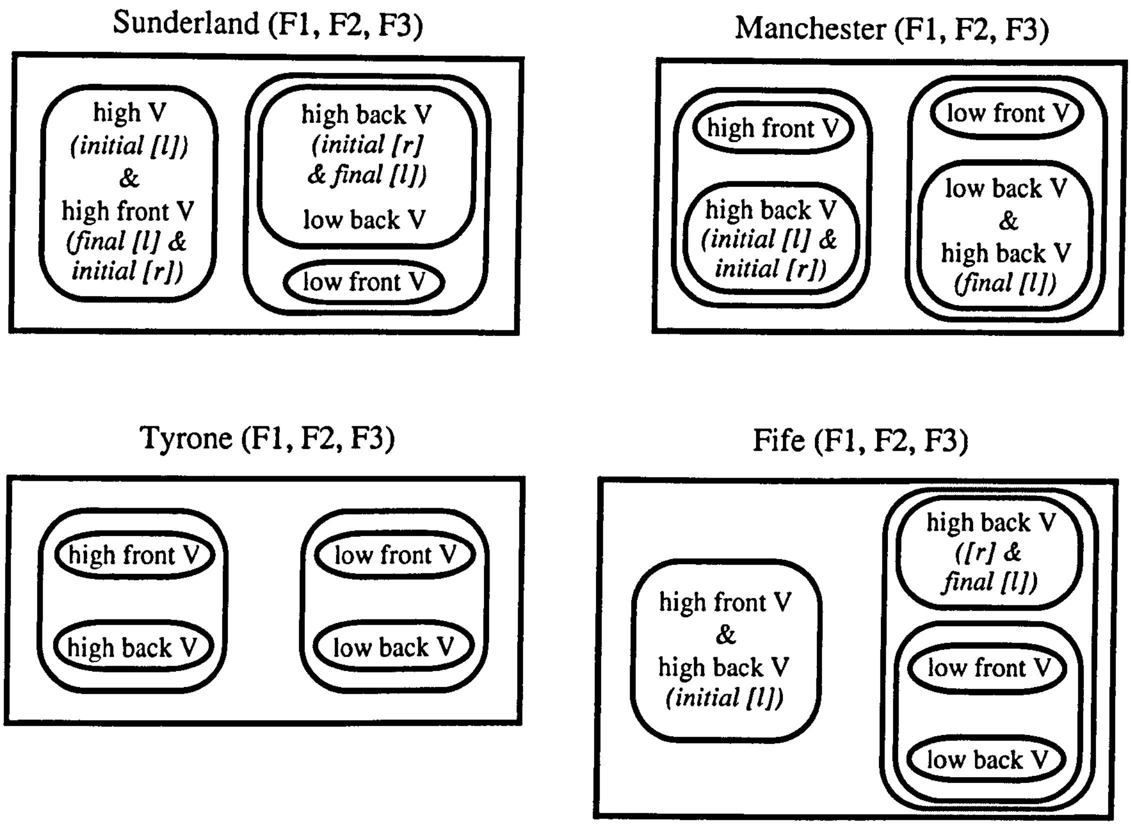


Figure 23. Summary of cluster analysis of vocoids (dimensions: F1, F2 & F3 frequencies). Upper panels: nonrhotic varieties; lower panels: rhotic varieties. Left panels: clear initial [l] varieties; right panels: dark initial [l] varieties.

The dendrograms produced for the vocoid {F1, F2, F3} matrices in rhotic varieties (summarised in the lower panels of Figure 23) show splits for the most part based on vowel quality, which seems to be more independent of the liquids than vowel quality in the nonrhotic varieties. High vowels are separated from low vowels; front vowels are separated from back vowels. Tautosyllabic liquids have negligible effect in these cases, although for the Fife speaker [r] and final [l] cause high back vowels to cluster with low vowels. Dendrograms which exclude the effect of F3 on the vocoid are very similar to those in Figure 23 and are not presented here (but see Appendix 3 for full details).

6.1.2 F2 and F2-F1 frequency relationships

6.1.2.1 Nonrhotic varieties

Final tokens have been excluded from the data of nonrhotic speakers in this section, since final liquids are not contrastive in these tokens.

Figure 24 summarises the state of affairs in the nonrhotic varieties with respect to F2 frequencies in initial liquids: the Sunderland speaker has a relatively high F2 in syllable-initial laterals and a relatively low F2 in syllable-initial rhotics, while the Manchester speaker has a relatively low F2 in syllable-initial laterals and a relatively high F2 in syllable-initial rhotics.

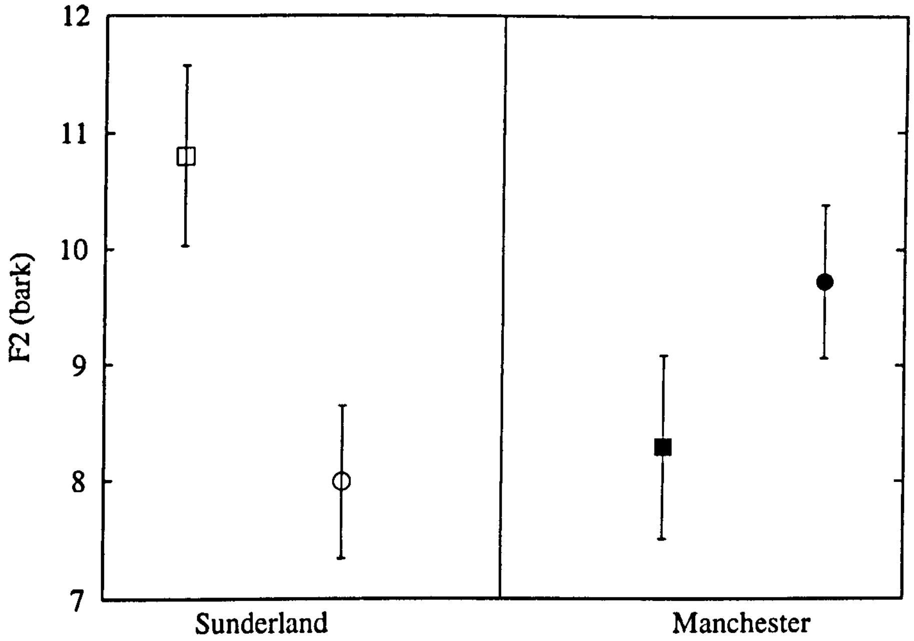


Figure 24. Mean F2 (bark) in initial liquids for nonrhotic speakers (error bars indicate standard deviation). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

The data presented in Tables 16 and 17 confirm that the Sunderland speaker has a higher F2 frequency and greater F2-F1 space for syllable-initial [l] than for syllable-initial [r], while the Manchester speaker has a lower F2 frequency and smaller F2-F1 space for syllable-initial [l] than for syllable-initial [r]. All t-tests are unpaired and two-tailed.

Variety	F2 (initial [l])	F2 (initial [r])	df	t	*p*
Sunderland	10.801 (1435 Hz)	7.992 (913 Hz)	14	7.864	<0.0001
Manchester	8.295 (962 Hz)	9.720 (1213 Hz)	14	3.9154	0.0016

Table 16. Mean frequencies of F2 (bark) in initial liquids; nonrhotic speakers.

Variety	F2-F1 (initial [l])	F2-F1 (initial [r])	df	t	*p*
Sunderland	7.824	5.741	14	4.9177	0.0002
Manchester	4.839	6.741	14	4.1532	0.0010

Table 17. Mean frequencies of F2-F1 (bark) in initial liquids; nonrhotic speakers.

The Manchester speaker has smaller F2-F1 spaces than the Sunderland speaker for each resonance quality. The dark Manchester liquid, [l], has a smaller F2-F1 space than the dark Sunderland liquid, [r] (t(14)=2.2125, *p*=0.0441). The clear Manchester liquid, [r] has a smaller F2-F1 space than the clear Sunderland liquid, [l] (t(14)=2.2942, *p*=0.0378).

The data presented in Tables 18 and 19 show that both nonrhotic speakers have a smaller F2-F1 space for [l] in syllable-final position than in syllable-initial position. For the Sunderland speaker, [l] also has a lower F2 in final position than in initial position.

Variety	F2 (initial [l])	F2 (final [l])	df	t	*p*
Sunderland	10.801 (1435 Hz)	7.911 (901 Hz)	14	8.0228	<0.0001
Manchester	8.295 (962 Hz)	7.913 (901 Hz)	14	1.1256	0.2792

Table 18. Mean frequencies of F2 (bark) in [l]; nonrhotic speakers.

Variety	F2-F1 (initial [l])	F2-F1 (final [l])	df	t	*p*
Sunderland	7.824	3.786	14	7.4383	<0.0001
Manchester	4.839	3.672	14	2.7418	0.0159

Table 19. Mean frequencies of F2-F1 (bark) in [l]; nonrhotic speakers.

The data presented in Tables 20 and 21 suggest that the major differences between the nonrhotic varieties in syllable-initial liquids could potentially also hold for the vocoids following syllable-initial liquids. However, with a small data set, there is no statistical evidence to support this claim. This absence of statistical significance provided a motivation for the larger data set in Experiment 2, to be discussed in Chapter 7.

Variety	F2 (vocoid following [l])	F2 (vocoid following [r])	df	t	*p*
Sunderland	11.035 (1487 Hz)	10.187 (1305 Hz)	14	0.6579	0.5213
Manchester	10.456 (1361 Hz)	10.613 (1394 Hz)	14	0.1280	0.9000

Table 20. Mean frequencies of F2 (bark) in vocoids following liquids; nonrhotic speakers.

Variety	F2-F1 (vocoid following [l])	F2-F1 (vocoid following [r])	df	t	*p*
Sunderland	6.859	5.871	14	0.4708	0.6450
Manchester	5.991	6.237	14	0.1402	0.8905

Table 21. Mean frequencies of F2-F1 (bark) in vocoids following liquids; nonrhotic speakers.

6.1.2.2 Rhotic varieties

Rhotic speakers show different F2 patterns from nonrhotic speakers: despite the variation in quality of initial [l], a similar pattern of relationships in resonance quality is shown in both rhotic varieties (Figure 25). Whereas in nonrhotic varieties, the F2 patterns differ depending on whether the initial lateral is clear or dark, in rhotic varieties, the (absolute) quality of the initial lateral makes no difference to the pattern of relationships in resonance quality. Syllable-final liquid qualities are appropriately included here since rhotic varieties do have liquid contrasts at that place in structure.

Tables 22-29 show the means of the bark transform of F2 in liquids for rhotic varieties.

The data presented in Tables 22 and 23 show that, unlike the nonrhotic varieties' data presented in Section 6.1.2.1, both clear initial lateral and dark initial lateral rhotic varieties show the same pattern: syllable-initial laterals have a larger F2-F1 space than syllable-initial rhotics. Indeed, if the 95% significance level is relaxed slightly, then both varieties also have syllable-initial laterals with a higher F2 frequency than syllable-initial rhotics.

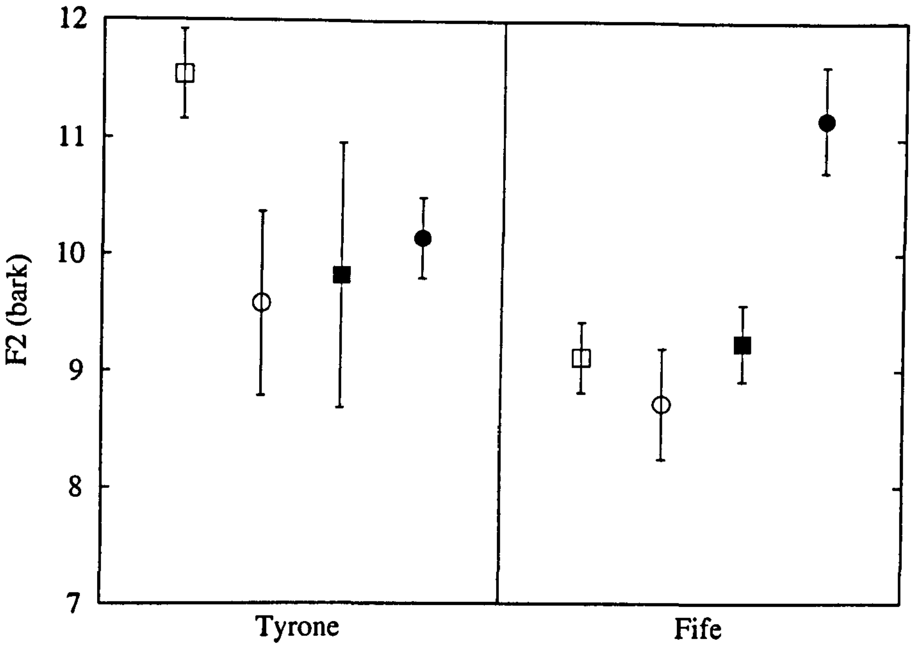


Figure 25. Mean frequencies of F2 (bark) in liquids for rhotic speakers (error bars indicate standard deviation). Squares represent laterals; circles represent rhotics. Open shapes represent initial liquids; filled shapes represent final liquids.

Variety	**F2 (initial [l])**	**F2 (initial [r])**	**df**	**t**	***p***
Tyrone	11.545 (1606 Hz)	9.577 (1186 Hz)	14	6.3402	<0.0001
Fife	9.117 (1102 Hz)	8.718 (1032 Hz)	14	2.0023	0.0650

Table 22. Mean frequencies of F2 (bark) in initial liquids; rhotic speakers.

Variety	**F2-F1 (initial [l])**	**F2-F1 (initial [r])**	**df**	**t**	***p***
Tyrone	8.692	7.049	14	3.8376	0.0018
Fife	5.971	5.133	14	2.2982	0.0375

Table 23. Mean frequencies of F2-F1 (bark) in initial liquids; rhotic speakers.

The data presented in Table 24 show that the Fife speaker has higher F2 in syllable-final [r] than in syllable-initial [r]. For the Tyrone speaker, a similar relationship approaches significance. The data in Table 25 confirm that there is a larger F2-F1 space in final [r] than in initial [r] for the Fife speaker, but the relationship is reversed for the Tyrone speaker. This difference is due to a large and significant (t(14)=3.867, p=0.0017) difference in F1 between syllable-initial [r] (mean of 2.528 bark/252 Hertz) and syllable-final [r] (mean of 4.751 bark/481 Hertz) for the Tyrone speaker.

Variety	F2 (initial [r])	F2 (final [r])	df	t	p
Tyrone	9.577 (1186 Hz)	10.145 (1297 Hz)	14	1.8558	0.0847
Fife	8.718 (1032 Hz)	11.170 (1518 Hz)	14	10.507	<0.0001

Table 24. Mean frequencies of F2 (bark) in [r]; rhotic speakers.

Variety	F2-F1 (initial [r])	F2-F1 (final [r])	df	t	p
Tyrone	7.049	5.394	14	2.376	0.0323
Fife	5.133	6.935	14	2.8889	0.0119

Table 25. Mean frequencies of F2-F1 (bark) in [r]; rhotic speakers.

The data in Tables 26 and 27 show that, in syllable-final position, [l] has a lower F2 and a smaller F2-F1 space than [r] for the Fife speaker.

Variety	F2 (final [l])	F2 (final [r])	df	t	p
Tyrone	9.820 (1232 Hz)	10.145 (1297 Hz)	14	0.7678	0.4554
Fife	9.238 (1123 Hz)	11.170 (1518 Hz)	14	9.7199	<0.0001

Table 26. Mean frequencies of F2 (bark) in final liquids; rhotic speakers.

Variety	F2-F1 (final [l])	F2-F1 (final [r])	df	t	p
Tyrone	6.586	5.394	14	1.5298	0.1484
Fife	5.429	6.935	14	2.3532	0.0338

Table 27. Mean frequencies of F2-F1 (bark) in final liquids; rhotic speakers.

The data in Tables 28 and 29 show that syllable-final [l] has a lower F2 and a smaller F2-F1 space than syllable-initial [l] for the Tyrone speaker.

In vocoids following liquids in both rhotic varieties, there is no significant difference between the liquids in either variety although the tendency is for F2 to be higher when following a lateral than when following a rhotic (Table 30) and for the F2-F1 space to be greater when the vocoid follows a lateral than when it follows a rhotic (Table 31).

Variety	F2 (initial [l])	F2 (final [l])	df	t	*p*
Tyrone	11.545 (1606 Hz)	9.820 (1232 Hz)	14	4.0456	0.0012
Fife	9.117 (1102 Hz)	9.238 (1123 Hz)	14	0.7674	0.4556

Table 28. Mean frequencies of F2 (bark) in [l]; rhotic speakers.

Variety	F2-F1 (initial [l])	F2-F1 (final [l])	df	t	*p*
Tyrone	8.692	6.586	14	3.8113	0.0019
Fife	5.971	5.429	14	1.3837	0.1881

Table 29. Mean frequencies of F2-F1 (bark) in [l]; rhotic speakers.

Variety	F2 (vocoid following [l])	F2 (vocoid following [r])	df	t	*p*
Tyrone	10.682 (1409 Hz)	10.345 (1338 Hz)	14	0.2937	0.7733
Fife	11.642 (1630 Hz)	10.887 (1454 Hz)	14	0.7156	0.4860

Table 30. Mean frequencies of F2 (bark) in vocoids following liquids; rhotic speakers.

Variety	F2-F1 (vocoid following [l])	F2-F1 (vocoid following [r])	df	t	*p*
Tyrone	6.315	5.931	14	0.214	0.8337
Fife	6.625	5.683	14	0.5173	0.6130

Table 31. Mean frequencies of F2-F1 (bark) in vocoids following liquids; rhotic speakers.

The data presented in Tables 32 and 33 show that there is no significant difference in F2 or the F2-F1 space for vocoids preceding the two liquids in either rhotic variety.

Variety	F2 (vocoid preceding [l])	F2 (vocoid preceding [r])	df	t	*p*
Tyrone	10.237 (1315 Hz)	9.603 (1191 Hz)	14	0.5256	0.6074
Fife	10.744 (1422 Hz)	10.487 (1367 Hz)	14	0.2054	0.8402

Table 32. Mean frequencies of F2 (bark) in vocoids preceding liquids; rhotic speakers.

Variety	F2-F1 (vocoid preceding [l])	F2-F1 (vocoid preceding [r])	df	t	*p*
Tyrone	5.938	5.962	14	0.0142	0.9888
Fife	6.039	6.189	14	0.0753	0.9410

Table 33. Mean frequencies of F2-F1 (bark) in vocoids preceding liquids; rhotic speakers.

6.1.3 Variances

Variances are examined in this section in order to test whether Bladon & Al-Bamerni's (1976) suggestion that coarticulation was more prevalent with clear (syllable-initial) laterals than with dark (syllable-final) laterals holds in varieties with different associations of resonance quality and with [r] as well as [l]. The data may also be compared to Nolan's (1983:91) results which showed a considerably greater effect of following vocoid quality on initial laterals than on initial rhotics. Larger variances may be interpreted as reflecting a greater degree of coarticulation.

Figure 26 plots formant frequencies for F3 against F2 taken at the mid-point of the liquid for all speakers. Junctural rhotics (which appear to be syllable-final) are included for information: they pattern straightforwardly with syllable-initial rhotics for the Manchester speaker, but are widely dispersed for the Sunderland speaker, due to data also being taken from instances where juncture was not marked with a rhotic articulation but rather with some sort of laryngeal activity such as a glottal stop or creaky voice.

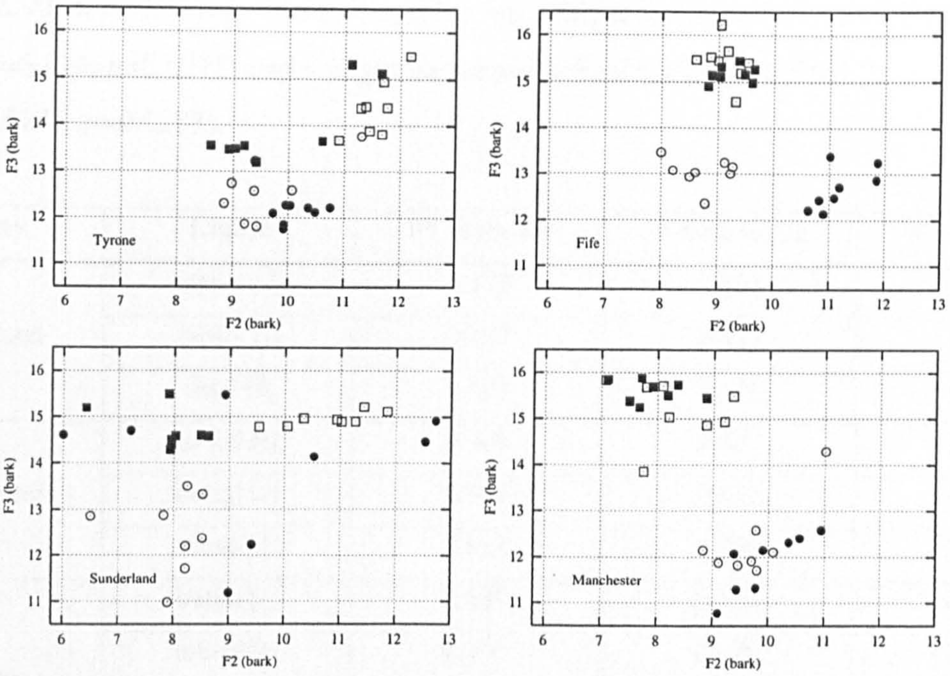


Figure 26. Scatter plot of individual tokens of F3 against F2 frequencies (bark) at mid-point of steady state in liquids. Open shapes represent initial liquids; filled shapes represent final liquids. Squares represent [l]; circles represent [r]. Upper panels: rhotic varieties; lower panels: nonrhotic varieties. Left panels: clear initial [l] varieties; right panels: dark initial [l] varieties.

Table 34 outlines the variances for bark-transformed formant frequencies in the liquids in the data presented in this chapter.

Of the four speakers, the only one with significant differences in F2 variances is the Tyrone speaker, whose initial [r] has a larger variance than final [r] (F(7,7)=5.1657, *p*=0.0458), and possibly also larger than initial [l] (F(7,7)=4.3555, *p*=0.0710). Final [l] has a larger variance than initial [l] (F(7,7)=9.11, *p*=0.0093) and final [r] (F(7,7)=10.8044, *p*=0.0056).

Differences in F3 variances are not straightforwardly related to whether the liquid is lateral or rhotic. The Sunderland speaker has a larger variance for initial [r] than for initial [l] (F(7,7)=31.1922, *p*=0.0002), and a larger variance for final [l] than for initial [l] (F(7,7)=7.5144, *p*=0.0163). The Manchester speaker has a larger variance for initial [l] than for final [l] (F(7,7)=8.1166, *p*=0.0130). The Tyrone speaker has a larger variance for initial [r] than final [r] (F(7,7)=10.8988, *p*=0.0054) and a larger variance for final [l] than for final [r]

(F(7,7)=16.9014, p=0.0014). The Fife speaker has a larger variance for initial [l] than for final [l] (F(7,7)=6.814, p=0.0215) and a larger variance for final [r] than for final [l] (F(7,7)=6.6271, p=0.0233).

Variety	Liquid	F1 variance	F2 variance	F3 variance
Sunderland	initial [l]	0.172	0.595	0.023
	initial [r]	0.307	0.425	0.711
	final [l]	0.547	0.442	0.171
Manchester	initial [l]	0.399	0.622	0.421
	initial [r]	0.147	0.437	0.716
	final [l]	0.617	0.300	0.052
Tyrone	initial [l]	0.099	0.144	0.377
	initial [r]	0.160	0.627	0.429
	final [l]	0.112	1.311	0.665
	final [r]	2.484	0.121	0.039
Fife	initial [l]	0.448	0.091	0.212
	initial [r]	0.233	0.227	0.101
	final [l]	0.296	0.107	0.031
	final [r]	1.720	0.209	0.206

Table 34. Variances of bark-transformed formant frequencies in liquids.

Both rhotic speakers have a larger F1 variance for final [r] than for both initial [r] (F(7,7)=15.4856, p=0.0018 for the Tyrone speaker and F(7,7)=7.3772, p=0.0172 for the Fife speaker) and final [l] (F(7,7)=22.2445, p=0.0006 for the Tyrone speaker and F(7,7)=5.8038, p=0.0335 for the Fife speaker).

6.1.4 F2 frequency and the duration of liquids

There appears to be no straightforward correlation between the duration of liquids and their identity as [l] or [r] in a given syllable position. Nevertheless, there are some preliminary observations regarding duration which are worth making from the small data set in Experiment 1.

In Figure 27, F2 at the midpoint of laterals is plotted against the duration of laterals (including F2 transitions). Only 7 tokens from the Tyrone speaker are included because one target word was preceded by a pause and hence lacked an F2 transition into the liquid.

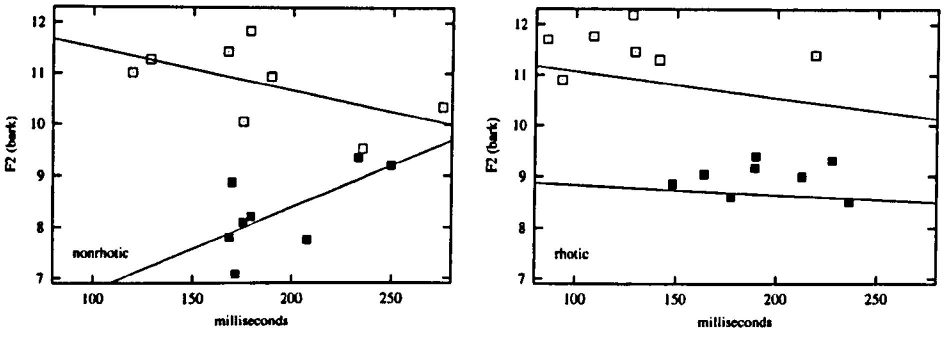


Figure 27. F2 frequencies (bark) at the mid-point of laterals plotted with regression lines against duration in milliseconds (as defined by the extent of F2 transitions) for syllable-initial laterals in Experiment 1. Left panel: nonrhotic speakers; open squares represent instances from the Sunderland speaker; filled squares represent instances from the Manchester speaker. Right panel: rhotic speakers; open squares represent instances from the Tyrone speaker; filled squares represent instances from the Fife speaker.

The relatively small data set used in Experiment 1 means that statistical results are not significant, but the indications are that the prediction that long duration is associated with darkness may be upheld in the clear initial [l] nonrhotic variety (Sunderland), but the dark initial [l] nonrhotic variety (Manchester) has the opposite pattern: the greater the duration of the initial lateral, the clearer that lateral is. The slope of the regression line for Sunderland laterals is –8.4135 ($r^2 = 0.3158$, p=0.1471); the slope of the regression line for Manchester laterals is +16.256 ($r^2 = 0.4318$, p=0.0766).

These p-values (particularly that for the Manchester laterals) are fairly small, despite not being significant at the 95% level. This finding might therefore be a slight indication that phonetic parameters related to liquids could be phased in different ways in different varieties, although nothing can be reliably concluded from this small data set.

There does not seem to be any evidence of such patterns in the rhotic varieties. Results for rhotic varieties are not at all statistically significant, but tend to approximate more to the

Sunderland speaker than to the Manchester speaker in that the slope of the regression line is negative. The slope of the regression line for Tyrone laterals is –0.5251 ($r^2 = 0.0033$, p=0.9026); the slope of the regression line for Fife laterals is –0.1904 ($r^2 = 0.0003$, p=0.9656).

6.1.5 Duration of F2 transitions

Table 35 shows the mean duration in milliseconds of the F2 transition into and out of initial liquids in the nonrhotic varieties. One transition into [l] is excluded from the Tyrone data and one transition into [r] from the Sunderland data because the target words were preceded by a pause and hence had no transition into the liquid. Table 36 tests the significance of these data.

Variety	**l**		**r**	
	transition into liquid	**transition out of liquid**	**transition into liquid**	**transition out of liquid**
Sunderland	59.6	51.3	75.9	42.6
Manchester	93.6	63.6	53.0	67.9
Tyrone	21.0	53.0	50.4	52.1
Fife	49.5	40.6	70.1	49.0

Table 35. Mean duration in milliseconds of F2 transitions into and out of initial liquids.

For the clear initial [l] nonrhotic variety (Sunderland), there is no significant difference between the duration of transitions into [l] and the duration of transitions out of [l]. The dark initial [l] nonrhotic variety (Manchester), however, has longer transitions into [l] than out of [l] and also longer transitions into [l] than into [r]. The Sunderland speaker has longer transitions into an initial rhotic than out of it.

Both rhotic speakers have shorter transitions into [l] than into [r]. The Tyrone speaker's short transitions into [l] are shorter than his transitions out of [l]; the Fife speaker's long transitions into [r] are longer than his transitions out of [r].

comparison	df	t	*p*
Sunderland transition into liquid ([l] vs [r])	13	1.4523	0.1701
Manchester transition into liquid ([l] vs [r])	14	6.4264	<0.0001
Tyrone transition into liquid ([l] vs [r])	13	6.2332	<0.0001
Fife transition into liquid ([l] vs [r])	14	3.7228	0.0023
Sunderland transition out of liquid ([l] vs [r])	14	0.5953	0.5611
Manchester transition out of liquid ([l] vs [r])	14	0.2345	0.8180
Tyrone transition out of liquid ([l] vs [r])	14	0.0563	0.9560
Fife transition out of liquid ([l] vs [r])	14	0.8125	0.4301
Sunderland [l] (transition in vs transition out)	14	0.6178	0.5466
Manchester [l] (transition in vs transition out)	14	2.6255	0.0200
Tyrone [l] (transition in vs transition out)	13	2.1665	0.0494
Fife [l] (transition in vs transition out)	14	1.2419	0.2347
Sunderland [r] (transition in vs transition out)	13	2.6689	0.0193
Manchester [r] (transition in vs transition out)	14	0.9644	0.3512
Tyrone [r] (transition in vs transition out)	14	0.2062	0.8396
Fife [r] (transition in vs transition out)	14	2.2797	0.0388

Table 36. Results of unpaired two-tailed t-tests on the durations of F2 transitions into and out of initial liquids, as shown in Table 35.

6.2 Experiment 1: discussion

6.2.1 Cluster analysis

The cluster analysis shows that formants in liquids pattern by whether the liquid is clear or dark, as well as whether the liquid is [l] or [r]. In the clear initial [l] nonrhotic variety (Sunderland), final [l] is always dark and here clusters with [r], which is also dark. The observed split is therefore a phonetic clear/dark split, rather than a simple [l]/[r] split. There is no evidence of coarticulation with the vocoid, since the most important splits include tokens with a variety of vowels.

The cluster analysis of the dark initial [l] variety (Manchester) produces a simple [l]/[r] split, at least in the {F1, F2, F3} dendrogram. Within the [l] group, however, there is a split with initial [l] followed by a high vowel — with low F1 and therefore relatively large F2-F1 space unlike the typically small F2-F1 space in Manchester laterals — being separated from other instances of [l]. This pattern may also be analysed as a clear/dark split in this variety since laterals are dark initially as well as finally. Here, vocoid quality does appear to have an impact on the clustering of initial [l]. As this is a dark [l] with prominent tongue back activity, it is possible that this is a case of vocoid-gesture to vocoid-gesture coarticulation. Liquid identity ([l] versus [r]) explains one of the nonrhotic patterns (Manchester), but resonance quality (clear versus dark) explains them both (Manchester and Sunderland).

In the {F1, F2, F3} cluster for the Tyrone speaker, there is some evidence of a clear/dark split with (dark) initial [r], (dark) final [l], and [r] after back vowels patterning together. (Clear) initial [l] and some (clear) final [r] tokens are separated from other liquids. However, in this case, an alternative analysis is equally tenable, namely that there is in fact a simple [l]/[r] split with only some final [l] tokens out of place. The Fife speaker has a simple [l]/[r] split.

In the {F1, F2} cluster, in the Tyrone clear initial [l] variety, (clear) initial [l] is separated from the other liquids; within the other grouping, (clear) final [r] is separated from the two dark liquids. In the dark initial [l] rhotic variety (Fife), the patterns are very similar, although it is final [r] (rather than initial [l] in the Tyrone case) which is separated from the other liquids. Within the other group, there is once again a clear/dark split.

In the {F1, F2, F3} clusters for the Sunderland speaker's vocoids, the influence of initial [r] and final [l] on the formant matrix of high back vowels (so they cluster with the low vowels) can be explained by these liquids being dark. Notably, Manchester initial [r] is clear and so it is only final [l] which has such an effect in the Manchester data.

The cluster analysis suggests that resonance is important for nonrhotic varieties but may be slightly less important for rhotic varieties. There seems to be a different temporal extent to resonance, with the liquids having less effect on the vocoids in the rhotic varieties than they do in the nonrhotic varieties. Following Tunley (1999), it is likely that the stressed nature of the vowel in the present study explains the lack of effect of F3 in the vocoids in all the varieties examined, as shown by the fact that {F1, F2, F3} dendrograms for the vocoids do not differ in great detail from the {F1, F2} dendrograms.

6.2.2 F2 and F2-F1 frequency relationships

As predicted from Kelly & Local's observations, the nonrhotic varieties display a polarity of resonance pattern in initial liquids, with the Sunderland speaker having higher F2 in initial [l] (clear) than in initial [r] (dark), and the Manchester speaker, conversely, having a lower F2 in initial [l] (dark) than in initial [r] (clear). However, the rhotic varieties all present the same pattern, namely that F2 in initial [l] is higher than F2 in initial [r]. Thus the rhotic varieties appear to be behaving like the nonrhotic clear initial [l] variety in this respect.

6.2.2.1 Nonrhotic varieties

Both nonrhotic varieties have laterals which are darker finally than initially (Tables 18 and 19), in accordance with Sproat & Fujimura's predictions. The difference is less pronounced in the dark initial [l] variety than in the clear initial [l] variety. This effect may be due to some constraint on how much darker final [l] may be than initial [l], given a dark starting point. This limit on darkness applying in the dark initial lateral variety could be expressed as an extreme of resonance effect: if initial laterals are dark, then there is not much acoustic space in which to squeeze a final, darker, lateral. This is not unlike an interpretation given by Huffman (1997:139) for some of her data on intervocalic [l]:

> '[one speaker] has consistently low F2 for /l/'s. Even the longer duration of /l/ in her Cəl items does not result in additional backing. Rather, her /l/'s appear to be up against the limit of backness she can or will produce.'

For the Manchester speaker, the difference between initial and final [l] is significant for F2-F1 but not for F2, indicating that a relatively high F1 may also have a role to play in increasing darkness once a minimum frequency for F2 has been reached.

West (2000), in discussing Carter (1999), claims that the fact that the dark initial lateral in the Manchester variety does not have a significantly higher F2 in onset position as compared to the lateral in rime position only weakly supports my analysis. In fact, this detail does support the analysis here and in Carter (1999) in that it means that a demonstrably dark lateral (with an early dorsal gesture) can be found in onset position in this variety, challenging Sproat &

Fujimura's claim that apical and dorsal gestures in [l] are intrinsically aligned to syllable structure.

Nevertheless, if the lack of statistical significance between syllable-initial [l] and syllable-final [l] is indeed a consequence of the presence of a very dark syllable-initial lateral, precluding any further lowering of F2, then it seems as if the Manchester speaker may be using a different strategy to achieve greater darkness in syllable-final laterals, namely manipulation of F1, resulting in a lower (rather than backer) resonance percept. Indeed, the mean F1 in final Manchester [l], 4.242 bark/424 Hz, is higher than the mean F1 in initial Manchester [l], 3.456 bark/342 Hz (t(14)=2.204, *p*=0.0448). This being the case, the statistical significance in the F2-F1 domain is also analytically significant, because relative darkness in the lateral is still being used as a marker of syllable-finality in laterals, though the phonetic resources being used to achieve darkness are not necessarily the same as in the Sunderland variety. Since there is no contrast in the liquid system in the rime, this darkness has no paradigmatic consequence (it is not needed to differentiate [l] from [r]), though it still has some prosodic consequence in marking higher level structure such as syllable position.

Not only do the reported resonance polarities reflect Kelly & Local's observations but also Manchester laterals are darker than Sunderland laterals and Manchester rhotics are clearer than Sunderland rhotics.

The longer-domain effects reported by Kelly & Local are not supported since the results for the vocoids presented here are not statistically significant, but if there is a trend it is in accordance with Kelly & Local's observations in that Sunderland vocoids have a higher F2 at their mid-point after [l] than after [r] and Manchester vocoids have a lower F2 after [l] than after [r].

Kelly & Local were examining much longer domains than the single syllable investigated here. Moreover, Heid & Hawkins (2000) found that the long-domain resonance effects could 'pass through' stressed syllables to affect even more distant unstressed syllables than those reported by Tunley (1999); it could be that the stress in the target word is reducing any longer-term resonance effects in the present data.

6.2.2.2 Rhotic varieties

Syllable-initial [l] can be taken as counting as relatively clear for both rhotic varieties, even when syllable-initial [l] is phonetically dark (in the case of the Fife speaker). There is, in fact, no significant difference between syllable-initial and syllable-final laterals for the Fife speaker either in the F2 domain or in the F2-F1 domain, leading to the suspicion that the syllable-initial laterals are already as dark as they can be in this variety. This suggestion may be supported by the fact that the direction of the difference in the F2-F1 (bark space) means, despite the lack of statistical significance, is consistent with the syllable-final laterals being darker than the syllable-initial laterals. It seems that F1 may be playing a greater role in clearness and darkness in varieties which have typically dark syllable-initial laterals. Note that, although the difference in means in F2 for the Fife speaker is not in the expected direction, the F2 difference is associated with a much larger *p*-value than is the F2-F1 difference in means. The F2 difference is therefore less reliable.

The rhotic speakers have darker initial rhotics than initial laterals (Tables 22 and 23) and final rhotics which may be clearer than both initial rhotics (Tables 24 and 25) and final laterals (Tables 26 and 27), although the evidence regarding final rhotics is not as strong. In rhotic varieties, the nonrhotic pattern (Figure 24) does not hold: initial rhotics in the dark initial lateral rhotic variety are not clearer than the initial laterals (as they are in the dark initial lateral nonrhotic variety, Manchester).

The possible lack of a significant difference between initial [l] and initial [r] in the F2 domain for the dark syllable-initial [l] variety (Fife) is reminiscent of the similar lack of a significant difference between initial [l] and final [l] for the dark syllable-initial [l] nonrhotic variety (Manchester) in Table 18. A similar explanation is possible, namely that F2 is so low in the syllable-initial [l] that there is little leeway for a lower F2 in any liquid in that variety which may count as darker. Just as the Manchester speaker seems to use a higher F1 to produce greater darkness in syllable-final [l] than in syllable-initial [l], so the Fife speaker seems to be using a higher F1 to produce a greater darkness in syllable-initial [r] than in syllable-initial [l], resulting in increased significance in the differences between the means when F1 is factored in. However, in itself, the mean F1 in Fife initial [r], 3.584 bark/355 Hz is not significantly higher than the mean F1 in Fife initial [l], 3.146 bark/311 Hz (t(14)=1.5039, *p*=0.1548).

This rhotic variety pattern is supported by Lehiste's (1964) American English data. Her speaker GEP is a good example of the distinction which must be drawn between absolute (phonetic) clearness or darkness on the one hand and relative (phonological) clearness or darkness on the other: like the Fife speaker, his initial laterals are (in an absolute sense) dark, but they count as clear within his system since they are clearer than either his final laterals or his initial rhotics. A subset of Lehiste's data comparable to the primary data presented in this chapter is plotted in Figure 28. This American English pattern is also reported by Olive *et al.* (1993).

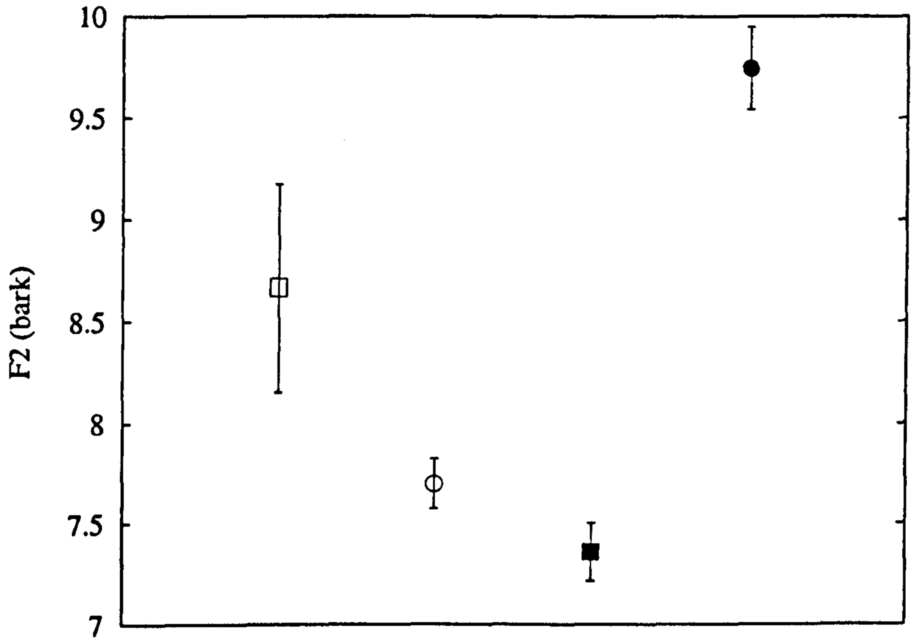


Figure 28. Mean F2 frequencies (bark) in liquids for a subset of Lehiste's (1964) American English data comparable to the Experiment 1 dataset (error bars indicate standard deviation). Squares represent laterals; circles represent rhotics. Open shapes represent initial liquids; filled shapes represent final liquids.

Table 37 contains comparisons within Lehiste's data. Interpretation of these results is difficult because Lehiste's reported data for each vowel context are themselves not individual tokens but means (relating to different numbers of tokens). However, the p-values are very small and so it is reasonable to suggest that Lehiste's American English data do indeed correspond with the data from rhotic varieties presented in this chapter.

comparison	df	t	*p*
initial [l] ~ final [l]	6	4.9393	0.0026
initial [l] ~ initial [r]	6	3.671	0.0104
initial [r] ~ final [r]	6	17.0821	<0.0001
final [l] ~ final [r]	6	19.2046	<0.0001

Table 37. Results of unpaired two-tailed t-tests on F2 frequencies in a subset of Lehiste's (1964) American English data (Table 12).

6.2.3 Variances

For the Tyrone speaker, the dark liquids have a wider range of variability than the clear liquids, in both F2 and F3. F1 data might suggest the opposite, though this is entirely due to a very large variance for F1 in final [r]. The data from this speaker appear not to support either of the extensions of Bladon & Al-Bamerni's analysis, namely that coarticulation might be more prevalent with, on the one hand, clear liquids or, on the other hand, syllable-initial liquids.

In general, what F3 patterns there are tend to suggest that the liquids which count as dark in the system coarticulate more than clear liquids, but the smaller number of results from F1 variances (and F3 for the Fife speaker) suggest the opposite.

There are sufficient instances of no significant difference between variances, and contradictions between those differences which do occur, to conclude that there is no consistent evidence from this data set to suggest that clearness or syllable-initiality is necessarily associated with wide ranges of variation.

6.2.4 F2 frequency and the duration of liquids

The results presented in Section 6.1.4 lack statistical significance but the indication is that longer Sunderland laterals may have a lower F2. This observation supports both Sproat & Fujimura's and Newton's analysis. However, the dark initial [l] nonrhotic variety (Manchester) appears to have the opposite pattern: the longer the lateral, the higher F2 may be.

In Chapter 8, I will take up the implications of these observations with regard to gestural phasing.

6.2.5 Duration of F2 transitions

The data presented in this chapter support Ladefoged & Maddieson's (1996:361) criticism of Sproat & Fujimura (1993), since the F2 transition data from dark laterals in this study seem to suggest dorsal gestures preceding apical gestures whether or not the lateral is in syllable-final position (longer second formant transitions in liquids are likely to reflect relatively slow dorsal gestures while shorter transitions reflect relatively fast apical gestures). Ladefoged & Maddieson point out that Sproat & Fujimura's analysis predicts that a dorsal gesture will follow an apical gesture in syllable-initial laterals, resulting in a slow F2 transition out of a syllable-initial dark lateral.

The clear initial [l] variety (Sunderland) might have approximately co-extensive apical and dorsal gestures in initial [l] since the duration of transitions into [l] are not significantly different from the duration of transitions out of [l]. The dark initial [l] nonrhotic variety (Manchester), however appears to have a noticeably early dorsal gesture in [l], particularly when compared with [r], since it has a long F2 transition into [l].

Sproat & Fujimura do indeed report an early dorsal gesture with final laterals and predict that initial laterals would have a relatively late (and relatively weak) dorsal gesture. This is evidently not the case for the Manchester speaker, who has noticeably dark laterals in all positions. The results presented here strongly imply that early dorsality is a correlate of darkness rather than of syllable-finality. Moreover, early dorsality in a syllable-initial [l] in Manchester English may go some way to explaining why shorter laterals may tend to have lower F2 in that variety, since longer Manchester laterals would include more time for a later apical gesture to become more prominent relative to the dorsal gesture.

The rhotic varieties appear to have relatively short transitions into [l] and relatively long transitions into [r]. While the equivalent comparison is not significant for the (nonrhotic) Sunderland speaker, it has high significance in the opposite direction for the (nonrhotic) Manchester speaker. As with the formant frequencies, both rhotic varieties approximate to the clear initial [l] nonrhotic variety (Sunderland) more closely than to the dark initial [l] nonrhotic variety (Manchester).

6.3 Conclusion

In this chapter I have shown that neither Sproat & Fujimura's (1993) account of laterals nor Kelly & Local's (1986, 1989) account of liquids in nonrhotic varieties of English can fully account for a data set including instances of [r] alongside instances of [l] as well as rhotic varieties alongside nonrhotic varieties of English.

Sproat & Fujimura's confirmation of the long-established finding that syllable-final laterals are darker than syllable-initial laterals is supported by the data in this chapter, but their identification of syllable-initial [l] as intrinsically clear is in need of revision.

Kelly & Local's observations have been confirmed for the nonrhotic varieties, with a high F2 and large F2-F1 space being associated with clear liquids and a low F2 and small F2-F1 space being associated with dark liquids. The variety with a clear initial [l] (Sunderland) does indeed have a dark initial [r]; the variety with a dark initial [l] has a clear initial [r]. However, the difference between a clear initial [l] and a dark initial [r] is greater than the difference between a dark initial [l] and a clear initial [r]. The rhotics as well as the laterals differ across the varieties, which leads to the conclusion that the data are not just an epiphenomenon of resonance quality in laterals, with clear laterals and dark laterals placed on either side of a constant, neutral rhotic — neither clear nor dark — which would appear clear or dark in contrast with whichever lateral is found in that variety.

Kelly & Local observed that vocoid qualities also vary with liquid resonance. Although the vocoids investigated here are temporally adjacent to the liquids, they are in a prosodic position (head of a stressed syllable) where the least variation might be expected, since vowel quality is relatively constrained. This prosodic account explains why the effect is often noticeable but not reliable enough to achieve statistical significance: it may still contribute to the coherence of the signal (as suggested by Heid & Hawkins, 2000).

Rhotic varieties, however, do not show evidence of a differing pattern for clear versus dark initial lateral varieties. Whatever the absolute phonetic resonance quality of the initial lateral, the same pattern is found: a relatively clear initial lateral and a relatively dark initial rhotic alongside a relatively dark final lateral and a relatively clear final rhotic. This pattern is most closely associated with the nonrhotic pattern for the clear initial lateral variety.

It is possible that the clear 'final' [r] in the nonrhotic varieties (where a rhotic articulation is present as a marker of juncture) is just vestigial. It could be a remnant of an earlier rhotic system (note that the rhotic varieties have clear final [r]) which has now become nonrhotic and left the resonance quality of initial [r] relatively unconstrained.

There is little evidence in this data set for Bladon & Al-Bamerni's finding that clear syllable-initial laterals undergo greater coarticulation than dark syllable-final laterals. Once rhotics are added to the laterals, making a liquid system, the patterns of variability are, at the very least, more complex.

7 Experiment 2 (liquids in onsets): results and discussion

7.1 Introduction

In Chapter 6 I showed that resonance quality was sensitive to syllable position, liquid identity ([l] or [r]) and dialect type (rhotic versus nonrhotic). In the rhotic varieties examined, the polarity of resonance qualities turn up in only one pattern, with relatively clear initial laterals, whereas the nonrhotic varieties examined are variable in this respect, with one variety (Sunderland) having relatively clear initial laterals and the other (Manchester) having relatively dark initial laterals. This chapter reports on Experiment 2, which investigates in more detail liquids in onset position in the nonrhotic varieties.

After a note on the time normalisation procedure in Section 7.2, Section 7.3 presents results of the investigation into time-normalised formant frequencies, first using classification and regression trees, supported by an analysis of formant frequencies. Section 7.4 outlines results of an analysis of formant frequencies in real time. In Section 7.5 I present the results of a spectral moments analysis which dynamically tracks the F2-F1 space. In Section 7.6 I present results of analyses of the duration of formant steady states and transitions. Discussion of the results is given in Section 7.7.

7.2 Normalisation in the time domain

For the purposes of this experiment, the liquid boundary was defined in terms of F2 transitions into the liquid, since F2 appeared to be the major acoustic correlate of clearness/darkness, playing such an important role in the patterns identified in Chapter 6. Figure 29 demonstrates that F2 transitions into the onset liquid on average begin before F1 transitions into the onset liquid (for further details on the timing of transitions, see Section 7.6). Using F2 therefore also gives the advantage of a greater coverage in time backwards into the preceding vocoid in the carrier phrase "Say ... again" than would be the case if the boundary were to be defined in terms of F1. (In a normalised time analysis, excessively short durations can make the data difficult to interpret since there may be very little or no difference in real time between the sample points). In fact, the F2 transitions out of the liquid end either after the F1 transitions out of the liquid or at the same time as the F1 transitions out of the liquid, so the proposed method also gives greater coverage in time into the vocoid, allowing the transitional portions to be more accurately investigated.

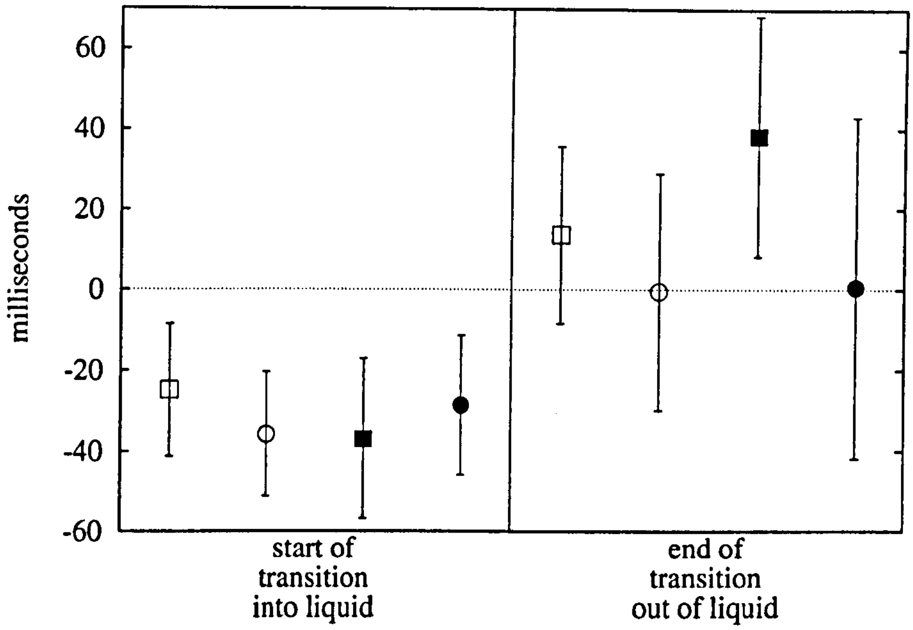


Figure 29. Means and standard deviations (indicated by errorbars) of relative timing of beginnings and endings of F1 and F2 transitions in onset liquids. Positive values indicate that the F1 landmark precedes the F2 landmark; negative values indicate that the F2 landmark precedes the F1 landmark. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

In order to normalise for duration, the five reference points in Figure 30 were identified for each token from its label file.

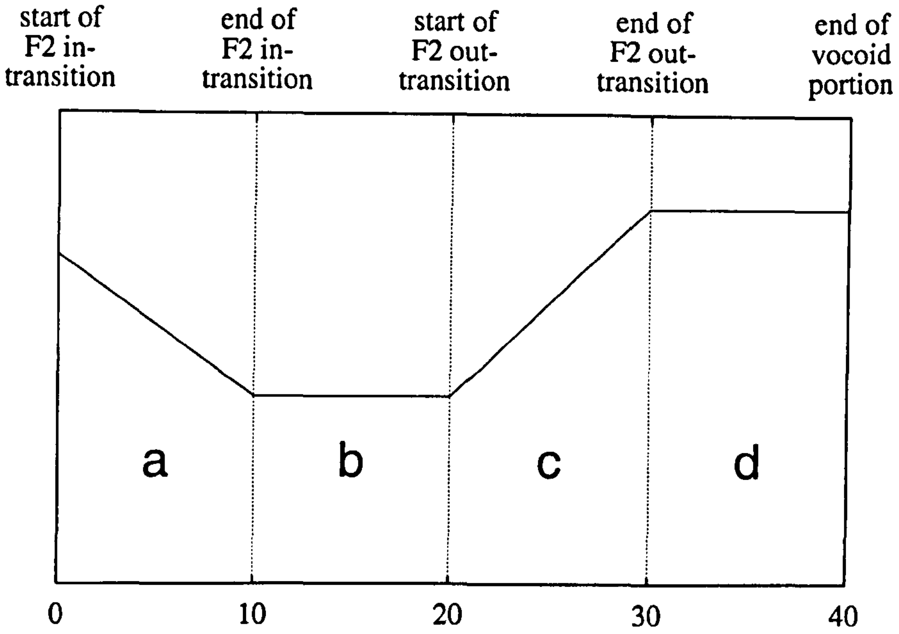


Figure 30. Labels used for onset time normalisation. The solid line represents a schematised formant trajectory.

Each of the regions (a, b, c, d) between each sequential pair of labels was normalised in the time domain by being divided into ten parts of equal duration for a given token, giving 41 sample points in total for each token: ten from the beginning of region a to just before region b (points 0 to 9), ten from the beginning of region b to just before region c (points 10 to 19), ten from the beginning of region c to just before region d (points 20 to 29), ten from the beginning of region d to just before the final nucleus boundary label (points 30 to 39) and one at the final nucleus boundary label (point 40).

7.3 Experiment 2 results: time-normalised formant frequencies

The formant analysis presented here extracted formant tracks (F1, F2 and F3) corresponding to sample points 0-40 in the time-normalised model presented above. In Section 7.3.1 I present first the results of classification and regression tree analysis to provide a knowledge-driven statistical overview of the data. The major findings of this analysis are then followed up in subsequent sections with analysis of individual formants and the space between formants.

7.3.1 Time-normalised classification and regression trees

In the following tree plots (Figures 31 to 35), the decision tree should be read from top to bottom, with the binary decisions represented by horizontal separation (in a similar fashion to the tree graphs commonly used in linguistics); a relatively long vertical line before the next (horizontal) split indicates that the previous decision has resulted in a relatively important split, with low deviances (a measure of node heterogeneity).

Figure 31 shows a classification tree, in graphical form, which predicts the variety and liquid identity of tokens based on the bark values for F1, F2 and F3 at sample point 15 (at the midpoint of the liquid steady state, as defined by the F2 transitions).

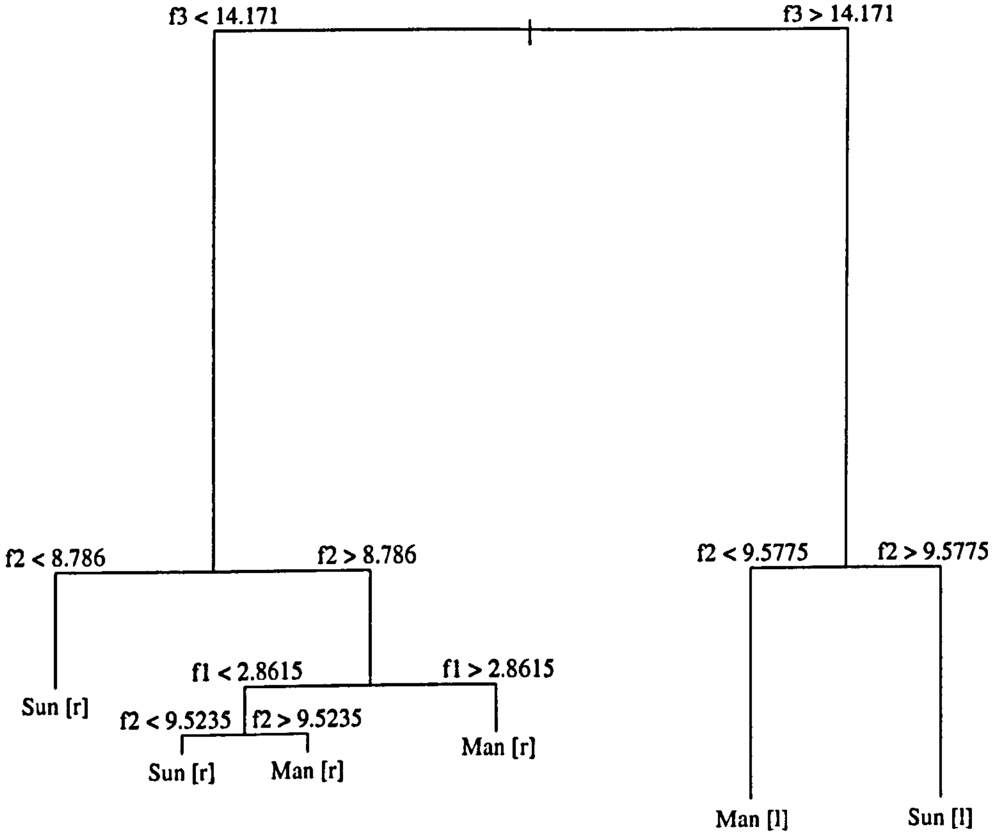


Figure 31. Classification tree predicting the variety and liquid identity of tokens based on F1, F2 and F3 frequencies (bark) halfway through the liquid steady state.

The first split in the tree is based on whether the frequency of F3 is less or greater than 14.171 bark (2380 Hz). By inspecting the terminal nodes, it can be seen that this decision in fact separates tokens of [r] from tokens of [l]. Compared to the vertical lines lower in the tree, the vertical lines emanating from this split are relatively long; this is therefore a relatively stable decision. In contrast, the split which results in the fourth and fifth terminal node (counting from the left) divides two groups of tokens of [r] from the Manchester speaker on the basis of whether F2 is less or greater than 9.3435 bark. The vertical lines in this case are relatively short; this is a less reliable split.

Within the set of tokens of [l] (high F3), the next decision is taken on the basis of the frequency of F2. A high F2 (above 9.5775 bark/1186 Hz) predicts a token of [l] from the Sunderland speaker; a low F2, below that frequency, predicts a token of [l] from the Manchester speaker. Following the [r] branch from the root of the tree (the left of the two branches), the next decision is also based on F2 frequencies. Frequencies below 8.786 bark (1044 Hz) predict that the liquid is a Sunderland [r]; frequencies above that level are mostly Manchester [r], although, following the high F2 branch reveals that an F1 below 2.8615 (284 Hz) in combination with an F2 below 9.5235 (1176 Hz) predicts Sunderland [r]. In summary, the classification tree identifies the following predictions for the midpoint of the liquid:

- high F3, high F2 ⇒ Sunderland [l]
- high F3, low F2 ⇒ Manchester [l]
- low F3, high F2 ⇒ Manchester [r]
- low F3, very low F2 ⇒ Sunderland [r]
  or low F3, low F2 & low F1

Figure 32 shows a regression tree which predicts the value of F2 in bark at sample point 15 (halfway through the liquid steady state, as defined by the F2 transitions) based on the values for variety, liquid identity and vowel features (height of following vowel, backness of following vowel, length of following vowel and whether the following vowel is a monophthong or a diphthong). Textual versions of this and subsequent regression trees giving full details of each node and unpaired two-tailed t-tests on each split are given in Appendix 4. The groups identified by each split in the regression trees are significantly different from each other at (at least) $p<0.003$.

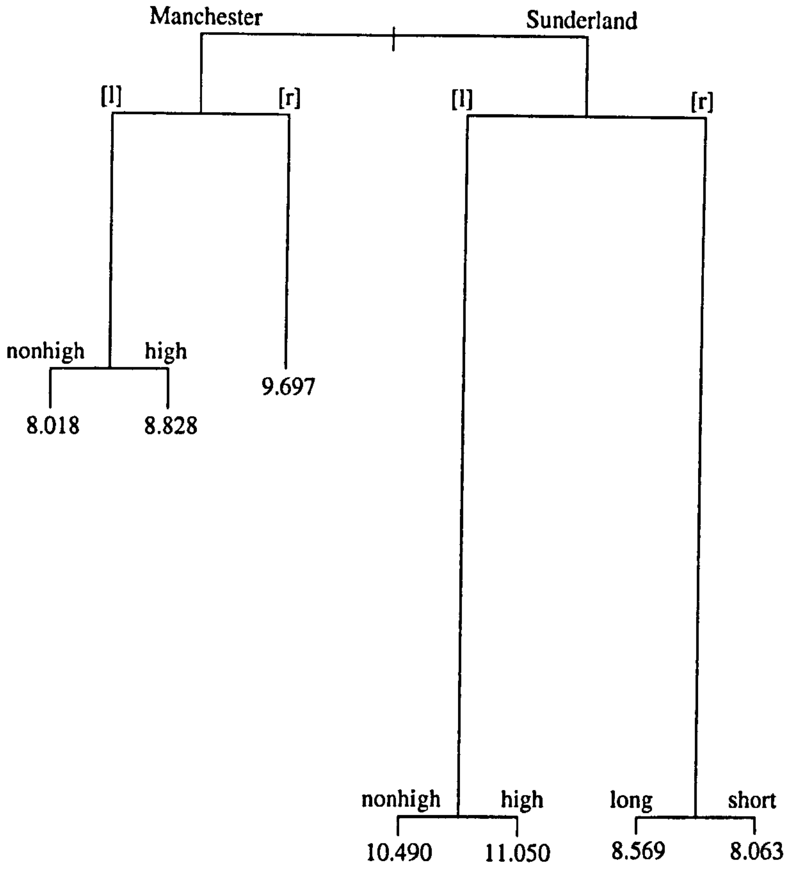


Figure 32. Regression tree predicting F2 frequency (bark) halfway through the liquid steady state based on values for variety, liquid identity and vowel features.

The regression tree in Figure 32 makes the first decision on variety, and then there are more stable splits based on liquid identity so that, for the Manchester speaker, if the liquid is [l] a low F2 is predicted (centred on 8.297 bark/962 Hz), and if [r], a high F2 (centred on 9.697 bark/1209 Hz) is predicted; for the Sunderland speaker, if the liquid is [l] a high F2 is predicted (centred on 10.69 bark/1411 Hz), and if [r] a low F2 (centred on 8.33 bark/967 Hz) is predicted.

Decisions of less consequence are taken at a lower level of the tree based on vowel features. For both speakers' tokens of [l], F2 is higher before a high vowel than before a nonhigh vowel (decisions in the regression tree analysis were based on ternary vowel height attributes; in both these cases, low and mid vowel contexts were clustered together and separated from high vowel contexts as an output of the algorithm). Additionally, tokens of [r] for the Sunderland speaker have a higher F2 before long vowels than before short vowels. These low level splits suggest that there is a relatively minor effect of following vowel context on the quality of the liquid, particularly [l].

The classification tree in Figure 31 identified that F1 has an influence on decisions in certain circumstances. A regression tree is therefore presented in Figure 33 which incorporates F1 by predicting the value of the F2-F1 space in bark at sample point 15 (halfway through the liquid steady state, as defined by the F2 transitions) based on the values for variety, liquid identity and vowel features.

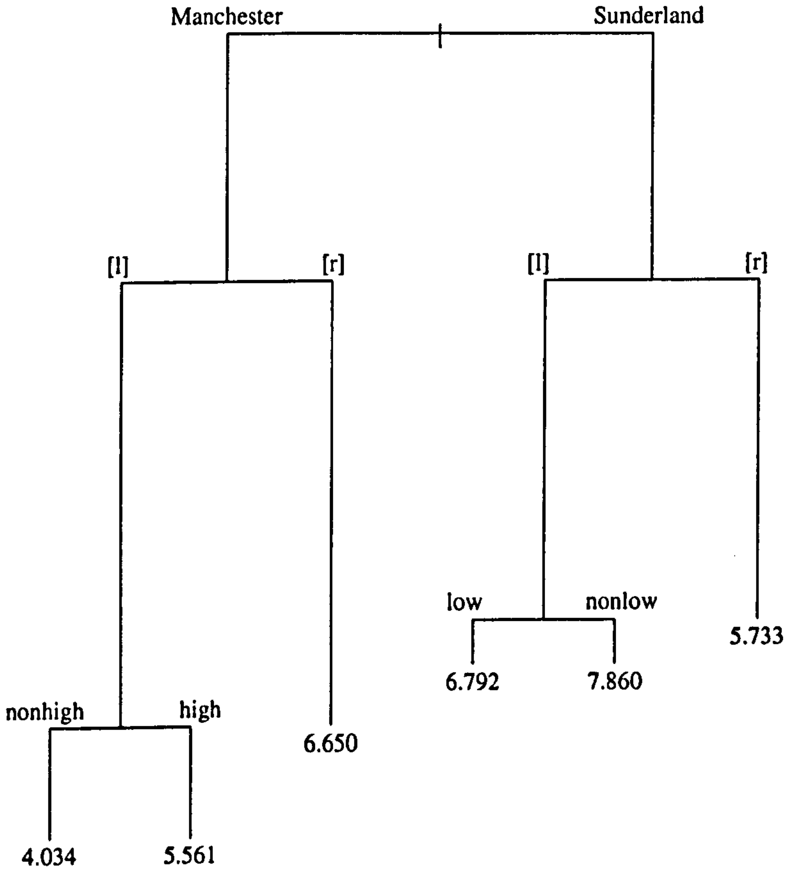


Figure 33. Regression tree predicting F2-F1 frequency (bark) halfway through the liquid steady state based on values for variety, liquid identity and vowel features.

It can be seen that the predictions for the F2-F1 space in Figure 33 are very similar to the predictions for F2 in Figure 32. However, introducing F1 into the equation as well as F2 evens out the relative stability of the liquid identity splits across the two varieties: in Figure 32, liquid decisions for Sunderland are more reliable than those for Manchester whereas in Figure 33 the liquid decisions are similar for both varieties.

Vowel height has a relatively small, though noticeable, role to play in predictions of F2-F1 for tokens of [l] in both varieties (similar to its role in predicting F2), indicating that coarticulation due to following vowel context is more extensive in tokens of [l] than in tokens of [r] for both speakers.

For the Manchester speaker, a small F2-F1 space (centred on 4.561 bark) predicts [l] while a large F2-F1 space (centred on 6.65 bark) predicts [r]; for the Sunderland speaker, a small F2-F1 space (centred on 5.733 bark) predicts [r] while a large F2-F1 space (centred on 7.59 bark) predicts [l].

The story is different midway through the vocoid. Figure 34 presents a regression tree predicting F2 values midway through the vocoid on the basis of variety, liquid identity and vowel features. Figure 35 presents a similar tree which predicts the F2-F1 space instead of F2 alone.

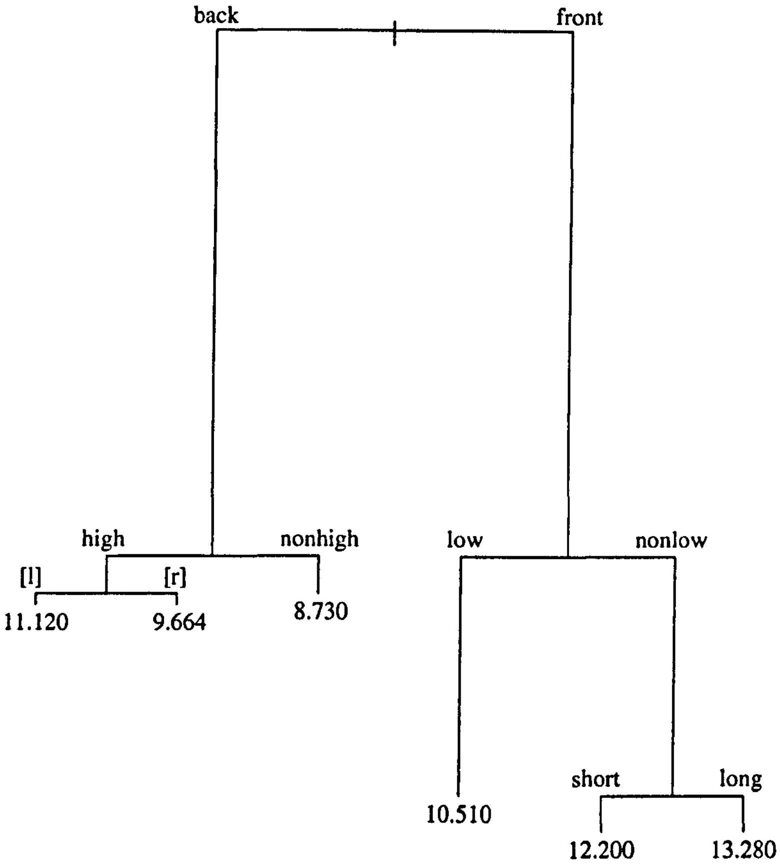


Figure 34. Regression tree predicting F2 frequency (bark) halfway through the vocoid based on values for variety, liquid identity and vowel features.

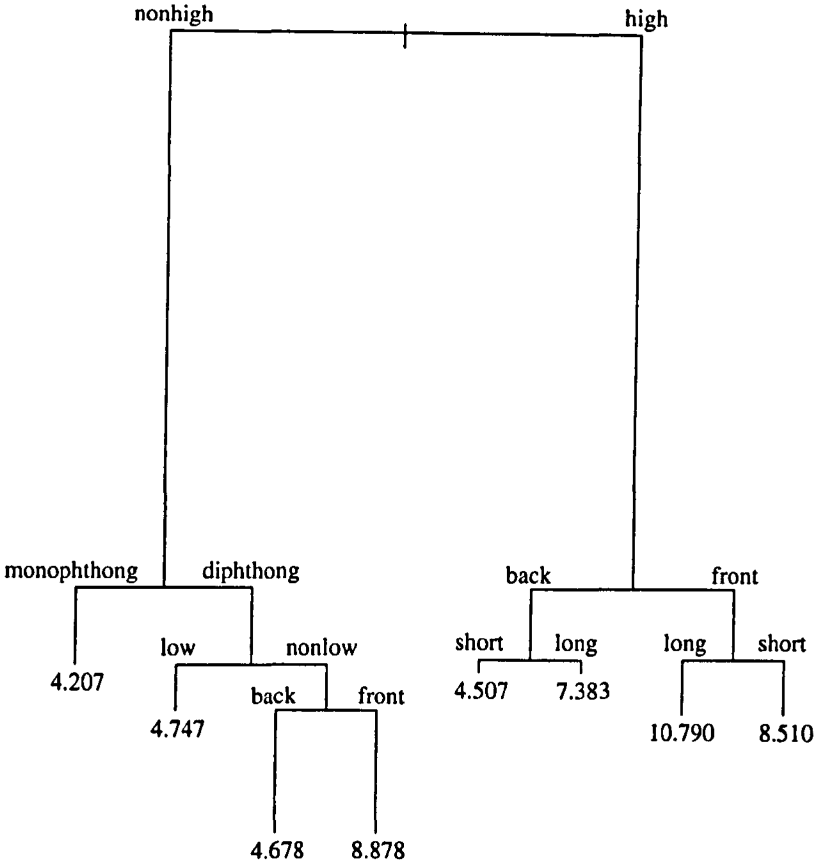


Figure 35. Regression tree predicting F2-F1 frequency (bark) halfway through the vocoid based on values for variety, liquid identity and vowel features.

It is clear from Figures 34 and 35 that liquid identity — and indeed variety — do not have much bearing on the predictions of F1 and F2 frequencies in the vocoid: they are almost completely absent from the trees. Instead, the vowel features height and backness have the effect that would be expected, with front vowels and (to a lesser extent) high vowels predicting a high F2, and high vowels and (to a lesser extent) front vowels predicting a large F2-F1 space. There seems to be little evidence in these regression trees of perseveratory coarticulation in the vocoid due to the preceding liquid, with the only case being that of high back vowels, which are predicted to have a noticeably higher F2 after tokens of [l] (11.12 bark / 1506 Hz) than after tokens of [r] (9.664 bark / 1202 Hz); this is, nevertheless, a relatively unreliable split.

7.3.2 Time-normalised F3 and F2 frequencies in liquid steady states and transitions

Figure 36 and Table 38 display measurements of F2 and F3 at sample point 15 in all 676 tokens in the time-normalised analysis; that is, midway between the end of the F2 transition into the liquid and the start of the F2 transition out of the liquid. This point corresponds approximately to the midpoint measure in Chapter 6. Unless otherwise stated, all plots represent data from all 676 tokens.

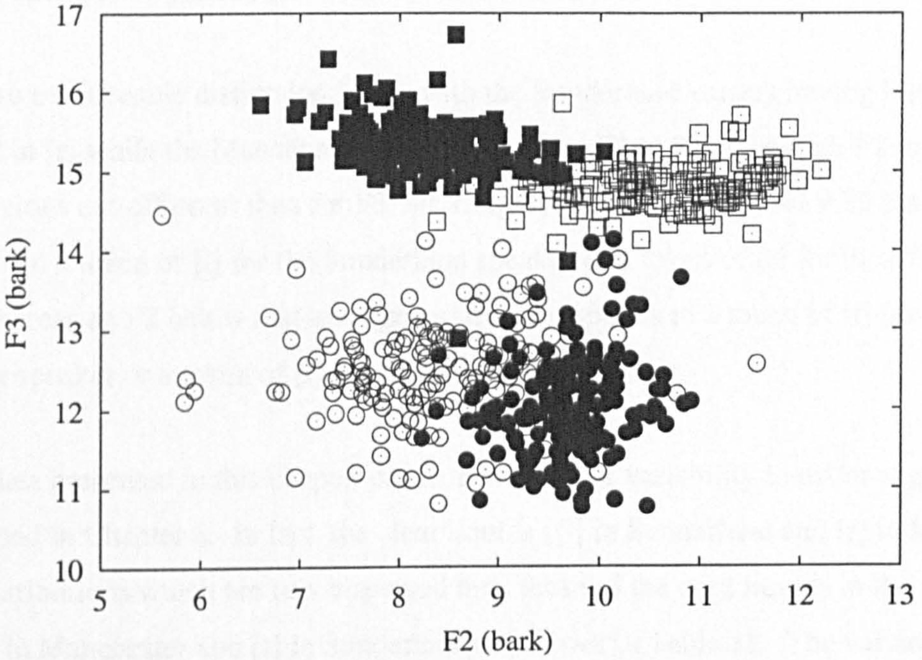


Figure 36. Scatter plot of F3 against F2 frequencies (bark) midway through the steady state (region 'b' in Figure 30) of the liquid as delimited by F2 transitions (sample point 15). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

Almost all tokens of [r] have a lower F3 than tokens of [l] in both varieties. Generally, an F3 above about 14 bark (2320 Hz) corresponds to a token of [l], while an F3 below that level corresponds to a token of [r] (as in the classification tree in Figure 31). The distribution of F3 is wider for [r] than for [l], with F3 in [r] having a standard deviation of 0.685 (mean 12.281 bark/1794 Hz) and a range of 3.701 bark, while F3 in [l] has a standard deviation of 0.410 (mean 15.066 bark/2726 Hz) and a range of 3.835 bark.

		F2		**F3**	
		mean	**SD**	**mean**	**SD**
Sunderland	**l**	10.685 (1410 Hz)	0.720	14.812 (2622 Hz)	0.268
	r	8.330 (967 Hz)	0.900	12.524 (1860 Hz)	0.643
Manchester	**l**	8.297 (962 Hz)	0.603	15.309 (2830 Hz)	0.373
	r	9.697 (1209 Hz)	0.500	12.043 (1731 Hz)	0.643

Table 38. Means and standard deviations for F3 and F2 frequencies (bark) midway through the steady state of the liquid as delimited by F2 transitions.

There is also a noticeable distinction in F2, with the Sunderland variety having high F2 in [l] and low F2 in [r] while the Manchester variety has a low F2 in [l] and a high F2 in [r]. There is a less obvious cut-off point than for F3 but, roughly, an F2 above about 9.25 bark (1126 Hz) corresponds to a token of [l] for the Sunderland speaker or a token of [r] for the Manchester speaker, whereas an F2 below that level generally corresponds to a token of [l] for the Manchester speaker or a token of [r] for the Sunderland speaker.

The extra data presented in this chapter cause the ranges of variability to differ slightly from those reported in Chapter 6. In fact, the clear liquids ([l] in Sunderland and [r] in Manchester) have F2 distributions which are less dispersed than those of the dark liquids in the same variety ([l] in Manchester and [r] in Sunderland) as shown in Table 38. The variance for Sunderland [l], 0.5178, is less than the variance for Sunderland [r], 0.8102 ($F(162,169)=1.5647$, $p=0.0041$). The variance for Manchester [r], 0.2501, is less than the variance for Manchester [l], 0.3634 ($F(176,165)=1.4529$, $p=0.0155$). However, in general, the Manchester F2 distributions are tighter than the Sunderland F2 distributions. The variance for Manchester [l] is less than the variance for Sunderland [l] ($F(169,176)=1.4247$, $p=0.0204$). The variance for Manchester [r] is less than the variance for Sunderland [r] ($F(162,165)=3.2389$, $p<0.0001$).

Three of the four F2 frequencies coincide with the values identified in the regression tree in Figure 32. An extremely small difference from the regression tree (a difference of 0.005 bark, or 1 Hz) in the frequency for Sunderland tokens of [l] is probably a result of a single outlier which has an F2 frequency of 8.379 bark (975 Hz) which would be excluded from the decisions of the regression tree, resulting in a mean which is lower than the prediction of the tree.

A first pass at revealing the temporal extent of the distinction between the four groups (Manchester and Sunderland laterals and rhotics) can be grasped by plotting equivalent distributions at different points in the time-normalised portion of speech, as in Figure 37. The upper left panel of Figure 37 plots F3 against F2 at sample point 5 in all 676 tokens; that is, midway through the F2 transition into the liquid. The upper right panel of Figure 37 plots F3 against F2 at sample point 15 in all 676 tokens; that is, at the midpoint of the liquid. The lower left panel of Figure 37 plots F3 against F2 at sample point 25 in all 676 tokens; that is, midway through the F2 transition out of the liquid. The lower right panel of Figure 37 plots F3 against F2 at sample point 35 in all 676 tokens; that is, midway through the vocoid portion.

The plot at point 5 demonstrates that a similar state of affairs (with a separation between the four groups) to that in the steady state (point 15; see also Figure 36) is already evident during the transition into the liquid portion. The polarity effect (where F2 associations are dependent on the variety even though a high F3 is routinely associated with [l] and a low F3 with [r] in both varieties) is noticeable, but the four groupings are less well separated than at point 15, at the mid-point of the liquid (as defined by F2 trajectories).

The four-way split is breaking down at point 25 (midway through the F2 transition out of the liquid and into the vocoid), though the groupings are still partially separable. The F3 split between tokens of [l] and tokens of [r] is still evident, though the F2 splits (dependent on variety) are much less obvious than at point 15.

Once into the following vocoid (point 35), the differences between the groupings have broken down considerably. There is still a small difference between the F3 frequencies for tokens of [l] and tokens of [r] (though this is diminished), but each of the four groupings by variety and liquid show very similar ranges of variability in the F2 domain.

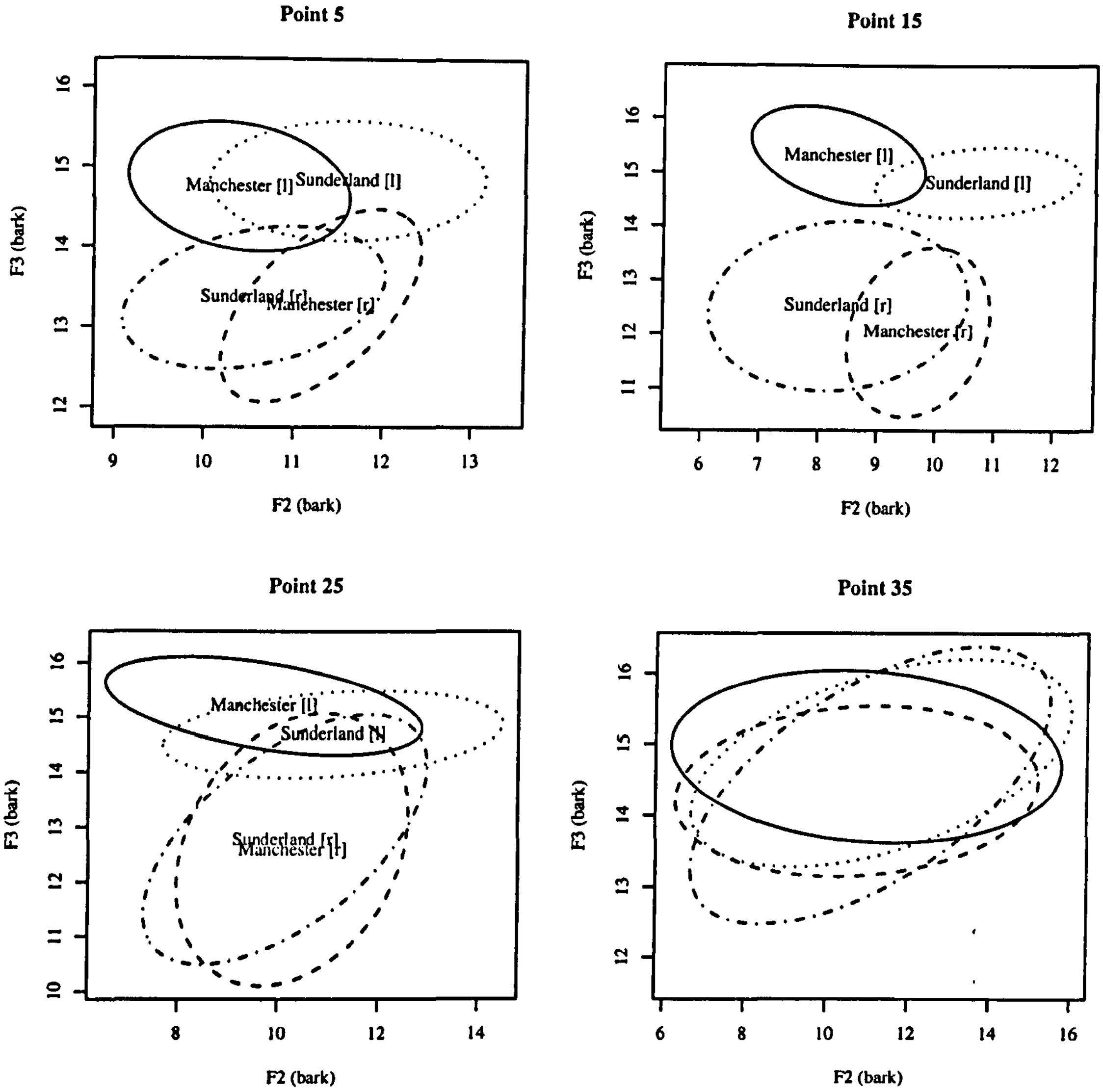


Figure 37. Ellipse plots of F3 against F2 frequencies (bark). Ellipses represent a 95% confidence range. The solid ellipses enclose instances of Manchester [l]; the dotted ellipses enclose instances of Sunderland [l]; the dashed ellipses enclose instances of Manchester [r]; the dotted and dashed ellipses enclose instances of Sunderland [r]. Point 5: midpoint of the F2 transition into the liquid (region 'a' in Figure 30). Point 15: midpoint of the steady state (region 'b' in Figure 30) of the liquid as delimited by F2 transitions. Point 25: midpoint of the F2 transition out of the liquid (region 'c' in Figure 30). Point 35: midpoint of the vocoid portion following the liquid (region 'd' in Figure 30).

7.3.3 Time-normalised dynamic formant analysis

In this section, dynamic aspects of the spectral detail will be examined more closely, using the normalised time data. Figure 38 provides an overview of this section with plots of the normalised time trajectories for the first three formants for each speaker and liquid using the full set of data (676 tokens in all). In these and subsequent similar plots of mean formant trajectories, normalised time proceeds in a left-to-right direction along the abscissa. The data will then be discussed formant by formant.

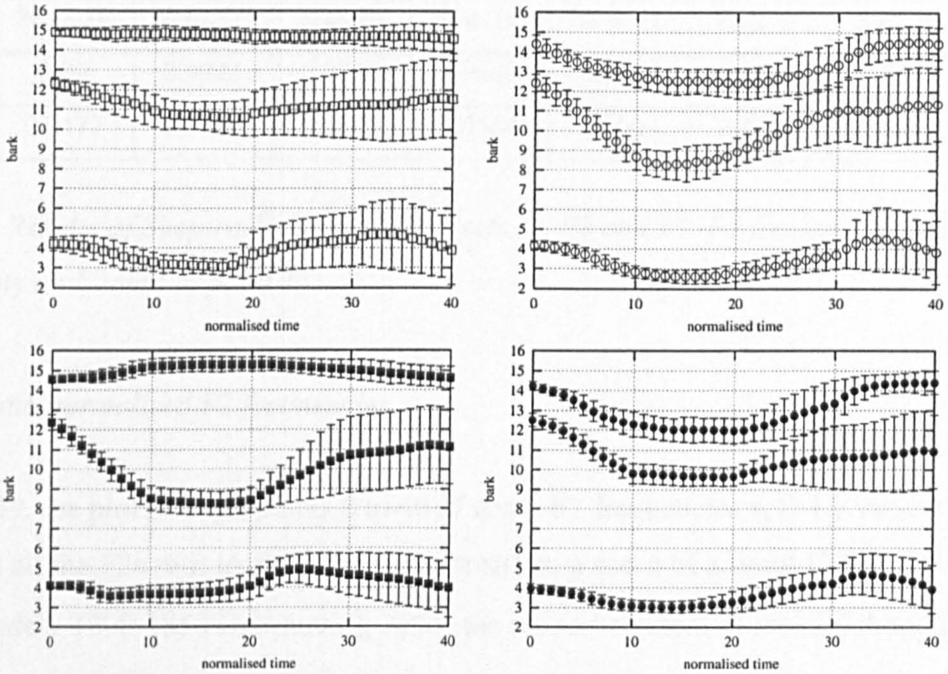


Figure 38. Mean frequencies (bark) with standard deviations for the first three formants in onset liquids. Open shapes represent the Sunderland speaker (upper panels); filled shapes represent the Manchester speaker (lower panels). Squares represent [l] (left panels); circles represent [r] (right panels).

Shapiro-Wilk tests for normality show that, for both F2 and F2-F1 expressed in the bark scale, each liquid in each variety has formant frequencies which are approximately normally distributed in the liquid steady state (with the exception of a few sample points in F2-F1 for Manchester [l] and Sunderland [r]) and often also in the transitions on either side of the steady state. As an example, the results of the Shapiro-Wilk tests at point 15 are given in Table 39. Ratios of variances were almost all below 4. Although this is not enough evidence to be absolutely certain that an analysis of variance is appropriate for all points through this model (particularly as the p-values for the Shapiro-Wilk tests are variable), it is enough to suggest that ANOVAs might be worthwhile pursuing in order to shed some more light on the relationships obtaining in the spectral data. Using multiple ANOVAs in this way would normally require an adjustment in the degrees of freedom but, given the large number of ANOVAs (41 per plot) and the consistency in the effects I describe, they are left as if they were individual ANOVAs independently calculated at each sample point.

	F2 (bark)				**F2-F1 (bark)**			
	Man. [l]	**Man. [r]**	**Sun. [l]**	**Sun. [r]**	**Man. [l]**	**Man. [r]**	**Sun. [l]**	**Sun. [r]**
W	0.99	0.9923	0.9817	0.9839	0.9668	0.9916	0.9593	0.9704
p	0.2477	0.5160	0.0245	0.0564	0.0003	0.4390	<0.0001	0.0014

Table 39. Results of Shapiro-Wilk normality tests on F2 and F2-F1 frequencies (bark) for each variety and liquid at point 15.

7.3.3.1 Time-normalised F2 frequencies

In Figure 39, the plot through points 0 to 40 of mean F2 frequencies split by variety and liquid shows that all the F2s start in much the same position: a mean of around 12.3 - 12.5 bark (approximately 1800-1850 Hz) moving out of the second element of the diphthong [eɪ] in the lexeme *say* in the carrier phrase. However, by about halfway through the transition into the liquid, the trajectories are differentiated. Through the liquid portion itself and most of the transition into the following vocoid, the curve corresponding to the mean F2 in Sunderland [l] tokens is higher than the other three trajectories. Approximately 1 bark lower in the liquid portion (points 10-20) is the Manchester [r] trajectory. A further 1.4 bark or so lower are the trajectories for Manchester [l] and Sunderland [r]. By the end of the transition out of the liquid, the four curves come together again, though they are more separated than they are before the transition into the liquid. While the Sunderland [l] trajectory remains high throughout the vocoid portion, the Manchester [r] trajectory moves relatively low and becomes the lowest curve in the vocoid: the polarity effect in the liquid changes into a variety-independent liquid effect in the vocoid (vocoids after the laterals have relatively high F2 frequencies while vocoids after the rhotics have relatively low F2 frequencies). In the vocoid, the primary observable grouping of the F2 trajectories is by variety, with Sunderland vocoids having a relatively high mean F2 while Manchester vocoids have a relatively low mean F2.

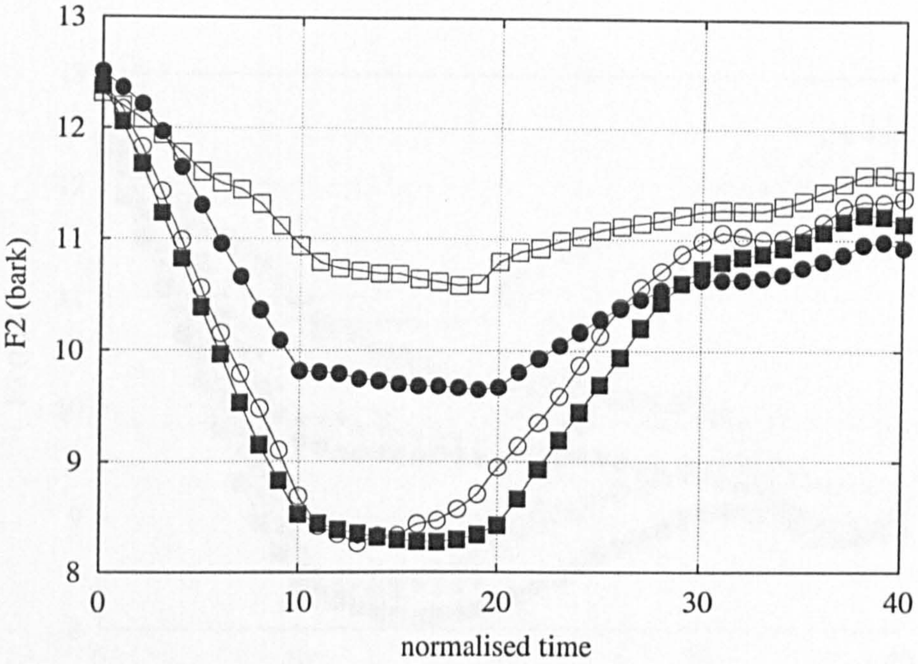


Figure 39. Mean F2 frequencies (bark) for onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

Figure 40 additionally differentiates front and back vowel context and gives an impression of the coarticulatory effects of such vowels on a preceding liquid. Anticipatory coarticulation here seems to be mainly limited to the transitional portions. There is little difference from the plot in Figure 39 up to about the mid-point of the liquid, at which point some divergences become apparent. It is obvious that by the onset of the vocoid portion, the formant trajectories have divided neatly into front and back vowel contexts, as would be expected for an F2 trajectory. Most of the front/back splits appear at around sample point 20, i.e. the beginning of the F2 transition into the vowel as labelled from the original waveforms. However, there is a notable exception: the Sunderland [l] trajectory bifurcates at the beginning of the liquid portion (with the back vowel context curve lower than the front vowel context curve) and then shows a second, further, divergence in the transitional period. By the end of the steady liquid portion (at sample point 20) these two curves are already approximately 0.9 bark apart. In the vocoid portion, while there are two widely distinct groups of curves (approximately 3 bark apart) which represent front vowels and back vowels, within each of those groups there is still the difference between the varieties identified in Figure 81, namely that Sunderland mean F2 is higher than Manchester mean F2.

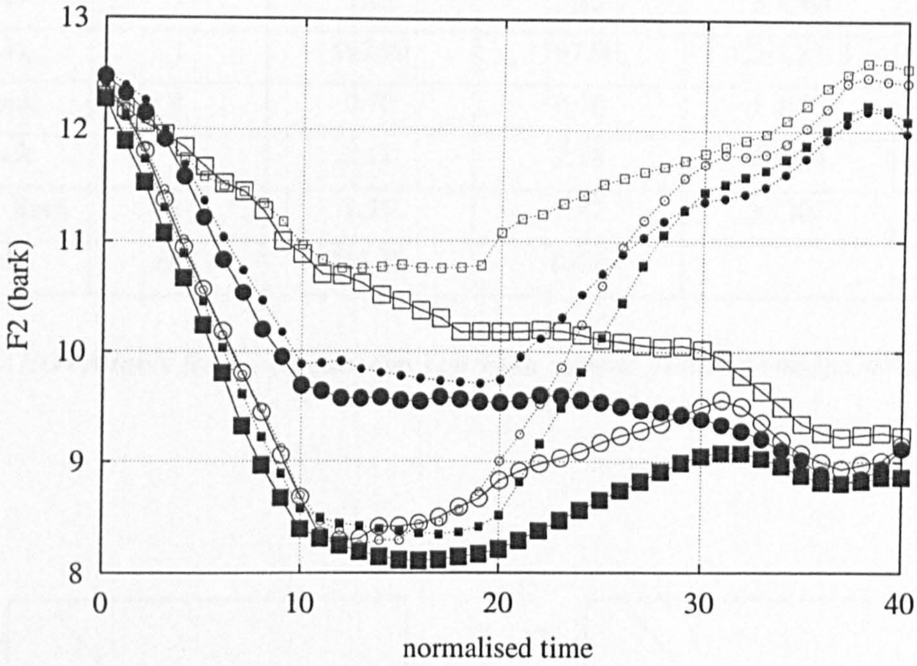


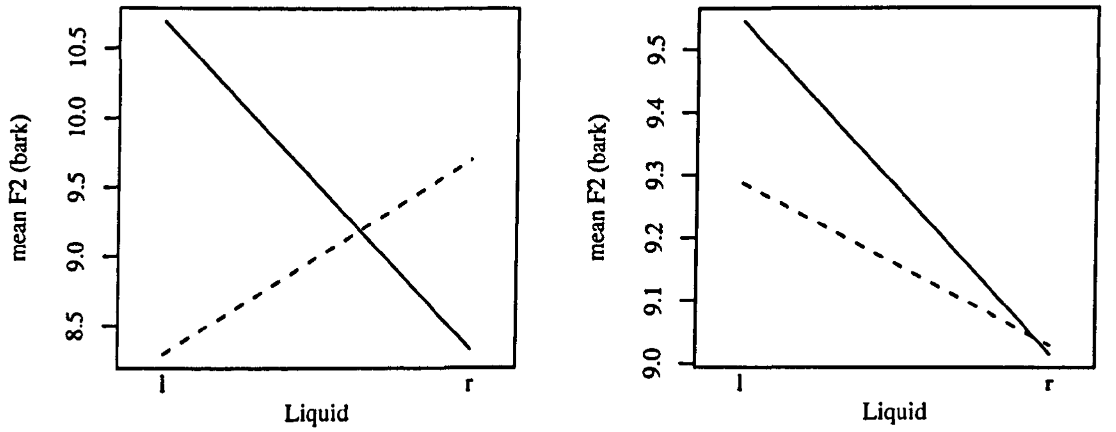
Figure 40. Mean F2 frequencies (bark) for onset liquids split additionally by backness of the following vowel. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r]. Small shapes with dotted lines represent front vowel contexts; large shapes with solid lines represent back vowel contexts.

Table 40 gives the results of a factorial ANOVA on the F2 data at sample point 15 (the midpoint of the liquid as defined by the F2 transitions). F2 at this point is worked through as an example; ANOVA tables for other sample points are to be found in Appendix 5.

At point 15, the interaction between variety (Manchester or Sunderland) and liquid ([l] or [r]) is highly significant, as are the main effects for variety and liquid. Backness of the following vowel (front or back) and the interaction between liquid and backness are also significant. Interaction plots are given in Figure 41.

Factor(s)	degrees of freedom	sum of squares	mean square	F value	probability (>F)
Variety	1	52.52	52.52	111.2624	<0.0001
Liquid	1	34.21	34.21	72.4699	<0.0001
Backness	1	1.82	1.82	3.8564	0.0499
Var * Liq	1	597.90	597.90	1266.7413	<0.0001
Var * Back	1	0.70	0.70	1.4871	0.2231
Liq * Back	1	2.18	2.18	4.6224	0.0319
Var * Liq * Back	1	1.57	1.57	3.3307	0.0684
Residuals	668	315.30	0.47		

Table 40. ANOVA table for F2 frequencies (bark) at sample point 15 (midpoint of liquid).



dashed line: Manchester; solid line: Sunderland

dashed line: back context; solid line: front context

Figure 41. Mean F2 frequency (bark) interaction plots for liquid by variety (left panel) and liquid by backness of following vowel (right panel); sample point 15.

Table 41 shows the result of two-tailed t-tests on F2 frequencies at point 15, used as planned comparisons. From the interaction plots and the planned comparisons, it is evident that the interaction between variety and liquid is the most important result of the ANOVA at point 15.

The results of ANOVAs on the F2 data show a significant interaction between liquid and variety from sample point 1 through to sample point 29; that is, there is a significant interaction in the liquid and the transitional portions on either side. Paired comparisons confirm that, within that range of sample points, the Manchester speaker's liquids are significantly different from each other (at $p<0.05$ or less) from point 1 to point 26. The Sunderland speaker's liquids are significantly different from each other (at $p<0.05$ or less) from point 2 to point 29. The varieties are significantly different from each other (at $p<0.05$ or less) from point 1 to point 29 for [l], and from point 1 to point 24 for [r]. From point 1 to point 24, where significant differences have been identified, Figure 39 (which is effectively a conglomeration of interaction plots) shows that there is a polarity effect in F2, namely that F2 is significantly higher in [l] than [r] for the Sunderland speaker while it is higher in [r] than [l] for the Manchester speaker. Both the Manchester speaker and the Sunderland speaker differentiate [l] and [r] in F2, but they do so in significantly different ways.

Comparison	**t**	**df**	***p***
Manchester ([l] versus [r])	23.3362	341	<0.0001
Sunderland ([l] versus [r])	26.4283	331	<0.0001
[l] (Manchester versus Sunderland)	33.564	345	<0.0001
[r] (Manchester versus Sunderland)	17.0761	327	<0.0001
back context ([l] versus [r])	1.6982	216	0.0909
front context ([l] versus [r])	4.5719	456	<0.0001
[l] (back context versus front context)	1.6125	345	0.1078
[r] (back context versus front context)	0.1156	327	0.9080

Table 41. Two-tailed t-tests on F2 frequencies (bark) at sample point 15.

Liquid identity is a significant factor in variation in the vocoid (from point 32 to point 40): F2 is higher after [l] than after [r], despite the fact that the relationship between F2 in [l] and in [r] varies between the varieties. Variety is also a significant factor throughout the vocoid, with F2 higher for the Sunderland speaker than for the Manchester speaker. There is no interaction between these main effects in the vocoid.

Backness of the vowel context has an effect on part of the transition into the liquid, then much of the way through the liquid and — unsurprisingly — all through the vocoid. The early division in the Sunderland [l] curve identified in Figure 40 is presumably what is cueing the early significance of vowel backness, although an inspection of Figure 40 reveals that through the steady state portion of the liquid, there is also a more general coarticulation with the following vocoid: only the Sunderland [l] curve shows an early divergence between front contexts and back contexts, and the Sunderland [r] curve shows less of a difference between front and back contexts, but in general the track of mean F2 for a given variety and liquid combination is higher in the context of a front vowel than in the context of a back vowel.

A difference between liquids in front and back vowels can be identified in Figure 40, though it is not consistently in the predicted direction (a state of affairs which means the difference is masked in Figure 39, with vocoid F2 trajectories in the context of preceding laterals being higher than those in the context of preceding rhotics for both speakers): back vowels for the Sunderland speaker have higher F2 tracks after laterals than after rhotics (by around 0.28 bark) while back vowels for the Manchester speaker have lower F2 trajectories after laterals than after rhotics (by up to 0.25 bark); however, front vowels have higher F2 trajectories after laterals than after rhotics for both varieties (by around 0.12 to 0.2 bark for the Sunderland speaker and up to 0.15 bark for the Manchester speaker).

7.3.3.2 Time-normalised F3 frequencies

Figure 42 shows means of F3. The most obvious differentiation present is between the means for [l] and the means for [r] (around 2 bark difference in the liquid for the Sunderland speaker and around 3.5 bark difference in the liquid for the Manchester speaker). F3 means for Sunderland [l] are higher than those for Manchester [l] early in the transition into the liquid; F3 means for Sunderland [r] are higher than those for Manchester [r] early in the transition into the liquid. There is a greater [l]-[r] separation earlier in normalised time for the Sunderland speaker than for the Manchester speaker, even though the Manchester speaker has a greater separation between F3 in tokens of laterals and F3 in tokens of rhotics during the liquid steady state itself and (with much less separation) through the following vocoid. Greatest separations are achieved during the steady state portion of the liquid, with differences of about 0.5 bark between varieties for each liquid.

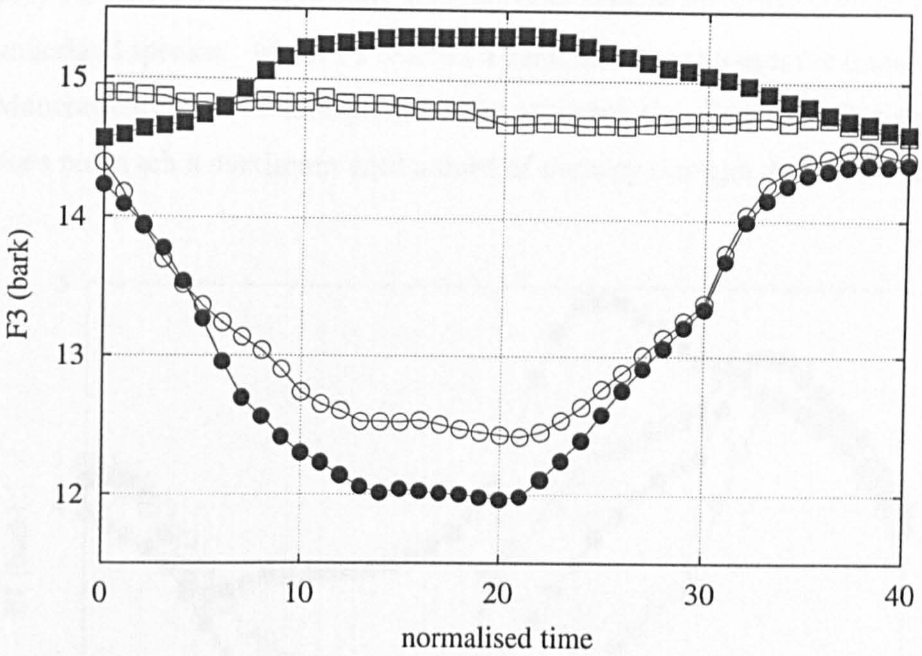


Figure 42. Mean F3 frequencies (bark) for onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

As with F2, there is a significant interaction (see Appendix 5) between variety and liquid identity throughout the liquid portion and most of the transitional portions. Both the Manchester speaker and the Sunderland speaker differentiate [l] and [r] in F3, as might be expected, but they do so in different ways, as is shown in the plots of the means. However, unlike the F2 data, the effect is one of magnitude rather than polarity: both varieties have higher F3 in [l] than in [r], but there is a greater separation between the liquids for the Manchester speaker than for the Sunderland speaker. Liquid identity has a significant effect on F3 throughout the whole section of the token being analysed. Backness only has an effect from halfway through the transition into the vocoid through the vocoid itself.

7.3.3.3 Time-normalised F1 frequencies

The means of F1 for all tokens are plotted in Figure 43. It is apparent in the plot that for both speakers, F1 is higher in [l] than in [r], at least during the liquid steady state portion and in the transitions out of the liquid. For the Manchester speaker, the difference is approximately 0.75 bark during the steady state portion; for the Sunderland speaker, the difference is approximately 0.5 bark during the steady state portion. The Manchester speaker has higher F1 than the Sunderland speaker. Mean F1 reaches a peak halfway through the transition into the vocoid in Manchester tokens including [l], but for other cells, mean F1 is still rising at this point and does not reach a maximum until a third of the way through the vocoid itself.

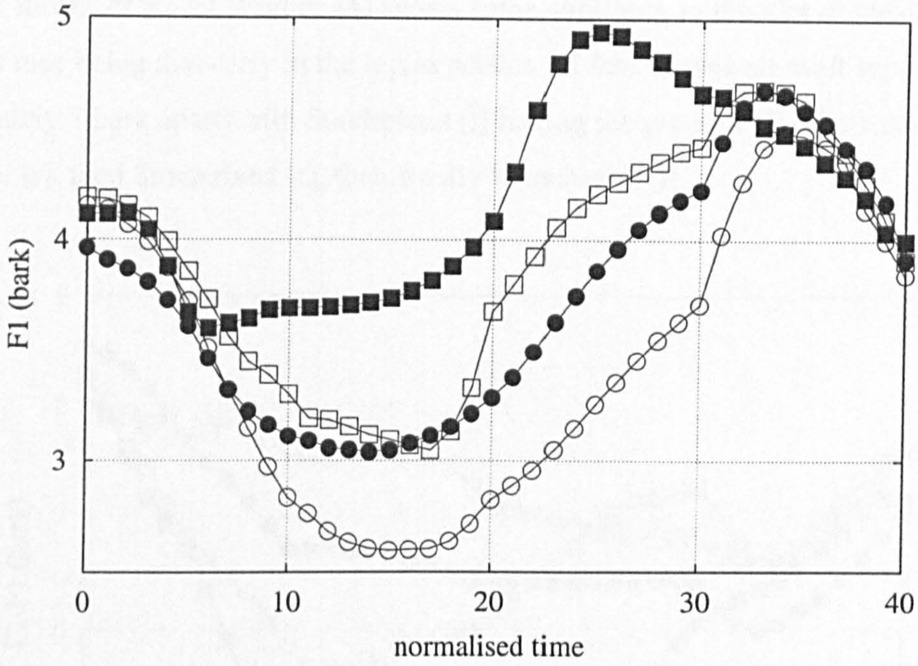


Figure 43. Mean F1 frequencies (bark) for onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

The ANOVA results (see Appendix 5) reveal that, through most of the liquid and the transitions on each side, variety and liquid identity have a significant effect on the frequency of F1. Backness also has an effect through almost all of the portion in question, though lexical constraints mean that phonological vowel backness is too closely correlated with phonological vowel height (χ^2=203.7159, *p*<0.0001) for both those factors to be included in an ANOVA, so the significances reported here may be an indirect result of high versus low vowel context (which would be expected to have a major effect on F1). The interaction between variety and liquid is significant between point 11 and point 18 (supported by planned comparisons at *p*<0.0001). Observation of the mean plots shows that liquid identity has an effect in the same direction in each variety (unlike for F2); all that differs is the magnitude and phasing of this effect (the maximum gap between F1 in Manchester [l] and Manchester [r] occurs at point 17 and is about 0.8 bark; the maximum gap between F1 in Sunderland [l] and Sunderland [r] occurs at point 12 and is about 0.6 bark.

7.3.3.4 Time-normalised formant differences

The plot of means of F2-F1 (Figure 44) shows some similarity to the plot of means of F2, the main difference being that early in the liquid portion all four curves are well separated (approximately 1 bark apart) with Sunderland [l] having the greatest F2-F1 space, then Manchester [r], then Sunderland [r], then finally Manchester [l].

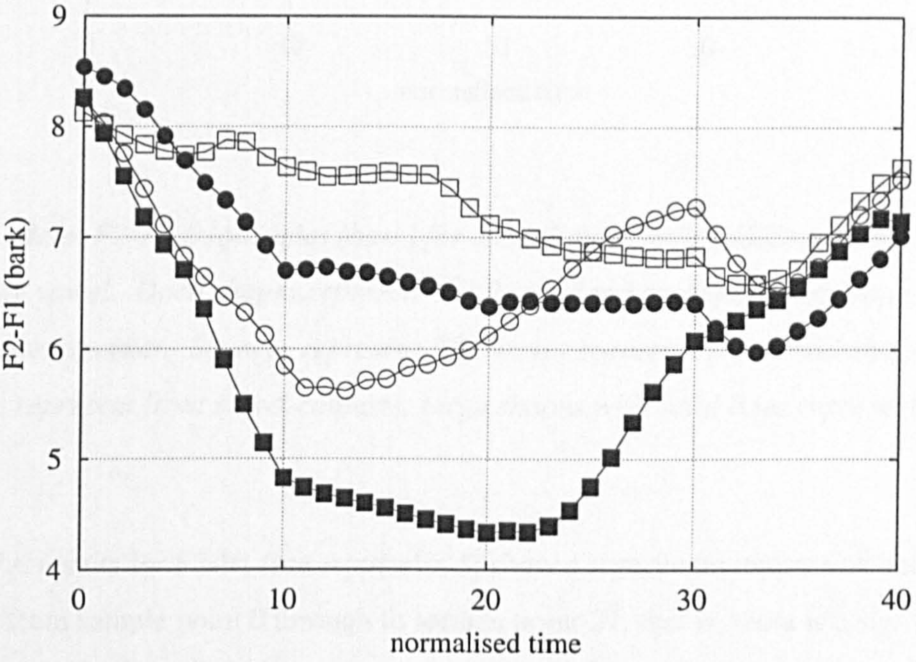


Figure 44. Mean F2-F1 frequencies (bark) for onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

There is a noticeable maximum in the Sunderland [r] F2-F1 curve at point 30 (the end of the transitional portion into the vocoid portion) which is more pronounced than the similarly-placed peak in the F2 curve. The plot which differentiates between front and back vowel context (Figure 45) once again seems to show that coarticulation due to the following context comes into play approximately halfway through the liquid.

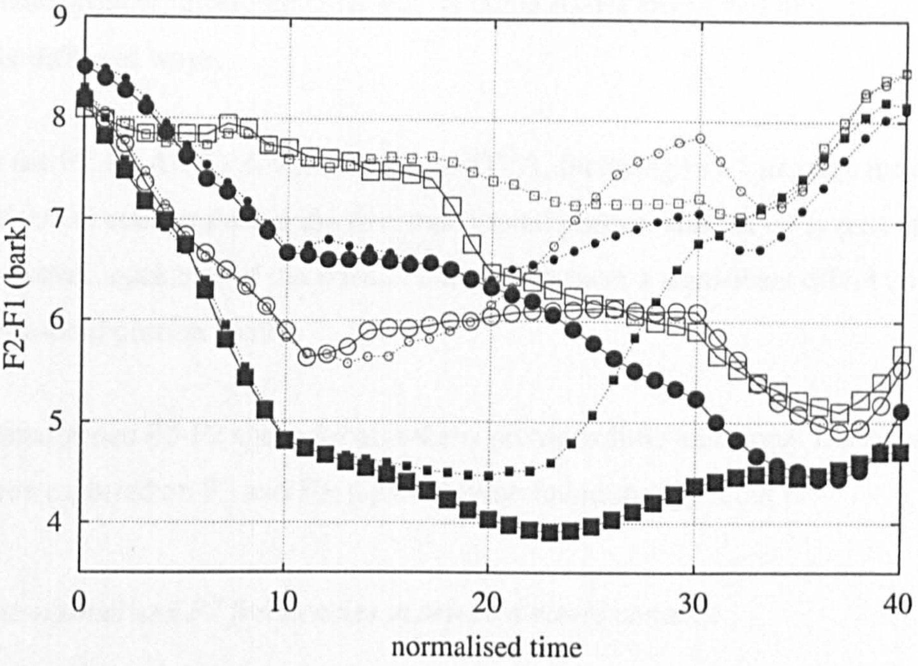


Figure 45. Mean F2-F1 frequencies (bark) for onset liquids split additionally by backness of the following vowel. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r]. Small shapes with dotted lines represent front vowel contexts; large shapes with solid lines represent back vowel contexts.

The ANOVA results for F2-F1 (see Appendix 5) show a significant interaction between liquid and variety from sample point 0 through to sample point 27; that is, there is a significant interaction in the liquid and the transitional portions on either side (recall that transitional portions in the normalised plots are defined with reference to F2 rather than the F2-F1 space; slopes in the F2-F1 plots which appear transition-like are not, in fact, transitions of the same kind, since they are conglomerated representations of more than one formant trajectory). Planned comparisons confirm that, within that range of sample points, Manchester liquids are significantly different from each other (at $p<0.05$) right through the range, from point 0 to point 27. Sunderland liquids are significantly different from each other (at $p<0.05$) at point 0 then from point 2 to point 23. The varieties are significantly different from each other (at $p<0.05$) at point 0 then from point 2 to point 27 for [l], and from point 0 to point 21 and from point 24 to point 27 for [r]. There is a polarity effect in F2-F1 between point 2 and point 21, namely that the F2-F1 space is significantly greater in [l] than [r] for the Sunderland speaker while it is greater in [r] than [l] for the Manchester speaker. Both the Manchester speaker and the Sunderland speaker differentiate [l] and [r] in the F2-F1 space, but they do so in significantly different ways.

Comparing the F2-F1 ANOVA with the F2 ANOVA, factoring in F1 negates the effect due to backness of vowel context during the first transitional portion and the early part of the liquid portion. However, backness of the vowel continues to have a significant effect on the F2-F1 space in the vocoid portion itself.

The bark-transformed F3-F2 space for all tokens provides little additional information, given what has been reported on F2 and F3; a plot may be found in Appendix 6.

7.3.3.5 Time-normalised F2 frequencies in selected vowel contexts

If there is some coarticulation between the liquid and the following vocoid, then it is worth separating out some sample vocoid qualities in order to tease out any effects there might be in the liquid. Previous plots in this chapter have all averaged over the whole range of vowel contexts and may therefore have smoothed over any subtle interactions with the liquids.

Figure 46 shows F2 tracks in normalised time in the context of selected vowels. Data presented earlier in this chapter has demonstrated that vowel backness only reliably has an effect on the formants in the liquid during the transition out of the liquid and into the following vocoid. As a consequence of that situation, it is no surprise that the three plots in Figure 46 all show F2 trajectories starting the transition out of *say* in the carrier phrase and into the liquid at around the same frequency, 12.5 bark (1853 Hz), as in Figure 39.

Examining the F2 trajectories in the liquid steady state portion (sample points 10 to 20) reveals some differences between the plots. There is little variation between the [r] curves for either speaker, with Sunderland [r] having a mean steady state of around 8.25 to 8.5 bark (954 to 995 Hz) and Manchester [r] having a mean steady state of around 9.75 to 10 bark (1219 to 1268 Hz), though this is slightly lower in the context of a following [ɔː] or [ɒ].

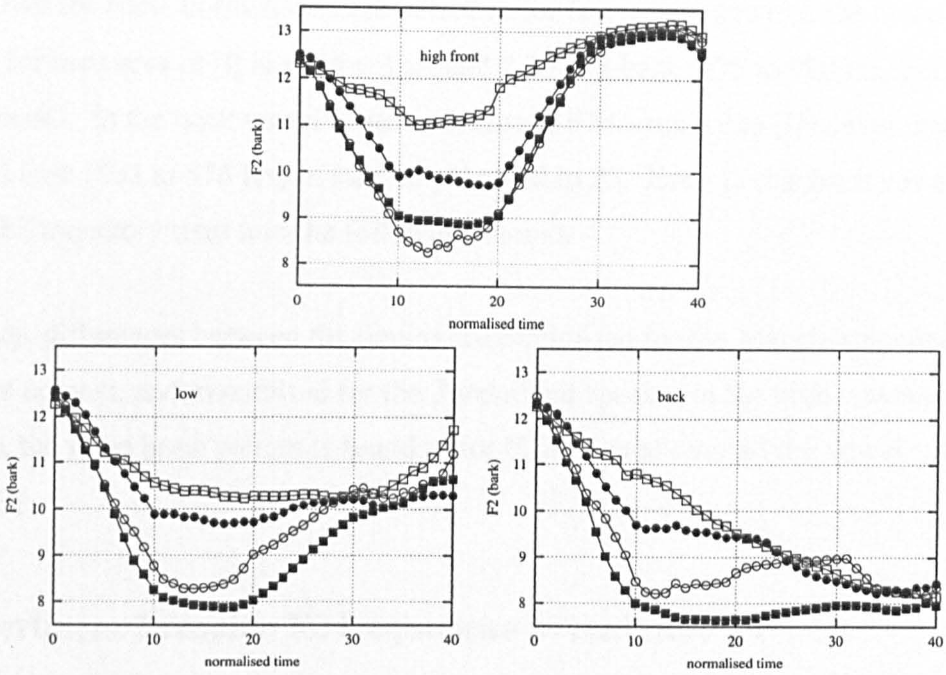


Figure 46. Mean F2 frequencies (bark). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r]. Upper panel: liquids before [iː] and [ɪ]. Lower left panel: liquids before [aː] and [a]. Lower right panel: liquids before [ɔː] and [ɒ].

The story is not the same, however, for the [l] curves. For both speakers there is evidence of a certain amount of coarticulation with the following vocoid. In the high vowel context, the Sunderland speaker has a mean F2 trajectory for instances of [l] which remains fairly steady during the steady state portion (sample points 10 to 20) at approximately 11 to 11.25 bark (1480 to 1536 Hz) before rising to the high F2 position in the vocoid. Over the same normalised time period in the low vowel context, the mean F2 trajectory for instances of [l] is steady at around 10.25 to 10.5 bark (1318 to 1370 Hz), with minimal change in the following transitional portion. In the back vowel context, the mean F2 drops through this portion from about 10.75 to 9.5 bark (1424 to 1172 Hz), going on to continue dropping at a similar rate towards the low F2 position appropriate for back vowels.

In the high vowel context, the Manchester speaker has a mean F2 trajectory for instances of [l] which remains fairly steady during the steady state portion (sample points 10 to 20) at approximately 8.75 to 9 bark (1038 to 1080 Hz) before rising to the high F2 position in the vocoid. Over the same normalised time period in the low vowel context, the mean F2 trajectory for instances of [l] is steady at around 7.75 to 8 bark (876 to 920 Hz) before rising into the vocoid. In the back vowel context, the mean F2 trajectory in [l] is even lower: around 7.5 to 7.75 bark (838 to 876 Hz) in sample points 10 to 20. Even in this back vowel context, the mean F2 trajectory rises into the following vocoid.

In summary, differences between the liquids are minimised for the Manchester speaker in the high vowel context, and maximised for the Sunderland speaker in the high vowel context. Otherwise, the same basic pattern is found as for F2 averaged over all the vowel contexts, as in Figure 81.

7.4 Experiment 2 results: F2 frequencies in real time

Earlier sections in this chapter have presented data in a normalised-time analysis. This has the advantage of presenting the data in a form which facilitates comparisons among tokens over a fairly wide extent. However, any short-term characteristics, such as coarticulation, which may operate over a particular period of time rather than over a particular piece defined in terms of acoustic events (such as a transitional portion) can be unwittingly factored out. For this reason, some of the data are presented here in real time, rather than normalised time.

Figures 47 and 48 show various formant trajectories in real time (with further plots in Appendix 6), centred around the point labelled in the waveforms as the start of the F2 transition out of the liquid into the following vocoid. These plots have 21 sample points, with the centre being the start of the F2 transition out of the liquid. The step between sample points is 5 ms (i.e. a sample rate of 200 Hz), so that the first sample point is taken 50 ms before the start of the F2 transition out of the liquid, and the last sample point is taken 50 ms after the start of the F2 transition out of the liquid. Naturally, with syllable durations differing from token to token due in no small measure to there being a variety of syllable structures exemplified in the word list, there is the possibility in a real-time analysis that there may be missing samples if the step in the sample points overruns the duration of any given token, i.e. if the syllable in question begins more than 50 ms before the start of the F2 transition out of the liquid or ends more than 50 ms after the start of the F2 transition out of the liquid. However, the sampling range was selected with this in mind: all syllables began at least 50 ms before the start of the F2 transition out of the liquid. Up to the penultimate sample point (45 ms after the start of the F2 transition out of the liquid), there were no missing samples: all syllables ended at least 45 ms after the start of the F2 transition out of the liquid. The last sample point (50 ms after the start of the F2 transition out of the liquid) had 113 missing points (16.7% of the total), comprising 17 tokens of Sunderland [l] (10.0% of the total number of Sunderland [l] tokens), 24 tokens of Sunderland [r] (14.7% of the total number of Sunderland [r] tokens), 31 tokens of Manchester [l] (17.5% of the total number of Manchester [l] tokens) and 41 tokens of Manchester [r] (24.7% of the total number of Manchester [r] tokens).

Figure 47 shows the mean F2 in bark in real time. Transitions associated with clear and dark liquids appear to move at different speeds. Transitions associated with dark liquids (Manchester [l] and Sunderland [r]) taking a relatively long time to reach a vocoid target which is more distant in that it has a higher F2. The mean Manchester [l] curve moves from a minimum of 8.286 bark 15 ms before the start of the F2 transition out of the liquid to a maximum of 10.103 bark 50 ms after the start of the F2 transition out of the liquid (a mean slope equivalent to 27.954 bark s^{-1}). The mean Sunderland [r] curve moves from a minimum of 8.419 bark 25 ms before the start of the F2 transition out of the liquid to a maximum of 10.883 bark 50 ms after the start of the F2 transition out of the liquid (a mean slope equivalent to 32.853 bark s^{-1}).

Transitions associated with clear liquids (Sunderland [l] and Manchester [r]) take less time (and have a less steep curve) to reach a vocoid target for which F2 is closer to the value in the liquid. The mean Sunderland [l] curve moves from a minimum of 10.59 bark 10 ms before the start of the F2 transition out of the liquid to a maximum of 11.256 bark 50 ms after the start of the F2 transition out of the liquid (a mean slope equivalent to 11.1 bark s^{-1}). The mean Manchester [r] curve moves from a minimum of 9.648 bark 5 ms before the start of the F2 transition out of the liquid to a maximum of 10.336 bark 45 ms after the start of the F2 transition out of the liquid (a mean slope equivalent to 13.76 bark s^{-1}).

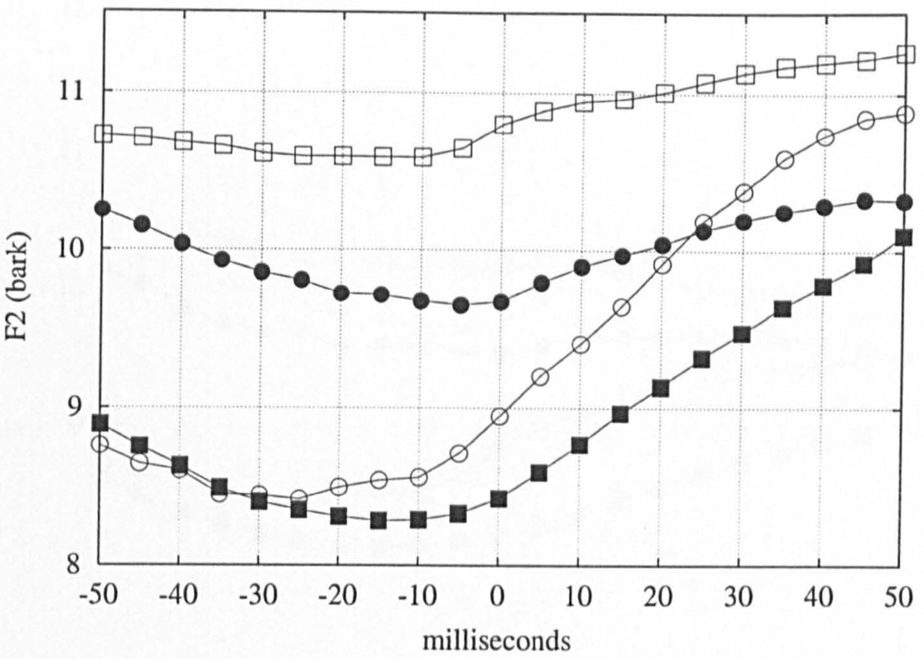


Figure 47. Mean F2 frequencies (bark) for onset liquids sampled in 5 ms steps aligned at the start of the F2 transition out of the liquid. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

Figure 48 shows the mean F2 in real time, split additionally by backness of the vowel context. In discussing Figure 40 (the plot of mean F2 in normalised time split by backness of the vowel), it was suggested that the divergences in the curves due to coarticulation with the vocoid became evident in the general case only in the transitions out of the liquid, although there was also significant coarticulatory effect during the liquid steady state portion itself. In this real-time plot (Figure 48), the formant trajectories diverge according to vowel backness consistently around 0 ms (the start of the F2 transition out of the liquid), with the exception of Sunderland [l], which shows some divergence at an earlier stage. The real-time data plots are centred around the labelled point at which the transition out of the liquid begins (0 ms in the real-time analysis; sample point 20 in the normalised-time analysis) so, in a sense, this divergence is present by definition, since the formant trajectories need to reach some sort of target for the appropriate vocoid. In the 50 ms before this point, the coarticulatory effects found in the normalised-time plot are also evident. Once again, the Sunderland [r] curves follow a very similar course up to the point of divergence at 0 ms; in contrast, other variety and liquid combinations show evidence of coarticulation with the vocoid in that mean F2 trajectories in the context of front vowels are higher than those in the context of back vowels.

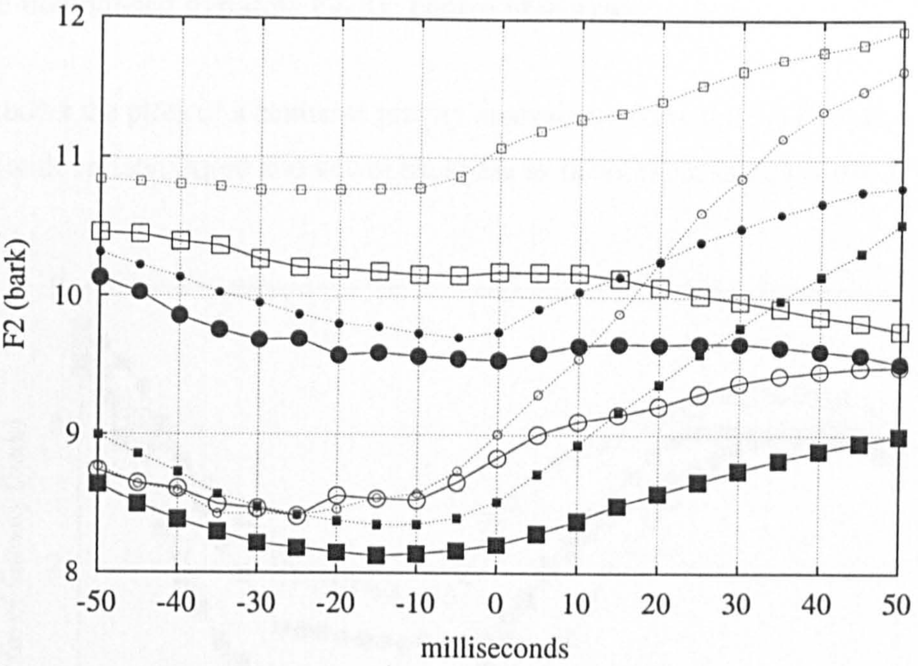


Figure 48. Mean F2 frequencies (bark) for onset liquids sampled in 5 ms steps aligned at the start of the F2 transition out of the liquid, split additionally by backness of the following vowel. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r]. Small shapes with dotted lines represent front vowel contexts; large shapes with solid lines represent back vowel contexts.

Real-time plots of other formants add little to the data presented in Section 7.3.3 on normalised-time plots, and are not presented here. Further plots may be found in Appendix 6.

7.5 Experiment 2 results: time-normalised spectral moments analysis

In this section, the results of a spectral moments analysis using a dynamic filter tracking F1 and F2 are presented. Other filters were tested but, in general, any cross-dialectal effects were eclipsed by the F3 differences between [l] and [r]. Plots resulting from analyses using other candidate filters (a low-pass filter set at the Nyquist frequency, 100 Hz to half a critical bandwidth above the highest value for F3 in the data and a dynamic filter tracking F1 and F3) are to be found in Appendix 7.

7.5.1 Time-normalised dynamic F2-F1: centre of gravity

Figure 49 shows the plots of a centre of gravity analysis tracking the F2-F1 space. Factorial ANOVAs (with variety, liquid and vowel backness as factors) are in Appendix 5.

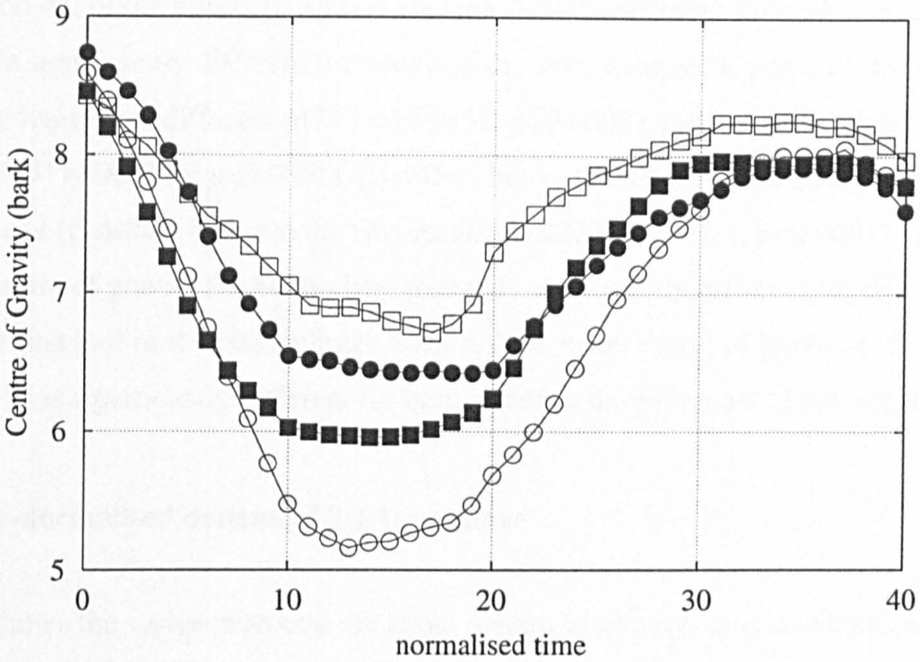


Figure 49. Mean centre of gravity for onset liquids with a range tracking F1 and F2 plus half the critical bandwidth for each formant. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

It can be seen that through the liquid, the Sunderland [l] curve has the highest centre of gravity, followed by the Manchester [r] curve (that is, the two clear liquids). The lowest centre of gravity belongs to the Sunderland [r] curve, followed by the Manchester [l] curve (that is, the two dark liquids). The Sunderland [l] curve is higher than the Sunderland [r] curve through the whole plot except for the first two sample points. The pattern for the Manchester speaker is different: the Manchester [l] curve is lower than the Manchester [r] curve through the transition into the liquid and the steady state portion of the liquid but then rises above the Manchester [r] curve just into the transition out of the liquid (at sample point 23) to make the interaction effect one of magnitude only, rather than polarity, through most of the transition out of the liquid and into the vocoid. The interaction between variety and liquid identity is significant from the beginning of the tracks right through to point 36 (sixty percent of the way through the vocoid).

Two-tailed t-tests carried out as planned comparisons on these centre of gravity data confirm that from early in the transition into the liquid, through the liquid itself and through most of the transition out of the liquid, [l] and [r] are significantly different for both varieties and the varieties are significantly different for both liquids. For example, at point 15, the two Manchester liquids are different ($t(341)=11.9152$, $p<0.0001$), the two Sunderland liquids are different ($t(331)=28.4875$, $p<0.0001$), [l] differs between the two speakers ($t(345)=21.9822$, $p<0.0001$) and [r] differs between the two speakers ($t(327)=21.4071$, $p<0.0001$). Additionally, the mean centre of gravity for Sunderland tokens is significantly different for [l] and [r] through the first half of the tautosyllabic vocoid. The mean centre of gravity for tokens containing [l] is significantly different for both varieties through most of the vocoid.

7.5.2 Time-normalised dynamic F2-F1: variance

Figure 50 shows the variance around the mean (centre of gravity) over a dynamically changing range tracking the F2-F1 space. Through the liquid steady state portion and most of the transitions, there is a noticeable polarity effect with a high variance for the clear liquids and a low variance for the dark liquids. This is borne out in an ANOVA (see Appendix 5) which shows significant interaction between variety and liquid identity over points 0 to 27.

Variance will, of course, be affected by the magnitude of the range within which spectral moments analysis is applied. Here, a dynamic range is applied, defined with reference to the F2-F1 space. It is therefore not surprising to find that Figure 50 parallels exceptionally closely the plot of mean F2-F1 in Figure 44: where there is a wide F2-F1 space, the variance around the centre of gravity is large; where there is a narrow F2-F1 space, the variance around the centre of gravity is small. In fact, for the whole set of data (41 samples in each of 676 utterances), the correlation coefficient of F2-F1 and the variance around the centre of gravity with a range tracking F1 and F2 plus half the critical bandwidth for each formant is 0.99. Given the large number of samples, Fisher's Z transformation results in a 95% confidence level that this is the true correlation.

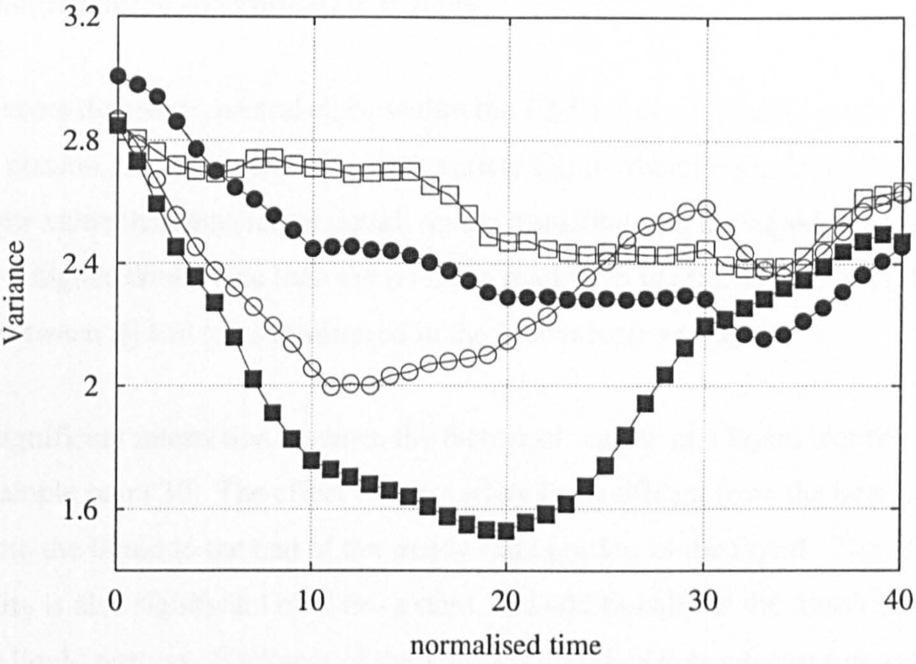


Figure 50. Mean spectral variance for onset liquids with a range tracking F1 and F2 plus half the critical bandwidth for each formant. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

7.5.3 Time-normalised dynamic F2-F1: skew

Figure 51 shows the mean spectral skew within the F2-F1 space in onset liquids. In the steady state liquid portion, the darker liquid in each variety ([l] in Manchester, [r] in Sunderland) has a higher skew value than the clearer liquid. In the transition into the liquid, the two [l] mean tracks have a higher skew value than the [r] mean tracks. In the transition out of the liquid, the difference between [l] and [r] is minimised in the Manchester variety.

There is a significant interaction between the factors of variety and liquid identity from sample point 1 to sample point 30. The effect due to variety is significant from the beginning of the transition into the liquid to the end of the steady state portion of the liquid. The effect due to liquid identity is also significant over this extent, and additionally in the transition out of the steady state liquid portion. Backness of the vowel is significant as a factor through most of the transition out of the liquid and all of the vocoid itself.

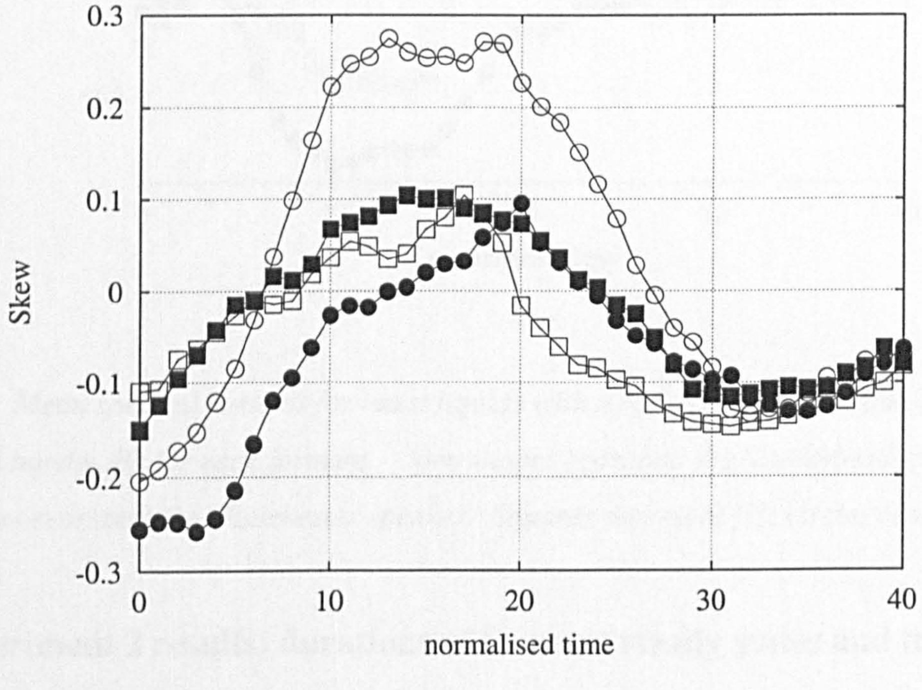


Figure 51. Mean spectral skew for onset liquids with a range tracking F1 and F2 plus half the critical bandwidth for each formant. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

7.5.4 Time-normalised dynamic F2-F1: kurtosis

Figure 52 shows a higher kurtosis corresponding to the dark liquids (Sunderland [r] and Manchester [l]) — perhaps reflecting a prominent peak in the spectrum around the F2-F1 area in dark liquids — and a lower kurtosis corresponding to the clear liquids (Sunderland [l] and Manchester [r]). Variety and liquid identity interact significantly through the liquid and part of the transitions, but this is a polarity effect only in the liquid portion itself.

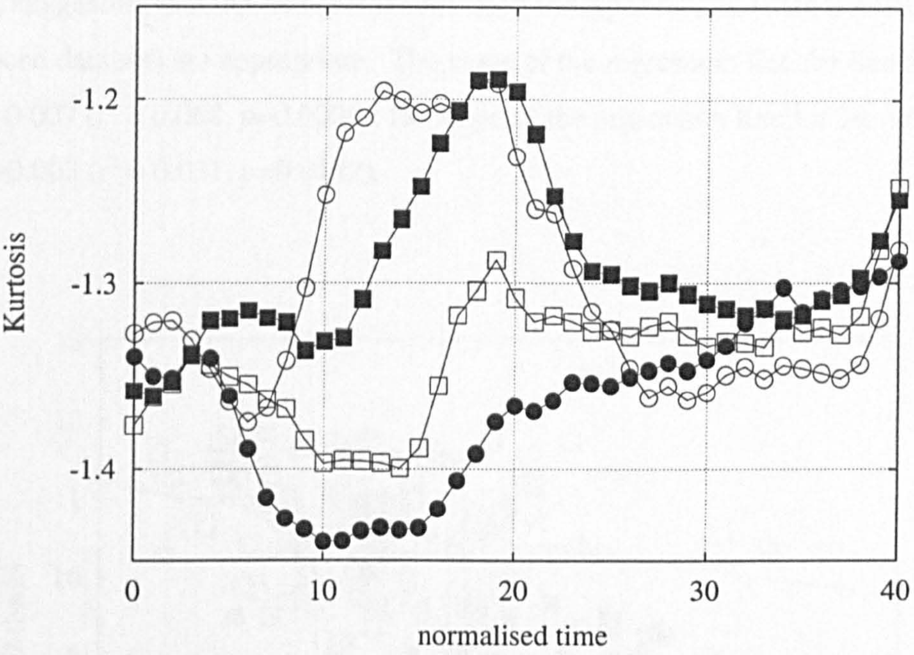


Figure 52. Mean spectral kurtosis for onset liquids with a range tracking F1 and F2 plus half the critical bandwidth for each formant. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

7.6 Experiment 2 results: durations of formant steady states and transitions

In this section, aspects of the timing of onset liquids in Experiment 2 (nonrhotic speakers) are examined. Given that clearness and darkness may be analysed in terms of F2, F2 durations are examined first (Section 7.6.1). F1 durations are reported in Section 7.6.2, and F3 durations in Section 7.6.3. In Section 7.6.4, a description is given of the durations of steady states and durations as defined by a combined complex of formants. The measurements are supported by factorial ANOVAs with variety and liquid as factors; ANOVA tables are to be found in Appendix 5.

7.6.1 F2 durations

Figure 53 shows a plot of the F2 frequency at point 15 against the duration of laterals (defined by the extent of F2 transitions). The frequency of F2 correlates less with the duration of the lateral than in the data set for Experiment 1, but the results from Experiment 2 are statistically significant, suggesting that the tendencies identified in Experiment 1 (with a much smaller but more balanced data set) are appropriate. The slope of the regression line for Sunderland laterals is –0.007 ($r^2 = 0.068$, $p=0.0006$); the slope of the regression line for Manchester laterals is +0.003 ($r^2 = 0.031$, $p=0.0182$).

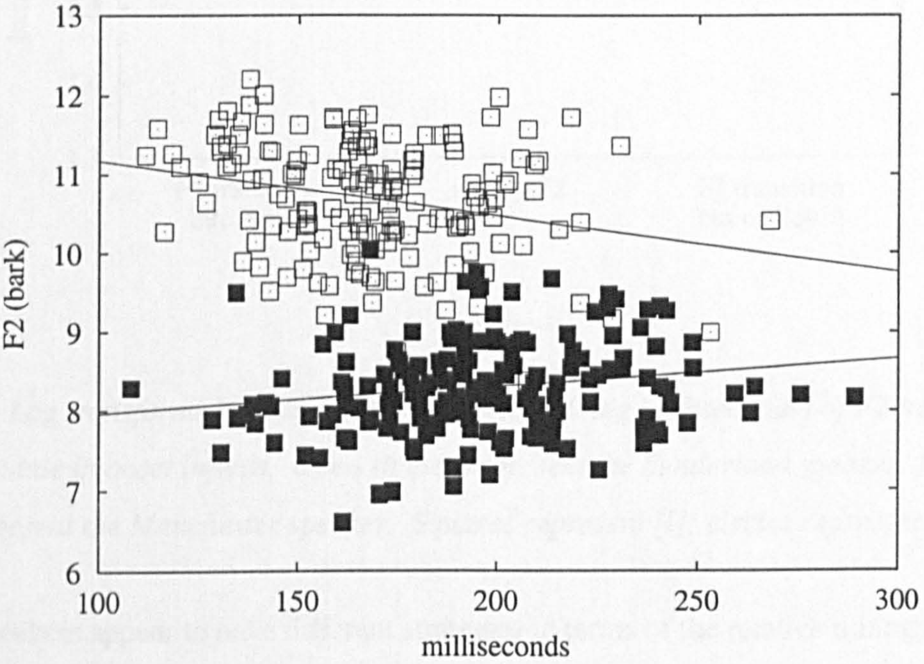


Figure 53. F2 frequencies (bark) at point 15 plotted with regression lines against duration in milliseconds (as defined by the extent of F2 transitions) for syllable-initial laterals in Experiment 2. Open squares represent instances from the Sunderland speaker; filled squares represent instances from the Manchester speaker.

Figure 54 shows the mean durations of the F2 transition into the liquid, the approximately steady state of F2 in the liquid and the F2 transition out of the liquid into the following vocoid. Time is expressed in base 10 logarithms of milliseconds because the distributions of the transformed data approximate more closely a normal distribution. In this and subsequent plots, dotted lines joining the plotted points are drawn solely as a visual aid and have no theoretical status themselves.

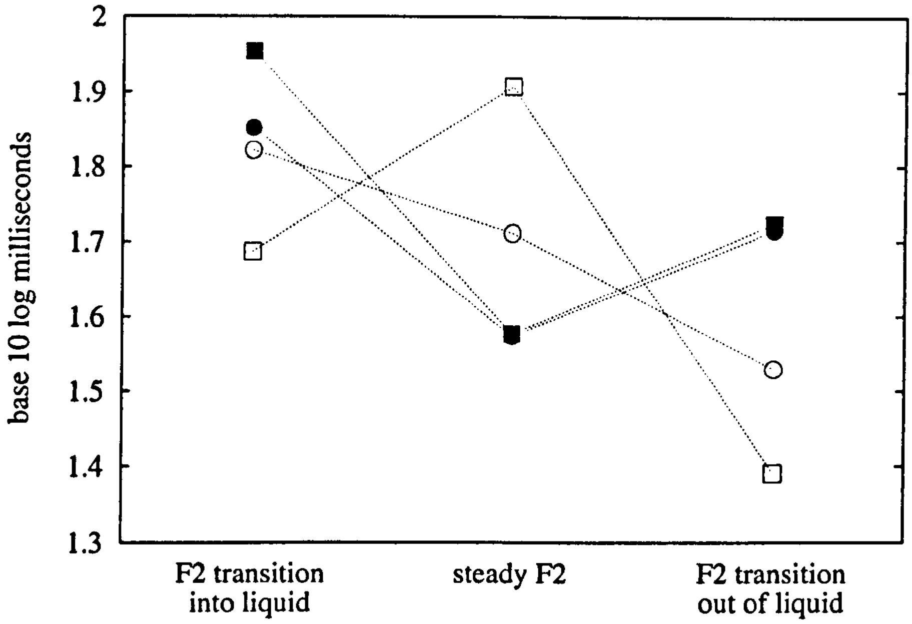


Figure 54. Log transformed mean durations (in base 10 log milliseconds) of F2 transitions and steady state in onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

The two speakers appear to have different strategies in terms of the relative timings of transitional portions and steady states in their liquids. Planned comparisons confirm that the Manchester speaker has longer F2 transitions than the Sunderland speaker both into the liquid (t(674)=14.0351, $p<0.0001$) and out of the liquid (t(674)=11.6551, $p<0.0001$). Conversely, the Sunderland speaker has longer F2 steady states in liquids than the Manchester speaker (t(674)=15.5749, $p<0.0001$).

The ANOVAs (see Appendix 5 for ANOVA tables) show that the interaction between liquid ([l] or [r]) and variety (Manchester or Sunderland) is highly significant for the duration of both transitions and the steady state as defined by F2.

The Manchester speaker has longer F2 transitions into the liquid for [l] than for [r] (t(341)=10.83, $p<0.0001$) whereas the Sunderland speaker has longer F2 transitions for [r] than for [l] both into the liquid (t(331)=7.7397, $p<0.0001$) and out of the liquid (t(331)=4.2394, $p<0.0001$). The Manchester speaker's [r] has longer F2 transitions than the Sunderland [r] (t(327)=2.5556, $p=0.0111$ for the transition into the liquid and t(327)=6.2606, $p<0.0001$ for the transition out of the liquid).

As in Experiment 1, the Manchester speaker has longer F2 transitions into [l] than out of [l] (t(352)=10.1287, $p<0.0001$). However, this is also true for each of the other liquids: t(330)=6.5001, $p<0.0001$ for Manchester [r], t(338)=10.5136, $p<0.0001$ for Sunderland [l] and t(324)=12.1249, $p<0.0001$ for Sunderland [r].

F2 steady states for [l] are longer than F2 steady states for [r] for the Sunderland speaker (t(331)=10.21, $p<0.0001$).

7.6.2 F1 durations

Figure 55 shows mean durations of F1 transitions into and out of the liquid, and the mean durations of the F1 steady state in liquids. The ANOVAs indicate that variety and liquid are both significant as main effects in both transitions and the steady state. The interaction between them is significant only for the transitions. The mean steady state is longer for the Sunderland speaker than for the Manchester speaker (t(673)=12.5314, $p<0.0001$), while mean F1 transitions are longer for the Manchester speaker than for the Sunderland speaker (t(674)=5.9471, $p<0.0001$ for the transition into the liquid; t(674)=14.1394, $p<0.0001$ for the transition out of the liquid). Unlike the F2 durations in Figure 36, both varieties show the same relative patterns between liquids, with longer F1 transitions in [r] than in [l] (t(331)=4.6435, $p<0.0001$ for the Sunderland speaker's transitions into the liquid, t(331)=9.3216, $p<0.0001$ for the Sunderland speaker's transitions out of the liquid, t(341)=2.5918, $p=0.0100$ for the Manchester speaker's transitions into the liquid, t(341)=20.0842, $p<0.0001$ for the Manchester speaker's transitions out of the liquid). The interactions in the ANOVAs therefore represent a magnitude effect (where the difference between the liquids is in the same direction for each variety) rather than a polarity effect (where the direction of difference between the liquids is different for each variety) as was found for F2 durations.

In terms of steady states, again, both varieties show the same pattern: F1 steady states for [l] are longer than F1 steady states for [r] in both varieties (t(340)= 4.4243, $p<0.0001$ for the Manchester speaker; t(331)= 10.5174, $p<0.0001$ for the Sunderland speaker).

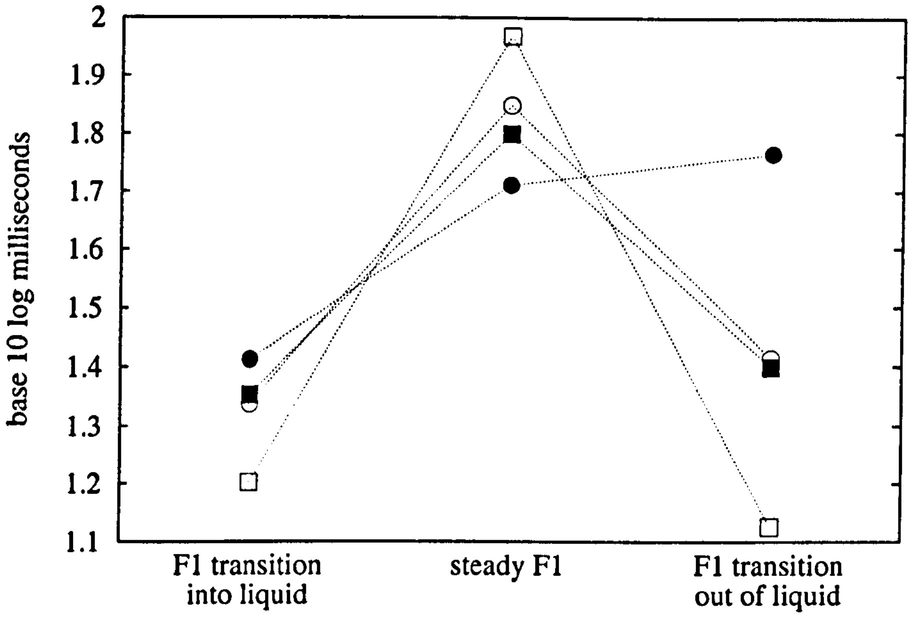


Figure 55. Log transformed mean durations (in base 10 log milliseconds) of F1 transitions and steady state in onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

7.6.3 F3 durations

Figure 56 shows mean durations of F3 transitions into and out of the liquid, and the mean durations of the F3 steady state in liquids. The ANOVAs indicate that variety and liquid are both significant as main effects in both transitions and the steady state. The interaction between them is significant only for the transitions. Given the characteristically low F3 in [r], it is not surprising that F3 transitions are longer for [r] than for [l] in both varieties:

t(331)=11.3186, $p<0.0001$ for the Sunderland speaker's transitions into the liquid, t(331)=7.3167, $p<0.0001$ for the Sunderland speaker's transitions out of the liquid, t(341)=8.7463, $p<0.0001$ for the Manchester speaker's transitions into the liquid, t(341)=12.828, $p<0.0001$ for the Manchester speaker's transitions out of the liquid. Here again, we observe that steady states are longer for the Sunderland speaker than for the Manchester speaker (t(674)=15.1828, $p<0.0001$), while F3 transitions are generally longer for the Manchester speaker than for the Sunderland speaker (t(674)=15.1744, $p<0.0001$ for the transitions into the liquid; t(674)=12.5231, $p<0.0001$ for the transitions out of the liquid).

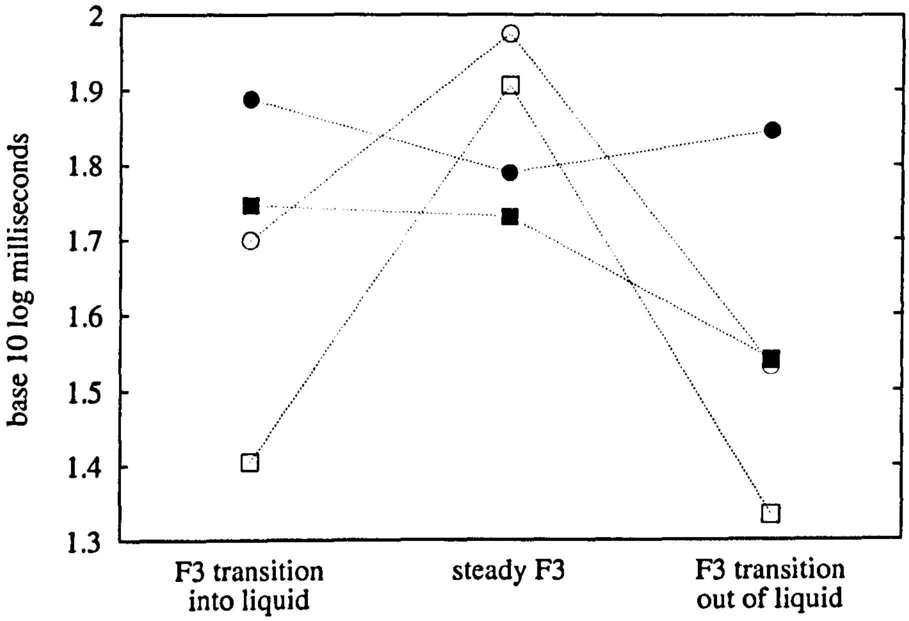


Figure 56. Log transformed mean durations (in base 10 log milliseconds) of F3 transitions and steady state in onset liquids. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

In terms of steady states, again, both varieties show the same pattern, although the pattern is reversed from that found in F1 and F2 transitions: F3 steady states for [l] are shorter than steady states for [r] in both varieties (t(340)=3.4521, $p=0.0006$ for the Manchester speaker; t(331)=4.3898, $p<0.0001$ for the Sunderland speaker).

7.6.4 Combined formant durations

Figure 57 shows the mean durations of steady state portions of liquids (defined as the period between the end of the last transition into the liquid— whether F1, F2 or F3 — and the start of the first transition out of the liquid) and the mean durations of transitional portions (defined as the sum of the portion between the start of the first transition into the liquid and the end of the last transition into the liquid and the portion between the start of the first transition out of the liquid and the end of the last transition out of the liquid). The Manchester steady portion means exclude the 6 tokens where transitions overlapped each other to such an extent that no steady portion was identified.

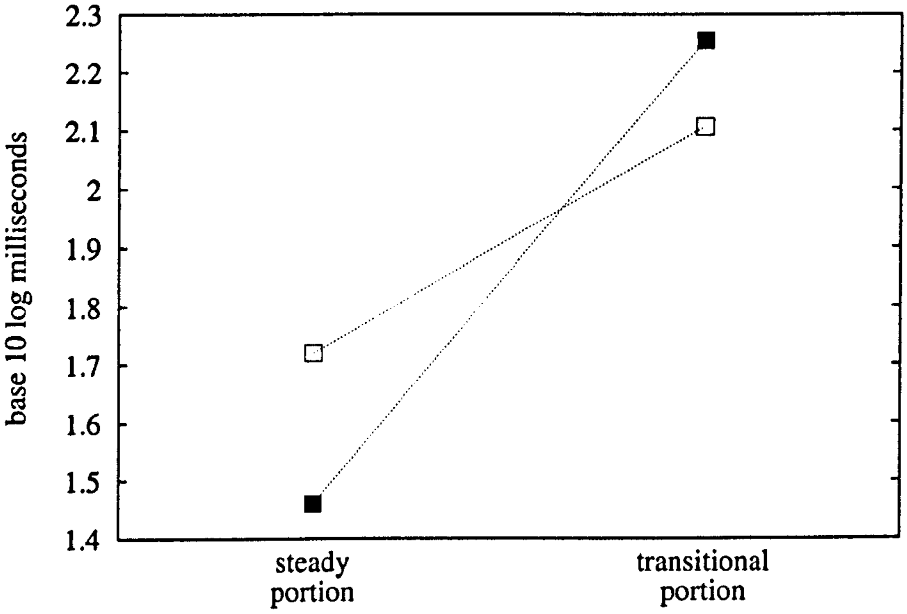


Figure 57. Mean duration (in base 10 log milliseconds) of steady states and transitional portions. Open squares represent the Sunderland speaker; filled squares represent the Manchester speaker.

Mean steady states are significantly longer for the Sunderland speaker than for the Manchester speaker (t(668)=17.0171, *p*<0.0001) while mean transitional portions are significantly longer for the Manchester speaker than for the Sunderland speaker (t(674)=20.1242, *p*<0.0001).

Table 42 presents the same data as in Figure 57, split additionally by the identity of the liquid. The Manchester steady portion means exclude the 6 tokens where no steady portion was identified. Factorial ANOVAs testing liquid and identity as factors (see Appendix 5 for ANOVA tables) revealed liquid variety and the interaction between them are all significant factors.

The Sunderland speaker and the Manchester speaker have significantly different steady portion durations for [l] as measured by a two-tailed t-test (t(343)=16.3354, *p*<0.0001); they also have significantly different steady portion durations for [r] (t(323)=8.5893, *p*<0.0001); in both cases, the Sunderland speaker has longer steady states. There are also significant differences between the varieties for the total transitional portions (t(345)=18.4806, *p*<0.0001 for [l]; t(327)=13.3276, *p*<0.0001 for [r]); in this case, it is the Manchester speaker who has longer transitional portions. Laterals and rhotics have significantly different total transition portion durations for the Sunderland speaker (t(331)=11.1295, *p*<0.0001); they also have significantly different total transition portion durations for the Manchester speaker (t(341)=5.7948, *p*<0.0001); in both these cases, the transitions in tokens of [r] are longer than the transitions in tokens of [l]. Laterals have significantly longer steady portions than rhotics for the Sunderland speaker (t(331)=5.9399, *p*<0.0001), but the Manchester speaker has no significant difference in duration in the steady portion of the two liquids (t(335)=0.4894, *p*=0.6249).

		steady portion		**total transitional portion**	
		mean	**SD**	**mean**	**SD**
Sunderland	**l**	1.778 (60.0 ms)	0.172	2.047 (111.4 ms)	0.106
	r	1.659 (45.6 ms)	0.194	2.167 (146.9 ms)	0.089
Manchester	**l**	1.454 (28.4 ms)	0.195	2.233 (171.0 ms)	0.081
	r	1.465 (29.2 ms)	0.212	2.279 (190.1 ms)	0.061

Table 42. Means and standard deviations of steady states and total transitional portions in onset liquids in base 10 log milliseconds, split by liquid identity.

7.6.5 Relative timing of formant transitions

Figure 58 shows the relative timing of the onset and offset of F1 and F2 transitions into and out of the liquid. Positive values indicate that the F1 event (e.g. the start of the transition) precedes the equivalent F2 event. Negative values indicate that the F2 event precedes the equivalent F1 event. Factorial ANOVAs (see Appendix 5 for ANOVA tables) indicate that the interaction between variety and liquid is significant for each of the four cases. Variety is also a significant factor in each case; liquid is a significant factor in all cases except the start of the transition into the liquid. Planned comparisons are shown in Table 43. Table 44 contains results of tests of the difference of the means from 0 (i.e. the value at which F1 events and F2 events are contemporaneous).

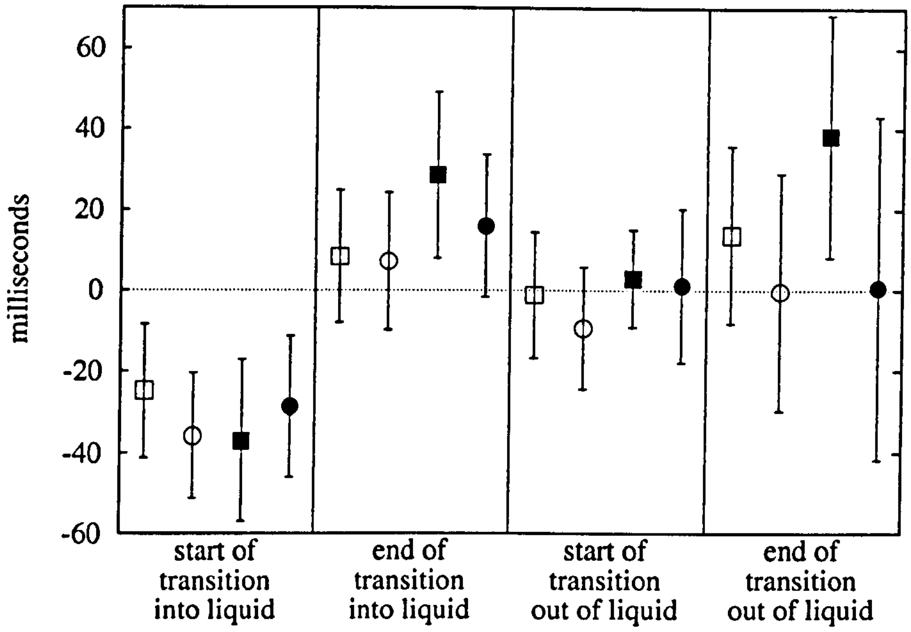


Figure 58. Means and standard deviations (indicated by errorbars) of relative timing of beginnings and endings of F1 and F2 transitions in onset liquids. Positive values indicate that the F1 landmark precedes the F2 landmark; negative values indicate that the F2 landmark precedes the F1 landmark. Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

Looking first at the start of the transitions from the end of the word "say" in the carrier phrase into the liquid, it is evident that all four cells have negative values: the start of the F2 transition on average precedes in time the start of the F1 transition. Within this general situation, there is a further notable observation to be made concerning the relative durations of these differences between the onset of the F2 transition and the onset of the F1 transition. For the Manchester speaker, the mean difference between the onset of the F2 transition into the liquid and the onset of the F1 transition into the liquid is greater in tokens of [l] (37.0 ms) than in tokens of [r] (28.6 ms). For the Sunderland speaker, the situation is reversed: the mean difference between the onset of the F2 transition and the onset of the F1 transition is greater in tokens of [r] (35.8 ms) than in tokens of [l] (24.8 ms). Moreover, the difference between the onset of the F2 transition and the onset of the F1 transition is greater in tokens of [l] for the Manchester speaker than in tokens of [l] for the Sunderland speaker, and the difference between the onset of the F2 transition and the onset of the F1 transition is greater in tokens of [r] for the Sunderland speaker than in tokens of [r] for the Manchester speaker.

Comparison	**df**	**start of transition into liquid**		**end of transition into liquid**		**start of transition out of liquid**		**end of transition out of liquid**	
		t	***p***	**t**	***p***	**t**	***p***	**t**	***p***
Man [l] vs [r]	341	4.1631	<0.0001	6.1353	<0.0001	1.0285	0.3044	9.5546	<0.0001
Sun [l] vs [r]	331	6.3002	<0.0001	0.6854	0.4935	4.8988	<0.0001	4.9712	<0.0001
[l] (M. vs S.)	345	6.1863	<0.0001	10.087	<0.0001	2.7626	0.0060	8.6945	<0.0001
[r] (M. vs S.)	327	4.0198	<0.0001	4.5281	<0.0001	5.5863	<0.0001	0.2565	0.7977

Table 43. Planned comparisons of relative timing of beginnings and endings of F1 and F2 transitions in onset liquids.

Case	**df**	**start of transition into liquid**		**end of transition into liquid**		**start of transition out of liquid**		**end of transition out of liquid**	
		t	***p***	**t**	***p***	**t**	***p***	**t**	***p***
Man. [l]	176	24.7274	<0.0001	18.5983	<0.0001	3.2261	0.0015	17.0011	<0.0001
Man. [r]	165	21.2615	<0.0001	11.5287	<0.0001	0.7852	0.4334	0.1785	0.8585
Sun. [l]	169	19.7029	<0.0001	6.6973	<0.0001	1.0038	0.3169	8.0887	<0.0001
Sun. [r]	162	29.7378	<0.0001	5.3902	<0.0001	7.9969	<0.0001	0.1938	0.8466

Table 44. Single sample t-tests (hypothesised mean = 0) of relative timing of beginnings and endings of F1 and F2 transitions in onset liquids.

For both varieties and both liquids, the F1 transition into the liquid ends before the F2 transition into the liquid. This is more noticeably the case for the Manchester speaker than for the Sunderland speaker. In addition, the time lag between the end of the F1 transition into [l] and the end of the F2 transition into [l] is greater than for the equivalent transitions into [r] for the Manchester speaker. There is little obvious difference between the start of the F1 transitions out of the liquid and the start of the F2 transitions out of the liquid for either speaker or either liquid, although the Sunderland [r] has a greater difference between F1 and F2 events than the Sunderland [l]. At the end of these transitions out of the liquid, however, there is a considerable time lag between the end of the F1 transition and the end of the F2 transition for tokens of [l] only; for tokens of [r] there is no difference between the mean end point of the F1 transition and the mean end point of the F2 transition.

7.7 Experiment 2: discussion

7.7.1 Spectral analysis

7.7.1.1 Classification and regression trees

The classification and regression tree analysis supports the polarity effects outlined in Chapter 6: the clear liquids (Sunderland [l] and Manchester [r]) are grouped together, as are the dark liquids (Sunderland [r] and Manchester [l]). Within each liquid category, F2 (and, to a lesser extent, F1) distinguishes the varieties. There is also evidence that formant space analysis may be a useful technique in improving robustness in cross-speaker comparisons in that a prediction of the F2-F1 space provides a more symmetrical regression tree than a prediction of F2. Introducing F1 in this way supports the analysis presented in Chapter 6, that F1 may have a role to play in clearness and darkness distinctions in the Manchester variety, since the importance of the [l]/[r] split for the Manchester speaker is increased when F1 is factored in.

In Chapter 6 I suggested that coarticulation cannot reliably be associated cross-dialectally with either syllable-position or resonance quality. However, Lehiste (1964:58) observed that initial [r] in American English is not affected by the following vowel, and Nolan (1983:91) found that vowel quality in southern British English has a greater effect on preceding laterals than on preceding rhotics. The regression trees presented in this chapter suggest that for both nonrhotic speakers, instances of [l] do indeed vary more with the following vowel than do instances of [r].

Regression tree analysis suggests that there is relatively little perseveratory coarticulation, since liquid identity has only a minimal presence in the trees in the vocoid portion.

7.7.1.2 Formant frequencies

There is a strong indication that liquid identity and the variety being examined interact with each other as factors, supporting the analysis that each variety produces its liquids in different ways. Liquid identity has a major effect on the spectrum throughout the liquid portion of the speech (in addition to the mid-point steady state data reported in Chapter 6), and vocalic factors such as backness have a major effect on the vocoid portions. There is evidence of a certain amount of anticipatory coarticulation, with vowel quality having spectral effects in the liquid. Coarticulation in the opposite direction is present but weaker.

All three of the formants examined show differences in tokens of [l] and [r] for the two varieties. F1 and F3 frequencies display magnitude effects within the liquid portion: both are higher in tokens of [l] than in tokens of [r]. F2 data, however, confirm the polarity effect reported in Chapter 6: F2 is high in Sunderland tokens of [l] and Manchester tokens of [r], while it is low in Sunderland tokens of [r] and Manchester tokens of [l].

Following vocoids are affected by the preceding liquid in the frequency of F3 and, less consistently and less significantly, in the frequency of F2. There is more evidence of F2 in the vocoid affecting the F2 trajectory in the liquid, with formant frequency data confirming the finding from the classification and regression trees that tokens of [l] coarticulate more than tokens of [r] in both varieties. Coarticulation across the liquid system does not therefore seem to be straightforwardly correlated with resonance quality.

The significant effect of liquid identity on F2 trajectories in the following vocoid is not consistently in the same direction as the F2 patterns in the liquid itself. In Experiment 1 (Section 6.1.2.1), a potential small coarticulatory effect in the vocoid was identified which did mirror the patterns of F2 in the liquid steady state but was not statistically significant. The results presented in this chapter suggest that that potential effect in the vocoid is probably unreliable.

There seems to be no obvious reason why the F2 data presented here should show the polarity effect in back vocoids after liquids but not in front vocoids after liquids, even though liquid is a significant factor in overall variation in the vocoid. Tunley (1999: 14ff) discusses the possibility that high front vowels may be relatively resistant to coarticulation, but concludes that coarticulation seems to vary with vowel length, height and stress pattern. Here there appear to be different effects in different vowels but the effects are not always the same as in the liquid steady state. Coarticulation may, therefore, not always be the most appropriate explanation for the variation.

It seems that anticipatory lateral/rhotic coarticulation in F3 occurs earlier for the Sunderland speaker than for the Manchester speaker. A low F3 in [r] is not particularly notable. The effect on F3 in the vocoid does support the results from RP and Manchester reported in Tunley (1999) and West (2000) who similarly find relatively low F3 persevering through vocoidal material following [r].

On average, F1 transitions out of Manchester [l] finish before the end of F2 transitions out of Manchester [l]. Since the time-normalised analysis is normalised with respect to F2, this phasing of transitions explains the finding that mean F1 reaches a peak halfway through the time-normalised transition into the vocoid in Manchester tokens including [l], but for Manchester [r] and both Sunderland liquids, mean F1 is still rising at this point and does not reach a maximum until a third of the way through the vocoid itself.

Polarity effects are found in investigation of the F2-F1 space, although coarticulation due to the vocoid is reduced in comparison with F2 data. No polarity effect is evident in the F3-F2 data, though there are still significant interactions between variety and liquid identity.

7.7.1.3 Spectral moments

Spectral moments analysis enables an approximation to a model which includes more information which may be perceptually appropriate such as the integrated peaks model (see Figure 17 on p.127), but one to which statistical analyses can more easily be applied. However, there is an issue to be resolved in respect of the filter to be applied to the spectrum before moments analysis is carried out.

None of the possible filters is obviously the one and only solution. Many previous spectral moments analyses have employed one or two static filters designed to cover the range of the spectrum that is of interest to the analyst. Centre of gravity measures based on spectra filtered in this way vary in the information they provide. If the whole spectral range is included (see Appendix 7), then the centre of gravity plots reflect lateral versus rhotic tokens. If a more restricted spectral range is examined (in line with previous spectral moments analyses) then a difference in magnitude is found between the two varieties, with a relatively large difference between centres of gravity in tokens of [l] and tokens of [r] for the Sunderland speaker, and a relatively small difference between centres of gravity in tokens of [l] and tokens of [r] for the Manchester speaker.

In most situations where vocoid-type spectra are encountered, formant peaks take precedence over the overall spectral envelope in perception. A dynamically changing filter, dependent on formant peaks, restores the predominance of formant peaks while retaining other spectral information appropriate for (relatively wide-bandwidth) liquids.

The major acoustic difference between laterals and rhotics —the low F3 in [r] — has a large influence on all the moments produced with the dynamic F3-F1 filter (see the plots in Appendix 7). The proximity of F3 to F2 in rhotics could potentially still affect the results of the moments analyses which tracked F2-F1, so the polarity effects ([l] and [r] patterning in opposite directions in the two varieties) are notable.

Overall, the curves in Figure 49 are fairly similar to the mean F2-F1 space in Figure 44, though with the obvious difference that the two dark liquid tracks (Manchester [l] and Sunderland [r]) are the other way round, with the lowest track in Figure 49 being the Sunderland [r]. There are other subtle differences such as the crossover between Manchester [l] and Manchester [r], which give a better representation of the detailed spectral characteristics of the F2-F1 space and throw light on the time-varying details of resonance quality. The Manchester [l] centre of gravity track is below the Manchester [r] track in the transition into the liquid and in the liquid itself, but in the transition out the tracks swap places. This provides another indication of early dorsality in Manchester [l].

In the liquid steady state portion, centre of gravity as measured with this dynamic F2-F1 filter quantitatively not only discriminates between clear liquids and dark liquids, but also between [l] and [r], since tracks representing laterals are overall higher than tracks representing rhotics, despite the polarity difference. This is because the difference between [l] and [r] for the Sunderland speaker is more than twice the difference between [l] and [r] for the Manchester speaker The spectral balance of [l] and [r] in the two varieties therefore differs both in polarity and in magnitude.

Within the range of this filter, a high centre of gravity indicates laterality and/or clearness; a low centre of gravity indicates rhoticity and/or darkness. The conclusion that laterals have a high centre of gravity and clear liquids have a high centre of gravity stems from the observation that clear [l] has the highest overall centre of gravity. Conversely, the conclusion that rhotics have a low centre of gravity and dark liquids have a low centre of gravity stems from the observation that dark [r] has the lowest overall centre of gravity. In the intermediate cases (dark [l] and clear [r]), the high centre of gravity associated with clear resonance appears to outweigh the high centre of gravity associated with laterality: the interaction between polarity and magnitude shows that the two clear liquids have a higher centre of gravity than the two dark liquids. By this measure, resonance is primary and articulation type is secondary.

The spectral variance with a dynamic F1 to F2 filter is extremely closely correlated with the straightforward F2-F1 formant space. Spectral variance over the whole spectral range shows a distinct polarity effect, with neither liquid identity nor variety on its own being a significant factor. Other filters produce similar patterns of significance to the centres of gravity.

Skew and kurtosis plots show some magnitude and some polarity effects depending on the filter applied. With the dynamic F1 to F2 filter, both demonstrate a polarity effect: clear liquids have relatively low skew and kurtosis values. However, although skew and kurtosis have been used in classifying obstruents (Forrest *et al.*, 1988), it is less clear how relevant these higher-level moments are for spectra with such prominent formant peaks as are found in liquids and vocoids.

It seems that a variety of filters can give a fuller picture of spectral variation, but the dynamic filter over an analytically-relevant portion of the spectrum in particular provides a useful addition to the analysis of formant frequencies. Patterns of clearness and darkness can also be identified here, in spectral representations which may help in more closely approximating hearers' perceptions.

7.7.2 Temporal analysis

The most notable example of the speakers' differing strategies in producing liquids is to be found in the duration of F2. The Manchester speaker has relatively long transitional portions and relatively short steady states, with this state of affairs being more extreme for [l] than for

[r]. In contrast, the Sunderland speaker has relatively short transitional portions and relatively long steady states. Once again, the situation is more extreme in [l] than in [r].

The analysis presented in Chapter 6, in which the dark liquids in nonrhotic varieties (Manchester [l] and Sunderland [r]) have longer F2 transitions into the liquid than out of it, needs to be modified. All liquids in the nonrhotic varieties in Experiment 2 have longer F2 transitions into liquids than out of them.

However, the Manchester speaker does have longer F2 transitions into [l] than into [r] whereas the Sunderland speaker has longer F2 transitions into and out of [r] than into and out of [l]. If F2 transitions reflect tongue dorsum displacements, then the Manchester speaker is displacing the dorsum over a greater period for [l] than for [r] in the transition into the onset liquid. Conversely, the Sunderland speaker is displacing the dorsum over a shorter period for [l] than for [r]. It is at least conceivable that this long duration dorsum displacement for [l] in the Manchester speaker is associated with displacement of the relatively slow-moving part of the tongue over a greater distance. The data from the relative timing of F1 and F2 landmarks in the formant transitions also support the notion of early dorsality being a correlate of darkness.

If relatively long F2 transitions are a correlate of darkness (*contra* Dalston, 1975, who acknowledged the perceptual importance of transitions in liquids but analysed their durations straightforwardly in terms of [r] or [l] without reference to resonance characteristics) , then once again Sunderland [r] appears darker than Sunderland [l], in accordance with the data presented elsewhere in this dissertation. However, even the [r] for the Manchester speaker has longer F2 transitions than the Sunderland [r], so this polarity effect does not precisely mirror the spectral analysis, in which Manchester [r] has a higher F2 frequency than Sunderland [r].

The high levels of statistical significance in these F2 results confirm similar relationships in the data from Experiment 1 (Chapter 6), not all of which were statistically significant, given the small scale of the data set in Experiment 1.

F1 and F3 duration data do not provide the sort of polarity effect found in F2 durations. Both speakers have longer F1 steady states in [l] than in [r] and shorter F1 transitions in [l] than in [r]. The Sunderland speaker's F1 steady states are longer than the Manchester speaker's F1 steady states, whereas the Sunderland speaker's F1 transitions are shorter than the Manchester speaker's F1 transitions. Both F3 transitions and F3 steady states are longer in [r] than in [l] for both varieties. However, once again, the Sunderland speaker's transitions are shorter than the Manchester speaker's transitions, while the Sunderland speaker's steady states are longer than the Manchester speaker's steady states. The two speakers distinguish [r] from [l] in similar ways with F1 and F3, but in different ways with F2.

Overall, then, formant steady states are longer for the Sunderland speaker than for the Manchester speaker; formant transitions are shorter for the Sunderland speaker than for the Manchester speaker. These findings based on the measurement of individual formants are supported by the fact that the overall transitional portion of the first three formants (the portion in which at least one of the first three formants is in transition into or out of the onset liquid) is greater for the Manchester speaker than for the Sunderland speaker. The steady state portion (the portion in which none of the first three formants is in transition into or out of the onset liquid) is greater for the Sunderland speaker than for the Manchester speaker.

An analysis in terms of different temporal strategies between the varieties provides a possible explanation for the increase in robustness in Newton's (1996) cross-dialectal analysis when 'minimum' (not including transitional portions) and 'maximum' (including transitional portions) durations of [l] were averaged together. This can be compared to perceptual studies (such as O'Connor *et al.*, 1957, and Polka & Strange, 1985) which identify a long steady state and short transitional portions as indicative of [l] while a short steady state and long transitional portions are indicative of [r]. It could be that the pattern reported in the perceptual literature is in fact typical of varieties in which syllable-initial [l] is phonologically clear (even if phonetically dark), while varieties with phonologically dark laterals in syllable-initial position have longer transitions (and shorter steady states) in [l].

7.8 Conclusion

A variety of spectral measures have been presented which shed light on resonance quality in onset liquids in the nonrhotic varieties of English under examination. Differences between the liquids and between the varieties have been identified in a range of different spectral measures. In particular I have demonstrated the usefulness of classification and regression tree analysis as an exploratory data technique and have confirmed its outputs with formant peak and spectral moments techniques.

Measures involving F1 and F3 have some cross-variety differences, but the noticeable effects are those in measures related to F2, which confirm the polarity effects hypothesised to exist in onset liquids in these nonrhotic varieties.

Evidence in timing differences support the results from Chapter 6, that indirect evidence of early dorsality is associated with darkness, particularly in tokens of Manchester laterals.

Liquid and variety interaction is statistically significant in the liquid steady state portion and in the transitions, but there is much less effect in the vocoids. The data in this chapter supports the conclusions drawn in Chapter 6, that effects may be present in the vocoids, but they are relatively small. However, there is more evidence of coarticulation in the other direction, with vowel backness having significant effects in the liquid portion (in measures which involve F2). There is some evidence that dark liquids vary more, but the strongest evidence is that onset laterals are more variable than onset rhotics in both varieties.

The minimal effect of resonance in the adjacent vocoid seems to contradict the findings of Kelly & Local (1986, 1989), but there are two factors which help to speak to this lack of effect in vocoids and explain the discrepancy. Firstly, all these vocoids are in strong (stressed) syllables (moreover, uttered in the very formal setting of word lists). Heid & Hawkins (2000) found that resonance effects were often minimal or not present in strong syllables, although the effects often seemed to 'pass through up to two stressed syllables' to temporally more distant weak syllables. In addition, West (2000:61) found that velar consonants in the frame for the target words (such as *again*) could obliterate subtle liquid resonance effects.

The data presented here must, however, be taken with a note of caution. With only one speaker per variety, it is *a priori* impossible to be sure that differences which show up in the analysis as due to the factor of language variety are not simply between-speaker differences. However, the fact that some of my findings confirm those findings in the literature which have incorporated the notion of resonance differences in liquids suggests that the results presented and discussed here are likely to be robust.

The following chapter will examine some of the phonological consequences of the phonetic findings and place them in the context of a wider phonological account of liquids in English.

8 Renewing the connection: what might an abstract non-segmental phonology of liquids in English look like?

8.1 Introduction

In this chapter I will bring together the sort of phonological approach I argued for in Chapter 2 with the phonetic observations in Chapters 5 to 7. In Chapter 2 I argued for a phonology which is

- declarative (only phonological operations which are structure-building are allowed)
- intensional (phonology describes linguistic objects)
- non-segmental (prosodic and melodic phonology are integrated)
- polysystemic (phonological meaning is meaning in context)
- abstract (phonological categories are labels of sets).

How might a phonology of this kind relate to the sort of phonetic detail which can easily be seen as a 'mush of general goings-on' (Firth, 1957a:XII)? I have argued that an abstract phonology necessarily requires an extrinsic phonetic interpretation mechanism in which phonological categories have no intrinsic phonetic content, but are nevertheless related in a systematic fashion to their phonetic associates. For example, a particular phonological category, such as [voice], has no intrinsic phonetic content, but the placing of [voice] in the phonological structure has regular consequences for its phonetic interpretation.

There are three major results stemming from the phonetic data presented in this dissertation:

(1) Initial laterals are clearer than final laterals as Sproat & Fujimura (1993) report;

(2) Nonrhotic varieties pattern as Kelly & Local (1986, 1989) suggest, with a clear/dark polarity in onset liquids which varies cross-dialectally

(3) Rhotic varieties have a fixed pattern of resonance qualities similar to that of the clear initial [l] nonrhotic variety, not dependent on absolute values for clearness or darkness.

The variation in the association of resonance qualities in nonrhotic varieties coupled with the lack of such variation in rhotic varieties poses a problem for a phonological account: how might the phonological structure have such an impact on the patterns evident in the phonetics?

I will discuss a phonological attribute set in declarative phonology and its appropriateness for the phonetic data from British English liquids, given an extrinsic interpretation mechanism linking the phonological representation and its phonetic exponents. A hierarchical prosodo-melodic phonological structure (as afforded by Firthian-inspired declarative phonologies and discussed in Chapter 2) allows for non-terminal node assignment of attributes; I will therefore also discuss possible locations in phonological structure for the attributes used to describe liquids and show how the choice of locations can account for the phonetic data presented in this dissertation relating to phasing of gestures. I will then discuss how this phonological analysis might be applied to further data.

In Section 8.2 I will discuss the phonological implications of resonance as observed in the phonetic data, laying out the basis of how the issues may be resolved in a non-segmental declarative phonology. I will also discuss the difficulties some alternative approaches might have in accounting for the data. In Section 8.3 an abstract set of phonological attributes is proposed. Section 8.4 looks at the location of attributes in the prosodic hierarchy. In Section 8.5 I examine distributional evidence relating to liquids and glides, paying particular attention to the notable case of onset clusters, and discuss how my phonological analysis relates to the distribution of liquids. Section 8.6 contains a discussion of a number of contemporary points of variation in British English liquids and glides and how they might be accounted for in the present analysis. The chapter closes with a discussion on some of the consequences of this analysis in terms of polysystems.

8.2 Phonological implications of resonance

8.2.1 Systems

Of prime importance for the phonetics-phonology interface is the finding that the resonance quality of syllable-initial liquids depends crucially on whether or not the variety in question is a rhotic variety. This is a long-distance effect of resonance in phonology and phonetics. Alongside the long-distance phonetics of some *acme* consonant (Kelly, 1989) which is marked for resonance quality and in a sense dominates a portion of speech, this phenomenon portrays long-distance structural effects (where contrasts in one part of the syllable impact on another part of the syllable) in which purely structural information has a bearing on the actual phonetics which turn up in a particular variety of English.

By combining Kelly & Local's analysis with the traditional account of laterals (as supported by Sproat & Fujimura) in this way, it is then possible to set up a phonological analysis in which resonance quality can be treated both as a *Grenzsignale* marker of prosodic position (as Sproat & Fujimura suggest) and as a variety-sensitive aspect of the difference between liquids (as Kelly & Local suggest).

The phonetic data presented in this dissertation suggest that final laterals may be darker than initial laterals in each variety. By definition, in nonrhotic varieties of English, syllable-final rhotic articulations do not reflect lexical or grammatical contrast; they are one of a series (such as [j], [w], [?]) of markers of juncture which are to a great extent predictable from the phonological context. So here we have a phonetic pattern (no difference between Sunderland and Manchester varieties in terms of their syllable-final liquids) which does not tally with a related phonetic pattern elsewhere (opposite resonance polarities in Sunderland and Manchester varieties in terms of their syllable-initial liquids). However, there is also a phonological pattern (contrast between [l] and [r] in syllable-initial position for both Sunderland and Manchester) which does not tally with a related phonological pattern elsewhere (no contrast between [l] and [r] in syllable-final position for either Sunderland or Manchester). The differences in the phonological patterns syllable-initially and syllable-finally suggest that these positions are not comparable for nonrhotic varieties after all, and so from a contrastive phonological point of view the mismatch in the phonetic pattern is no longer problematic.

In rhotic varieties of English, of course, [l] and [r] reflect phonological contrast both syllable-initially and syllable-finally and so the phonetic patterns are comparable and, indeed, we find that the syllable-initial pattern (no difference between Tyrone and Fife/General American varieties) tallies with the syllable-final pattern (no difference between Tyrone and Fife/General American varieties).

In a phonology built on relationships and contrast, it is important not to assume that particular pieces of phonetics are comparable with each other unless there is evidence to support comparability in the relationships into which they enter. This is an ontological, rather than heuristic, argument: in doing phonology, of course, comparisons must be made between pieces of phonetics in order to show that there is contrast, but in setting up the nature of a phonology, an active decision must be taken that particular pieces of phonetics are, or are not, comparable. It is by comparing that the legitimacy of comparison is established. The phonetic patterns reported in this dissertation strongly suggest that syllable-initial liquids and syllable-final liquids may legitimately be assumed to be members of the same overarching system in distinct syllabic positions and that the particular type of system (rhotic or nonrhotic) of which they are members has an impact on the phonetics associated with them.

8.2.2 Extrinsic phonetic interpretation

The phonetic data are consistent with the notion of extrinsic interpretation of phonological categories which was argued for in Section 2.3.3. In a rhotic dark initial lateral variety, a syllable-initial lateral counts as phonologically ‘clear’ because it contrasts with a dark rhotic in the same system. Yet this same lateral is phonetically dark: there is no sense in which the lateral is intrinsically clear. Such patterns of phonetic detail which interact with phonological categories in a partly absolute and partly relative fashion demand an extrinsic interpretation mechanism. Mapping from phonology to phonetics is arbitrary since clearness cannot be an intrinsic aspect of syllable initiality or of laterals. Mapping from phonetics to phonology is also extrinsic since the phonological importance of clearness and darkness can only be deduced in comparison with other objects in the phonological system. In this way, the phonetics-phonology interface is arbitrary but there are systematic interactions.

8.2.3 Differentiation

The patterning in the data could be explained by a principle of differentiation in extrinsic phonetic interpretation which may be phrased: ‘differentiate categories in the phonetic space.’

A differentiation principle bears some resemblance to an analysis of vowel systems in which ranges of variability and the placing of vowels in the IPA vowel quadrilateral (however inappropriate that may be as a descriptive tool) are predicted on the basis of the number of vowels in the system. Such an analysis might also be in accordance with quantal theory (Stevens, 1972, 1989) which predicts the nature of articulatory configurations to realise contrast on the basis of maximum exploitation of the acoustic space. A principle of differentiation differs from these accounts in that it would apply in conjunction with a polysystemic analysis of contrast to exploit the available variety of phonetic resources, and is a more appropriate metaphor than 'redundancy'. In the case discussed in this dissertation, the only contrast of importance is that between laterals and rhotics; and that contrast is divided into contrasts at different prosodic positions.

A differentiation principle differs also from Lindblom's (1990) H & H theory in that it does not (at this stage) take into account communicative principles beyond the expression of contrast in the linguistic system. However, Lindblom's approach can also be seen as polysystemic in a sense since different interpretative mechanisms apply in different contexts of communicative situation.

Extrinsic interpretation of categories with differentiation using the phonetic resources available is summarised in Figure 59. Phonological contrasts are identified in prosodic structural positions. The variety of phonetic resources available is used to keep the exponents of the contrasts in particular positions distinct.

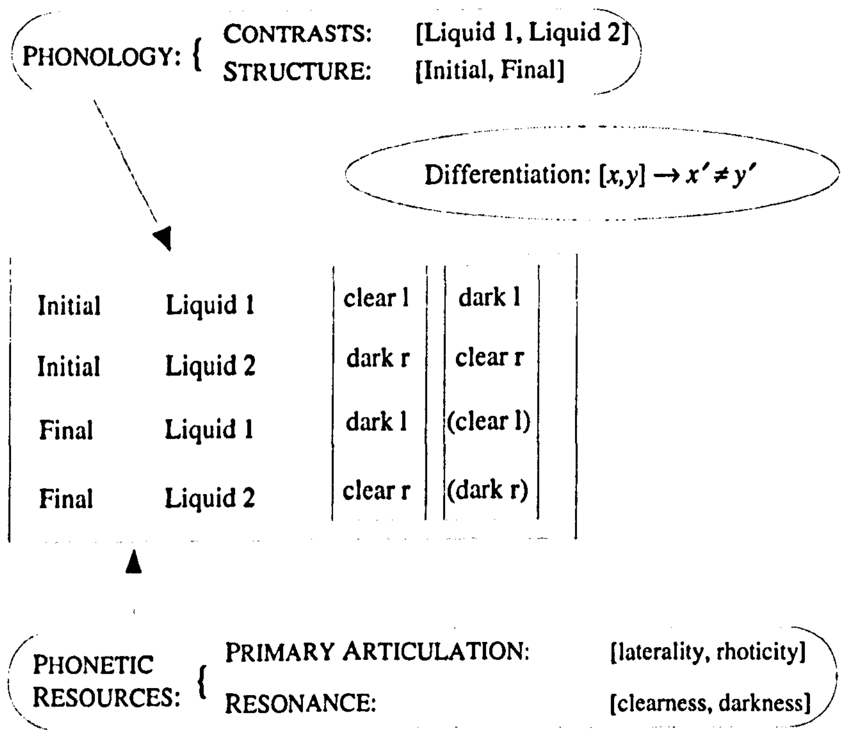


Figure 59. Schematic representation of extrinsic phonetic interpretation with differentiation of categories using available phonetic resources.

For nonrhotic varieties, differentiation predicts that [l] will be different from [r] in resonance as well as primary articulation. There is no contrast in syllable-final position so syllable-initial liquids do not have to be differentiated from syllable-final liquids: there need be no reference to syllable position in this statement. Syllable-initial and syllable-final systems are therefore different and so the phonetics of the final position has no bearing on the phonetics of the initial position. Given that resonance qualities are available as a strategy for differentiation, one liquid will be clear and the other dark, and it does not matter which is which. Differentiation thus predicts the variation in the pattern of clear and dark which is indeed found across nonrhotic varieties.

For rhotic varieties, syllable position matters since [l] and [r] contrast in both positions. If resonance quality is to be used to differentiate categories in the phonetic space then, for any given liquid, the other liquid in the same syllable position will contrast in resonance quality (to differentiate laterals from rhotics) and the same liquid in an opposite syllable position will also contrast in resonance quality (to differentiate syllable-initial position from syllable-final position). The two patterns in Table 45 are therefore predicted.

pattern	**initial [l]**	**initial [r]**	**final [l]**	**final [r]**
(1)	clear	dark	dark	clear
(2)	dark	clear	clear	dark
generalisation	*x*	*y*	*y*	*x*

Table 45. Possible patterns of contrast in resonance predicted by differentiation for rhotic varieties.

If initial [l] is clear (pattern 1) then initial [r] must be dark for it to be differentiated from the initial [l] (to reflect a contrast in liquid identity); final [l] must also be dark for it to be differentiated from the initial [l] (to reflect a contrast in syllable position); final [r] must be clear for it to be differentiated from both the initial [r] (to reflect a contrast in syllable position) and the final [l] (to reflect a contrast in liquid identity). Using the terms of the algebraic generalisation in Table 45, the value of *x* is 'clear' and the value of *y* is 'dark'.

If initial [l] is dark (pattern 2) then the same relationships of contrast obtain, but all the values of clear and dark are reversed. Using the terms of the generalisation in Table 45, the value of *x* is 'dark' and the value of *y* is 'clear'.

In fact, the real pattern in Table 45 is the generalisation itself: what matters is not what the content of the categories is but that the categories are different from each other.

The data in this dissertation are generally consistent both with Sproat & Fujimura's finding that initial [l] is clearer than final [l] and with pattern 1 in Table 45. It must be conceded, however, that there is nothing in this analysis which explicitly rules out pattern 2.

8.2.4 Articulatory phonology

The phonetic data, particularly from the Manchester speaker, suggest a model of gestural alignment closer to that in Figure 60 than the model outlined in Sproat & Fujimura (1993), schematised in Figure 8 (p.78). Instead of the syllable onset prosodic position being intrinsically (necessarily) associated with the phasing of an apical gesture before a dorsal gesture (Figure 8), both orders of precedence are possible, with the apical gesture phased before the dorsal gesture in a clear [l] and, conversely, the dorsal gesture phased before the apical gesture in a dark [l] (Figure 60). No claims are made regarding the relative prominence of the gestures. Early dorsality is here interpreted as a marker not necessarily of syllable-finality but of darkness. The arrangement of gestures is not intrinsic to the phonology of syllable structure since it is dependent not only on position in structure but also on dialect-specific phonetic interpretation. It follows that, in order to construct a robust panlectal phonology which encodes contrast and supports in its phonetic interpretation this variability in the phasing of gestures, extrinsic phonetic interpretation is required: 'hard-wiring' of the phasing of (phonetic) gestures into the (phonological) prosodic structure fails to account for the cross-dialectal data.

These findings pose problems for universalist natural phonetic explanations based purely on articulatory constraints, since phonological structure has a large impact on phonetic exponency. Phonetic interpretation requires knowledge of nonlocal but tautosyllabic systems of contrast in addition to phonetic gestural information. This structural impact is variety-specific rather than an intrinsic aspect of particular pieces of structure. It is not the case that syllable-initiality imposes clearness due to a vocalic dorsal gesture being phased after a consonantal apical gesture in order to be more closely associated with the syllable nucleus. Prosodic structure is essential to phonetic interpretation, but in a conventional manner: if there is no phonological contrast between the liquids in the (prosodic) syllable-final position (i.e. the variety is nonrhotic), then syllable-initiality appears to impose no constraint on the resonance quality of initial liquids other than that the lateral and the rhotic must have opposite resonance qualities. On the other hand, if there is a phonological contrast between the liquids in the (prosodic) syllable-final position (i.e. the variety is rhotic), then syllable-initiality does appear to be associated with a particular pattern of resonance: relatively clear [l] and relatively dark [r].

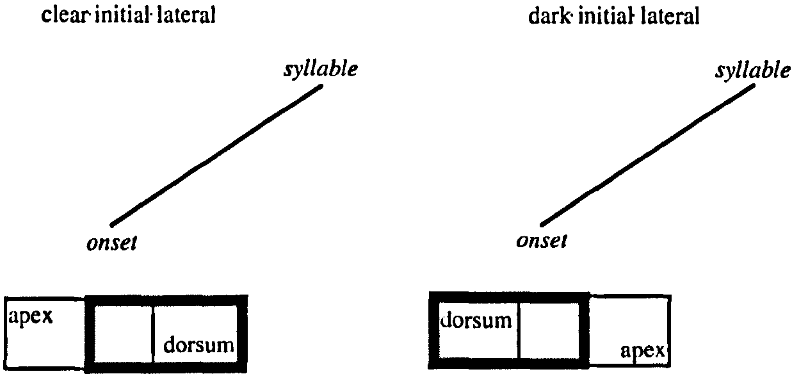


Figure 60. Gestural alignments for initial laterals showing dialect-specific gestural affinity.

One possible extension of Sproat & Fujimura's findings to make predictions about the behaviour of [r] as well as of [l] is to suggest that any liquid (at least in English) might be darker in syllable-final position than it is in syllable-initial position. If this is the case, it is surprising that the data presented in this dissertation show final rhotics as being clear. Of course, it could be that darkness in rhotics is produced by different articulatory means from darkness in laterals (as well as by similar means such as pharyngeal constrictions). Lip rounding stands out as a possible candidate for this role (see Section 3.4.1 for a discussion of the articulation of rhotics in English). Sproat & Fujimura's predictions could then be kept in a more appropriate domain, namely articulatory phonetics, allowing for tongue dorsum predictions only (as opposed to predictions relating to clearness and darkness) and keeping open the possibility that final laterals are dark and final rhotics are clear. However, such an extension of Sproat & Fujimura's findings would still not explain the variation in onset liquids presented in this chapter.

The relationship between phonology and its phonetic exponents needs to take account of great phonetic detail: the metaphor of redundancy used in its strict (and often universalist) sense is particularly unhelpful, since detail which may be seen as non-contrastive is, in fact, important to the structure of the phonology. As Nolan (1999:5) comments (in discussing Carter, 1999):

> '... the variation in degree of darkness of laterals and rhotics is more than could be accounted for by general principles. In particular, from the point of view of Articulatory Phonology, although the general trend for laterals to be darker syllable-finally than syllable-initially is susceptible to a generalisation in terms of the phasing and magnitude of gestures, the details of the implementation of the contrasting liquids across dialects is clearly not susceptible of explanation in dynamic terms, since it is part of the language- (or dialect-) specific information which must be part of what is volitionally variable.'

The importance of there being an arbitrary but systematic relationship between the phonetics of a particular utterance and its phonology has been noted as an essential part of a relational / contrastive phonology within a declarative framework. Allowing phonological categories to have intrinsic phonetic content leads to difficulties in defining precisely what is phonetics and what is phonology, as well as a loss of explanatory adequacy when faced with detailed cross-dialectal phonetic data.

Sproat & Fujimura's results for laterals are generally supported here (with reservations regarding the phasing of gestures in dark initial laterals). Future articulatory work needs to recognise abstract phonological entities (and hence extrinsic phonetic interpretation) as well as phonetic data in order to make more accurate predictions about the constraints on phonetic interpretation.

8.2.5 Government phonology

In Section 3.5.5 I discussed Harris's (1994) comments on resonance in liquids and Tollfree's (1996) criticism of the government phonology approach with reference to vocalised laterals.

Harris analyses clear [r] as [R, I] and dark [r] as [R, @]. However, element change within a single phonology is barred in government phonology, so these would not be admissible representations for rhotics which are clear in one syllable position and dark in another.

For similar reasons, Tollfree suggests [R, ?, @] or [R, ?, U] as representations for clear [l], and [R, ?, @] or [R, ?, U] as representations for dark [l]. However, even headship change in a derivation is problematic within government phonology.

In addition to the difficulties Tollfree identifies in accounting for cross-dialectal variation in laterals, there is a difficulty inherent in the prosodic structure of government phonology in appropriately describing the phonetic data presented in this dissertation: there needs to be a way of describing differences in syllable position. All of the variants discussed in this dissertation would be located in onsets within government phonology, as in Figure 61. The only differentiation which could be made between these onsets in government phonology is that in absolute final position, an onset liquid could be licensed by a following empty nucleus (as opposed to a filled nucleus); otherwise, there is no way of defining any structural difference between them and so it would be impossible to account for the resonance differences which obtain between syllable positions but within a variety (such as Fife initial [r] being dark and Fife final [r] being clear).

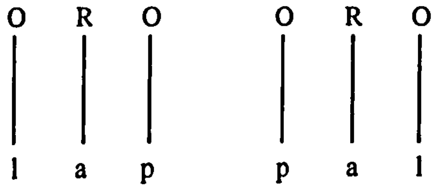


Figure 61. Prosodic structure for singleton liquids in government phonology.

How could variation between prevocalic and postvocalic liquids be described without a coda? Would coda [l] be post-nuclear and rimal? Of course, if no element variation is present, there could just be a rule of interpretation in dialects of English. Accounting for the polarities in liquid resonance qualities would result in typically dark lateral varieties having all laterals as dark and typically clear lateral varieties having all laterals as clear, but this solution is contrary to the universalist theory of interpretation adopted by government phonologists. In some situations, postvocalic laterals may be syllabified into a postnuclear rimal position (when another consonant follows which could not coexist in an onset with the lateral, such as in a word like *pelt*), but often postvocalic laterals must be in onset position (for example, in words such as *pail*, where the long vowel takes up the two rime positions, or domain-final *pal*), as in Figure 62. Given this state of affairs, not only is it not possible to describe postvocalic laterals as a coherent class, but also there is no theoretical distinction to be made between some postvocalic laterals and prevocalic laterals.

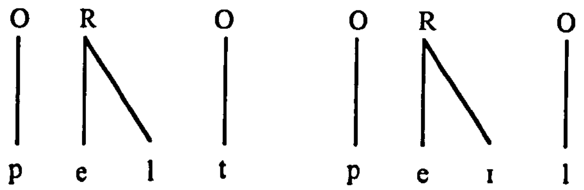


Figure 62. Variation in government prosodic representations of postvocalic liquids.

If government structural representations cannot account for structural variation, then perhaps elemental representations might account for the nonrhotic data, where syllable position is not as important as in the rhotic varieties. However, even if darkness (as opposed to clearness) is represented solely by adding [@] to the standard lateral representation [R, ?] and clearness is derived by general constraints on elemental complexity which would delink [@], it would not be possible to represent darkness in the same way in laterals and in rhotics which, in the varieties examined in this dissertation, show patterns of resonance which are complementary, since delinking would occur at an inappropriate place in structure for one or the other liquid. If structural constraints delink [@] to produce a clear onset [r], for example, then the same constraints would force delinking of [@] in onset [l], resulting in a clear [l] too. For such a government approach to be able to account for such data, general constraints would sometimes have to operate in reverse.

In fact, general constraints on delinking mean that it would only occur in laterals, since rules for delinking are based on the relative numbers of elements at different points in structure. Laterals have two elements ([R, ?]) plus a resonance element, while rhotics have only one element ([R]) plus a resonance element, so government phonology predicts that if delinking occurs in rhotics it must also occur in laterals. There would then be dark [r] and clear [l] in one variety (like Sunderland) but clear [r] and clear [l] in the other variety (unlike Manchester).

8.2.6 Optimality

Since the current mainstream phonological approach is often described as constraint-based phonology, it is worth briefly outlining how some proposed violable constraints might be used to account for liquids in English before going on to present an analysis in terms of (inviolable) declarative constraints.

The basic cross-dialectal alternation of liquid allophones (in segmental phonetic terms) could straightforwardly be portrayed in an OT-style tableau, using Hayes's (2000) /l/ IS DARK constraint, which would force [l] to be dark, and an OT version of Sproat & Fujimura's (1993:306) Gestural Affinity constraint (or, alternatively, Hayes's, 2000 PREVOCALIC /l/ IS LIGHT constraint). With only two constraints which have opposite ranking in each variety, no more would be being said than that one variety has dark laterals and the other obeys Gestural Affinity.

In Figure 63, the candidate output [ɫap] violates GESTAFFIN. This is the higher ranked of the two constraints and the violation is therefore crucial, since it defines the candidate [ɫap] as nonoptimal. The alternative output form [lap] violates /l/ IS DARK, but irrelevantly so since it is the lower-ranked constraint. In this way, a clear initial lateral is produced.

/lap/	GESTAFFIN	/l/ IS DARK
☞ lap		*
ɫap	*!	

Figure 63. OT-style tableau for /lap/, clear initial lateral variety.

In Figure 64, [pal] crucially violates GESTAFFIN, the higher ranked of the two constraints. It also violates /l/ IS DARK, but irrelevantly so since it is the lower-ranked constraint. In this way, a dark final lateral is produced.

	/pal/	GESTAFFIN	/l/ IS DARK
	pal	*!	*
☞	pał		

Figure 64. OT-style tableau for /pal/, clear initial lateral variety.

In Figure 65, [lap] violates /l/ IS DARK, just as in Figure 63, but this time it is a fatal violation since in this variety /l/ IS DARK is the higher-ranked constraint. The form [łap] violates GESTAFFIN, but the violation has no effect since the constraint is sufficiently lowly ranked. In this way, a dark initial lateral is produced.

	/lap/	/l/ IS DARK	GESTAFFIN
	lap	!*	
☞	łap		*

Figure 65. OT-style tableau for /lap/, dark initial lateral variety.

In Figure 66, as in Figure 64, [pal] violates both constraints and is rejected (whatever the relative ranking of the constraints), resulting in the dark final lateral form, [pał].

	/pal/	/l/ IS DARK	GESTAFFIN
	pal	*!	*
☞	pał		

Figure 66. OT-style tableau for /pal/, dark initial lateral variety.

No account is taken in these tableaux of resonance patterns in rhotics and how they interact with the laterals with which they are in system as liquids. In OT, a candidate form cannot know which other candidate forms have been accepted as optimal. It is not possible to formulate a constraint to specify that laterals and rhotics should have opposite resonance quality, since a candidate such as [ɹap] could not be checked against the optimality or otherwise of the candidates for another lexeme, [lap] or [łap]. An appropriate analysis could only be achieved by stipulating opposite constraints (such as /l/ IS DARK versus /r/ IS DARK), only one of which would ever affect candidate selection in a given variety.

8.3 An abstract attribute cluster

In this section I will propose an abstract non-segmental analysis of liquids in English. I will go on to test the analysis against a range of phonological data in order to assess its viability, its strength and its weaknesses.

8.3.1 [P] and [R] in liquids and glides

Let us assume that the traditionally accepted primary articulatory aspects of liquids identify both [l] and [ɹ] as patterning with apicals generally, whereas the closely-related glides [j] and [w] have tongue body articulations. In an effort to avoid confusion with phonetic labelling of phonological categories, let us set up an attribute associated with this primary articulation, **[P]**. The discussion of the data presented in previous chapters has demonstrated the importance of resonance in English liquids. Let us set up an attribute associated with this secondary articulation or resonance quality, say, **[R]**. The two attributes might be given the following binary values (as in Table 46): [**P**: *α*] might typically have apical gestures as phonetic exponents, while [**P**: *δ*] might have dorsal gestures. [**R**:*y*] would have clear resonance as its phonetic exponents, while [**R**:*w*] would have dark resonance as its phonetic exponents. The use of *y* and w will be unsurprising, given the typical Firthian use of these mnemonics, as by Firth himself (1948a):

> '[some] sounds of this semi-vowel nature which lend themselves to prosodic function are r and l, and these often correspond or interchange with y or w types of element.'

The identification of liquids as candidates for prosodic nature is, of course, a result of their particular patterning within syllable structure and hence their syntagmatic importance.

The values *y* and *w* are used so as to alleviate the confusion between phonetically (absolutely) clear or dark on the one hand, and phonologically (relatively) clear or dark on the other. So, for instance, the phonetic exponents of [R:*y*] can be dark but they will not be as dark as the phonetic exponents of [R:*w*]. Manchester and Fife (and General American) initial laterals are both phonetically dark but Manchester [l] is an exponent in part of [R:*w*], whereas Fife (and General American) [l] is an exponent in part of [R:*y*].

attribute	**value**	**characteristic exponent**
P	*α*	apical approximation
	δ	dorsal approximation
R	*y*	clear resonance
	w	dark resonance

Table 46. Values and typical exponents of [P] and [R].

The two binary attributes predict a four-item system (unlike the predictions of the cns/voc field analysis). The segmental phonetics of the liquids and glides are then associated with phonological attributes as in Table 47 (assuming, for now, a clear initial [l] nonrhotic variety — see Section 8.6.1 for comments on other varieties), with clear resonance and dark resonance being produced with particular articulators appropriate for each liquid. The liquids both have a phonological attribute associated with apical articulation, [P:*α*]. Clearness and darkness in the liquids is handled with a separate attribute, [R], whose articulatory exponents can be different for each liquid. Darkness can be associated, for example, with labialisation, velarisation or pharyngealisation. Indeed, the exponents of [R:*w*] can differ in rimes from in onsets (recall that the Manchester and Fife speakers enhance the darkness produced with a low F2 in onsets by raising F1 in rimes). Darkness is not an extra feature or attribute superimposed on a liquid: clearness and darkness have equal phonological status (note that there is some evidence, such as that presented by Recasens *et al.*, 1998, that it is possible that [l] and [ɫ] can each have two articulatory targets).

Note, incidentally, that phonetic descriptions such as laterality do not enter into this scheme. This is for phonological reasons but also has some phonetic plausibility, since laterality can be identified as a phonetic consequence of the combination of apicality and dorsality, thereby narrowing the tongue as it lengthens (Ladefoged & Maddieson, 1996:182; see also Walsh Dickey, 1997:49, who explicitly excludes [lateral] from her phonology).

P	characteristic phonetic exponent of P	R	characteristic phonetic exponent of R	segmental phonetic exponent
α	apical approximation	*y*	front tongue body configuration	[l]
α	apical approximation	*w*	labialisation	[ɹ]
δ	dorsal approximation	*y*	front tongue body configuration	[j]
δ	dorsal approximation	*w*	labialisation	[w]

Table 47. Segmental transcriptions of liquids and glides associated with [P] and [R] phonological attributes in a clear initial [l] nonrhotic variety.

The glides are associated with [P:*δ*] which has dorsal approximation as an exponent. Clearness and darkness are handled in a similar fashion to the liquids, with [l] and [j] being associated with [R:*y*], while [ɹ] and [w] are associated with [R:*w*] (see, for example, Macken, 1995:678, who comments that [l] interacts with [j], and [ɹ] with [w] in the acquisition of English). Yod is an interesting case, since both phonological attribute-value pairs, [P:*δ*] and [R:*y*] have similar articulatory exponents: dorsal approximation and front tongue body configuration respectively. In Section 8.6.2.3 I will show how such an analysis of yod can account for cross-dialectal variation in British English. Keating (1988) has also analysed palatals as complex articulations, although Recasens (1990) claims that palatals are not complex and Gick (1999) agrees, with specific reference to yod in English.

Gick's analysis of [w] is that the labial gesture is consonantal and the velar gesture is vocalic, although both could be defined as phonetically vocalic since neither produces an extreme obstruction in the vocal tract. The exponents of the attribute [P] are equivalent to articulatory phonology's consonantal gestures and the exponents of the attribute [R] are equivalent to articulatory phonology's vocalic gestures. Gick's analysis of [w] is therefore incompatible with the scheme outlined here. However, it is based on ambisyllabic [w]: the analysis of glides proposed here allows for glides in the onset but not the rime, so the issue of ambisyllabicity does not arise.

8.3.2 Generalising [P] and [R] beyond liquids and glides

An objection could be raised to the more abstract nature of [**P**] and [**R**] as compared to previous declarative phonological structures: the generalisation across place of articulation attributes is lost so, for example, the phonology associated with [l] would no longer share structure with other alveolars, as in Table 6 (p.112). A YorkTalk-type analysis with two binary features in the [cns] field predicts four places of articulation (Coleman, 1998:284): labial ([cns:[grv:+, cmp:-]), alveolar ([cns:[grv:-, cmp:-]), palatal ([cns:[grv:-, cmp:+]) and velar ([cns:[grv:+, cmp:+]). Labiovelars are handled by underspecification: [cns:[grv:+, cmp:_]]. Coleman's (1998) place of articulation templates may or may not differ from these (YorkTalk) values in that the velar template is identical to the palatal template and distinguished by the attribute [src:[str]] (p.289) but the YorkTalk values for velars are used in the expanded forms (pp.285-6).

Since the stop system in English does not share the same distribution as the liquid or glide system, it is not straightforwardly obvious that there is a need to generalise these phonological descriptions beyond the liquid or liquid and glide system. However, some aspects of the distribution of stops and liquids are best expressed with the use of more general attributes (see Section 8.5 for details). Might there be a way of expanding the [**P**]/[**R**] scheme I have outlined to describe more English phonology without the overgeneration described in Section 3.5.6? It is clear from the stop system in English that three places of articulation need to be accounted for in the phonology. If [**P**] is to be extended beyond liquids, then a third value would be needed to account for labial articulations, say [**P**:*λ*]. But the [cns] and [voc] field analysis can generate a fourth place of articulation, namely palatal.

The palatal template is used by Coleman in three places: yod within the glide system, distinguishing [ʃ] from [s], and for the affricates [tʃ] and [dʒ]. I will briefly examine each of these uses of the palatal template to see if the [**P**]/[**R**] scheme can adequately account for the same phenomena without the need for an extra specification for place of articulation.

Yod has been dealt with in Table 47 as a combination of [**P**] and [**R**] values, [**P**:*δ*, **R**:*y*], in place of an explicit palatal place of articulation specification.

The sibilants [s] and [ʃ] can be distinguished using the [**R**] attribute, using a distributional argument to account for their complementary distribution in onset clusters with liquids, as outlined in Section 8.5.1.

The affricates [tʃ] and [dʒ] are distinguished not only by a palatal place of articulation but also by having the values [src:[str:+, cnt:-]]. In fact this is another point at which Coleman departs from the YorkTalk system: YorkTalk models the affricates with a completely unspecified [cns] field, distinguishing them only by the [src] attributes.

It is therefore possible to avoid the need for a special palatal place of articulation in the phonology of English, replacing most of its functions with values of [**R**] which are independently required for the liquids and glides.

If, in order to generalise the [**P**]/[**R**] analysis, there is a need for only one more value for [**P**] than is necessary to account for liquids and glides, giving [**P**:*λ*|*α*|*δ*], is there a need for any more values of [**R**]? Another place where clear and dark items seem to operate in English is in juncture between syllables, along with a central resonance (linking or intrusive [r]); so, broadly, *the oar* [ði:jɔ:] (front resonance, [j]), *to order* [tʊwɔ:də] (back resonance, [w]), *law and order* [lɔ:ɹəndɔ:də] (central resonance, [ɹ]). Perhaps a third value might be appropriate for [**R**], giving [**R**:*y*|*ə*|*w*]. This leaves a [**P**] system with three values (two of which are used in the liquid and glide system) and an [**R**] system with three values (two of which are used in the liquid and glide system), generating a possible total of 3x3=9 structures. The following stipulatory constraints would need to be imposed on the liquid and glide system: *[**P**:*λ*], *[**R**:*ə*] (constraints which are, in fact, shorthand for the positive constraints [**P**:*α*|*δ*] and [**R**:*y*|*w*]).

An extension of the [**P**]/[**R**] analysis to juncture (requiring the value [**R**:*ə*]) is, however, undesirable for two reasons. Firstly, the approximant which appears in juncture is entirely predictable from the vowel context, and so the necessary phonological information is already specified elsewhere in structure; linking [ɹ] and the other junctural approximants would therefore be better treated as aspects of the phonetic interpretation of certain kinds of syllable juncture. Secondly, if [**P**] and [**R**] are to do some of the work of the [cns] and [voc] field analysis, then stops (for example) would receive a specification for [R] in unification with other syllabic constituents. This is, however, only an apparent problem, since its solution is exactly the same as that described in Section 3.5.6.1 in order to keep constraint (3.1) non-procedural: stops would share values of [R] with the tautosyllabic vowel while liquids might accidentally have values for [R] which are identical to those associated with the tautosyllabic vowel.

In any case, there is no phonological reason (in the Firthian tradition) to compare systems which have different numbers of terms. Under this view, [P:α] in the liquid system cannot mean the same as [P:α] in the stop system, since the former is a member of a two-term system (α, δ) and the latter is a member of a three-term system (λ, α, δ).

In summary, it is not desirable to generalise [P] and [R] beyond liquids and glides. An abstract [P]/[R] analysis (with two values for each attribute) is more constrained in the predictions it makes about what consonants are found in English; as demonstrated in Table 9 (p.117), the [cns]/[voc] field analysis predicts the existence of many bundles of features which do not occur. However, the great advantage of the [voc] field approach is that it accounts for resonance effects with exactly the same mechanism with which it describes vowels. [R], on the other hand, relates approximately to only one part of the vowel system: frontness and backness. Attributes associated with vowel height and length are not found in the [P]/[R] analysis. In YorkTalk, vowel length is in fact dealt with elsewhere (as a rimal attribute). Nevertheless, a separate analysis for vowel height (perhaps with the values [ι, ε, ɑ], in the manner of Whitley, ms) would still be necessary in order to generalise the [P]/[R] analysis to account also for vowels.

8.4 Attribute location in the prosodic hierarchy

Given a (non-segmental) phonology (Local, 1992, 1995b; Ogden, 1992) in which features or attributes are distributed across the prosodic hierarchy rather than being restricted to a terminal node or (auto-)segmental level, the issue of the location in the (prosodo-melodic) hierarchy of the attributes associated with liquids in English arises.

In this section I will discuss how the attributes I have set up ([P] and [R]) might be related to the prosodic hierarchy. In doing so, I endeavour to abandon composite vertically-integrated segmental units such as the phonemes /l/ and /r/. I will discuss the consequences for the temporal coordination of the phonetic parameters associated with [P] and [R] of the location of these two attributes in the prosodic hierarchy.

8.4.1 Consequences of an abstract non-segmental phonology

As discussed in Section 2.4, a segmental phonology (even if it has some sort of overarching prosodic structure) attaches features, elements or attributes to slots in the skeletal tier: melodic information, in the shape of feature bundles or collections of elements (even if they have their own internal structure, as in feature geometry), is kept apart from the prosodic/metrical structure. In a non-segmental phonology, features or attributes may potentially be attached to any part of the hierarchical phonological structure.

In an extrinsically-interpreted phonology, naming of attributes is arbitrary and attributes stand only as labels for particular kinds of relations: the labels [P] and [R] in the analysis presented in Section 8.3 mean nothing in themselves. There is nothing, aside from secondary considerations of parsimony, which prohibits the setting up of attributes relating to initial liquids which differ from those for final liquids. It is a potential weakness of extrinsic phonetic interpretation that the phonetics is related arbitrarily to the phonology. Indeed, this has been put forward as a criticism of extrinsically interpreted phonologies such as Firthian Prosodic Analysis. However, in a declarative approach such as is developed here, the relationship is constrained by the phonetic interpretation being not only arbitrary but also systematic: phonetic exponency is compositional (Dowty *et al.*, 1981; see also Coleman, 1998:170ff) and stated in terms of structural information.

The patterning and interactions reported in previous chapters support the notion of a single liquid system with phonological attributes at more than one place in the syllable, since phonetic effects found in liquids in the onset are closely related to phonetic effects found in liquids in the rime. Moreover, distribution data in the rime has an effect on the phonetic interpretation of attributes in the onset (see Chapter 6): if a particular variety is nonrhotic, there is a particular kind of cross-dialectal variation in onset liquids; if the variety is rhotic, this variation is not found. This is the motivation for referring to an overarching liquid system, rather than two entirely independent systems, one in the onset and one in the rime. Following the notion of syllable constituency in Pike & Pike (1947) and the more precise structure outlined by Fudge (1969, 1987) and Selkirk (1982), it is assumed that syllables have the internal structure σ→OR; R→NC (expressed in terms of phrase structure rules) or, equivalently, in terms of attribute-value matrices and dags in Figure 67.

$$\left[\text{syllable}:\begin{bmatrix}\text{onset} & \\ \text{rime}: & \begin{bmatrix}\text{nucleus}\\ \text{coda}\end{bmatrix}\end{bmatrix}\right]$$

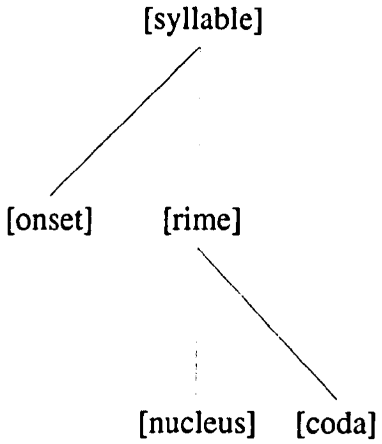


Figure 67. Syllable structure in attribute-value matrix and directed acyclic graph representations.

Clearly the liquid systems can differ in the two places, particularly in nonrhotic varieties which have a two-term liquid system in the onset and only a one-term system in the rime, but it is justified to use the term *liquid system* to partially describe the two subsyllabic systems just mentioned. Whatever names are given to the liquid attributes, they are the same for initials as they are for finals.

In an abstract phonology, it is not possible *a priori* to compare prevocalic liquids with postvocalic liquids. This state of affairs is akin to the classical phoneme theory example of [h] and [ŋ] which are in complementary distribution in English but which are not counted as allophones of the same phoneme because they do not display sufficient phonetic similarity to one another to be classed as the same object in such a concrete phonology. Prevocalic liquids and postvocalic liquids are in complementary distribution by definition of the terms *prevocalic* and *postvocalic*, since they occupy mutually exclusive positions in the structure defined with reference to the vowel. But prevocalic liquids (on the one hand) and postvocalic nasals (on the other) are also in complementary distribution by definition of the terms *prevocalic* and *postvocalic* (independently of any meaning of the terms *liquid* and *nasal*): they never contrast with each other. Clearly, something more than simple distributional information is required for the setting up of attributes in an abstract, relational phonology. The argument put forward in this dissertation is a less concrete and more systematic version of the classical phonemic argument of phonetic similarity: phonetic patterns (i.e. relationships rather than objects) provide evidence that these two systems can in fact be counted as one overarching system operating at two points in structure.

8.4.2 Possible locations in the hierarchy

There are a number of logically possible locations in syllable structure for attributes associated with prevocalic and postvocalic liquids. Figure 68 shows these locations (in the manner of the directed acyclic graph representation in Figure 67) where prevocalic and postvocalic liquid attributes might be placed. For the moment — and for ease of exposition — [P] and [R] attributes are conflated into single representations for prevocalic (**L-**) and postvocalic (**-L**) liquids. I will expand the discussion to the two separate attributes [P] and [R] in Section 8.4.3.

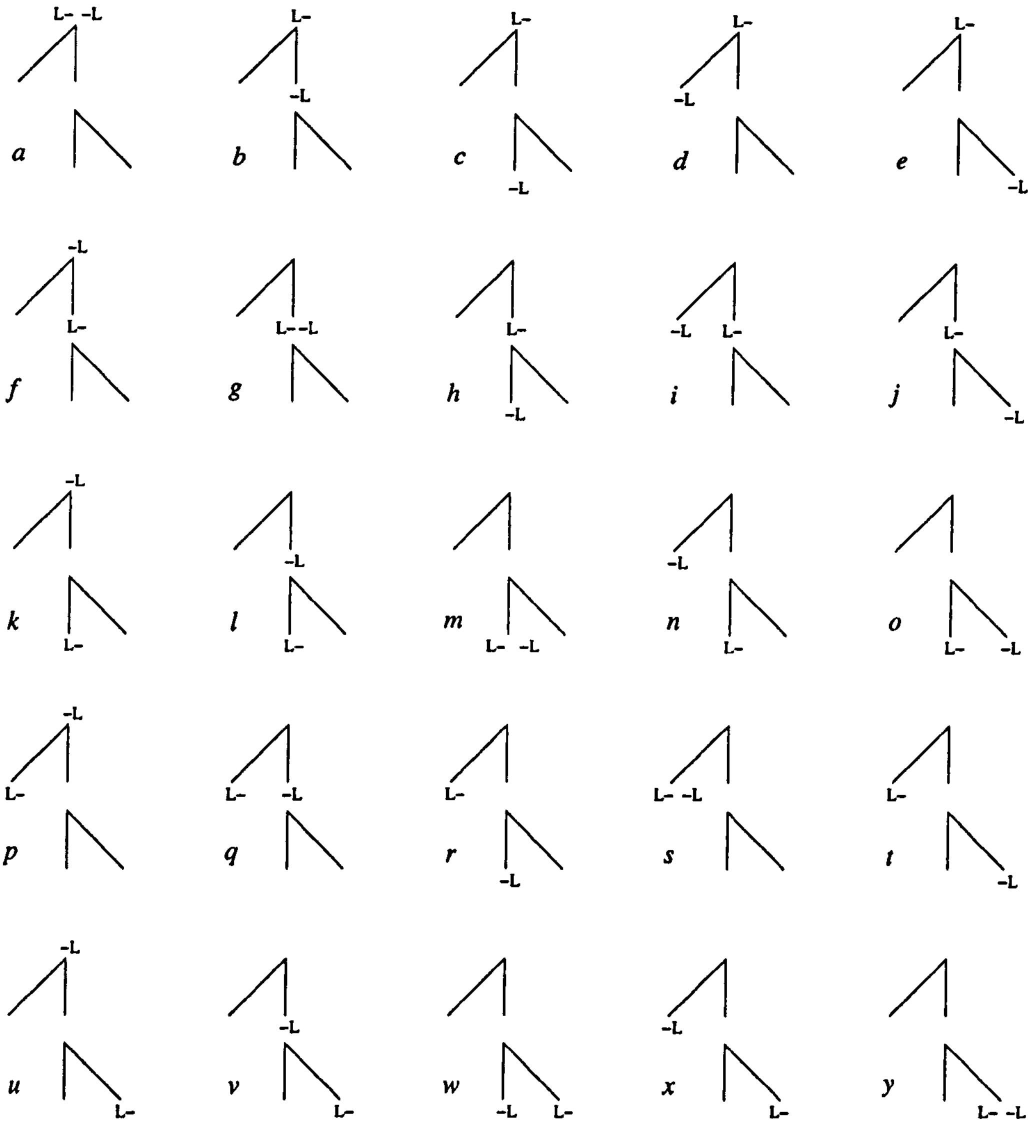


Figure 68. Logically possible locations in the syllable for prevocalic and postvocalic liquids. L- indicates prevocalic liquids; -L indicates postvocalic liquids.

In a schematic fashion, Figure 69 elaborates the structures in Figure 68 with the possible temporal extents of the exponents of prevocalic and postvocalic liquids which are local to the syllable. These representations are associated with the representations of prosodo-melodic structure in Figure 68, following the systematic temporal exponency scheme developed for YorkTalk (Local, 1992; Ogden, 1992; Coleman, 1994). The nucleus is the head of the rime, and the rime is the head of the syllable. Attributes at the head of a domain are phonetically interpreted before attributes at other points in the domain and, crucially, they can have exponents over the whole extent related to the domain of which they are the head, rather than simply over that related to the nodes they dominate, so the exponents of the nucleus attributes are coextensive with the exponents of the rime attributes (the nucleus is the head of the rime), and the exponents of the rime attributes are coextensive with the exponents of the syllable attributes (the rime is the head of the syllable).

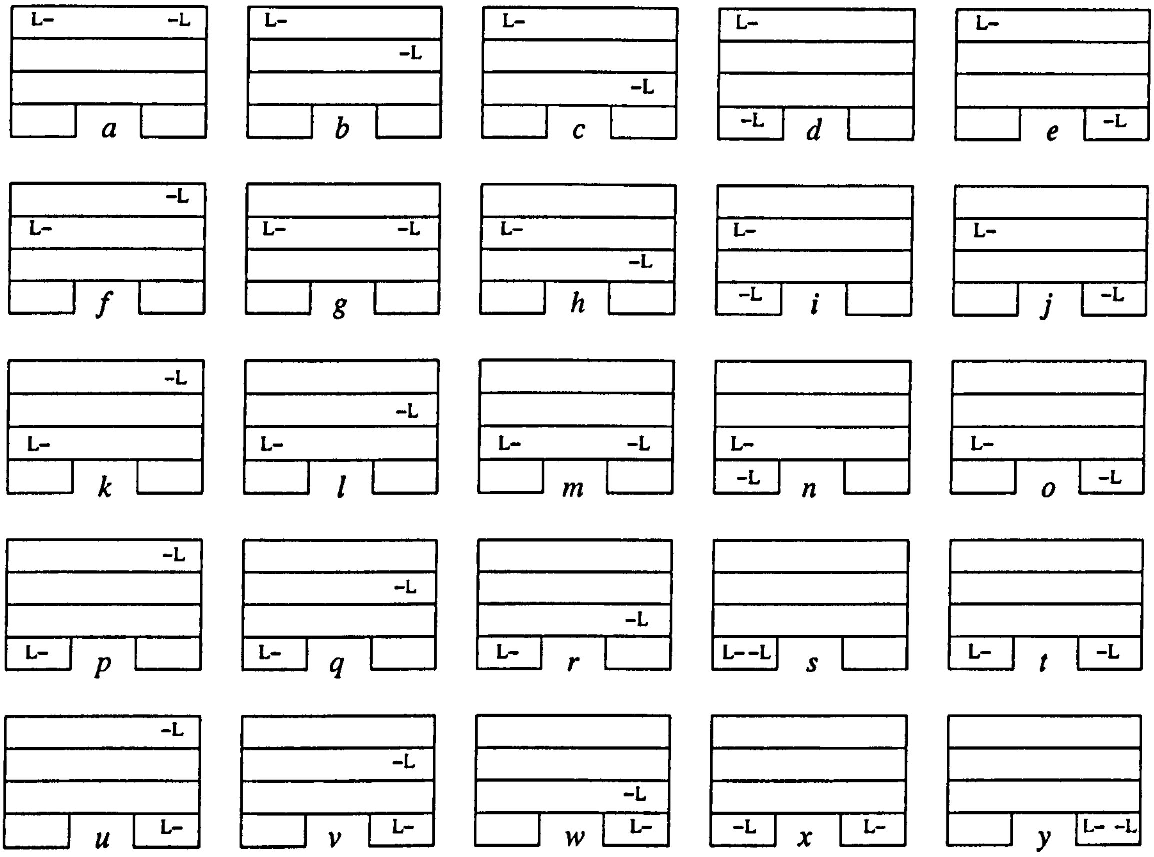


Figure 69. A schematic representation of the logically possible extents associated with locations in the syllable for prevocalic and postvocalic liquids. **L-** *indicates prevocalic liquids;* **-L** *indicates postvocalic liquids. In each box diagram, the top full-width bar represents the extent of syllable exponents, the middle represents the extent of rime exponents and the bottom full-width bar represents the extent of nucleus exponents. The bottom left short bar represents the extent of onset exponents; the bottom right short bar represents the extent of coda exponents.*

If there is a single liquid system, then the phonological attributes of syllable-initial liquids must not conflict with the phonological attributes of syllable-final liquids. In practice, this means that neither of these two sets of attributes must dominate the other in case they have opposite values; this rules out representations *b*, *c*, *d*, *e*, *f*, *h*, *j*, *k*, *l*, *p*, *u* and *v* in Figure 68, perhaps using some version of the Foot Feature Principle employed in declarative approaches to phonology and syntax, as defined by Broe (1991), based on Gazdar *et al.* (1985), in which the foot features of the mother must be identical to the foot features of every daughter, or alternatively, using Selkirk's (1982:341) suggestion that

> 'selected distinctive features may be assigned to a node of syllable structure, with the interpretation of this being that any segment or constituent dominated by a node labelled [+F] is characterised as [+F]'

(feature percolation is a redundant operation since it merely replicates the coproduction-based head-first interpretation mechanism developed for YorkTalk — it is only required if the interpretation mechanism has access only to terminal node information, even if some features are found at non-terminal levels, as in Vincent, 1986). Neither of the two sets of attributes may occur at the same point in structure as the other (ruling out representations *a*, *g*, *m*, *s* and *y*). Liquid attributes may therefore not occur at syllable level since the syllable level dominates all other possible positions for the second set of attributes.

The general constraints on temporal interpretation imply that the attributes of syllable-initial liquids must be in onset position. Representations *i*, *n* and *x* have postvocalic liquid attributes in the onset. While the exponents of the syllable, nucleus and rime are logically permitted to co-occur with the exponents of the onset, they must also continue after the end of the onset exponents since otherwise the exponents of the coda would not be integrated with the rest of the syllable. By the definition of *postvocalic*, then, these representations are ruled out. For similar reasons, the prevocalic attributes in the coda of representation *w* are impermissible.

These constraints result in only four of the representations being possible: *o*, *q*, *r* and *t*. Carter (1995) suggests that laterals in particular may be analysed as being less integrated with the vocoid when they are in prevocalic position than when they are in postvocalic position. Moreover, the cross-dialectal phonetic data in the current study suggest that vocalic-type gestures in liquids may be phased close to the vowel when in the rime (as Sproat & Fujimura, 1993, predict) but that in the onset there is no such binding with the vowel. Representation *o* may not therefore reflect the most appropriate analysis.

Prevocalic liquid attributes are best analysed as being onset attributes. Three possibilities remain for the location of attributes associated with postvocalic liquids: *q* (postvocalic liquid attributes at rime level), *r* (postvocalic liquid attributes at nucleus level) and *t* (postvocalic liquid attributes at coda level).

Clements *et al.* (1995) suggest that [l] might best be placed in the nucleus. However, nucleus level attributes would threaten the (segmental) generalisation that the nucleus bifurcates since liquids may follow long vowels (which can be represented as taking two nuclear places, as in Figure 70) and the association between consonantal material and the coda would be lost. On the other hand, vocalic lengthening effects such as those reported by Coleman *et al.* (1994, in which it is reported that laterals behave much like vowels in their relative durations before voiced and voiceless codas) and Carter (1995) might suggest that laterals share some nature with vocoids, rather than being assigned, like consonants, to coda position. Indeed, Coleman (1998:283) suggests that diphthongs resulting from historical vocalisation of a rhotic (such as /ir/, in his analysis) are best analysed as being at rime level, since they pattern with whole rimes rather than nuclei as they can occur in open syllables. The historical vocalisation of rhotics and contemporary possibilities for vocalisation of laterals might suggest a compromise solution with rime liquids in nonrhotic varieties and coda liquids in rhotic varieties, but this solution would lose the generalisation of a panlectal phonology.

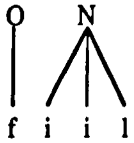


Figure 70. An example (in <feel>) of a nuclear liquid following a long vowel.

In summary, there seems to be evidence of attributes associated with liquids located either at rime level or at coda level (in addition to the attributes related to prevocalic liquids at onset level).

8.4.3 Where might the attributes associated with liquids be? — a proposal

Stemberger (1983:141) argues from American English speech error data that

> '/r/ and /l/ are not parallel to either glides [in which category the second portion of diphthongs are included] or consonants. They are not as integrally associated with the vowel as glides are, but nor are they as loosely associated with it as consonants are.'

Stemberger analyses liquids only in terms of terminal nodes in the prosodic hierarchy. By contrast, non-segmental phonology allows attributes to be located anywhere in the hierarchy.

In an abstract [P]/[R] analysis, liquids are represented by two distinct phonological attributes, one which is associated with typically consonantal gestures and another associated with typically vocalic gestures: Coleman's glide constraint (example 3.1) is only a descriptive constraint, since 'Glide' is not a phonological atom in Coleman's analysis. This is also true of the analysis presented here. If [P] and [R] are not components of the same phonological atom, the possibility arises that [P] and [R] might not be located at the same place in syllable structure.

In Section 3.5, I discussed evidence from liquids leading to a variety of analyses in which liquids are made up of both consonantal and vocalic material. The seemingly consonantal ([P]) and seemingly vocalic ([R]) attributes of 'postvocalic' liquids might be separated, with the vocalic attribute at rime level (to avoid too loose an association with vocalic material) and the consonantal attribute at coda level (to avoid too integral an association with vocalic material), as in Figure 71 (with its associated temporal exponency schematic, as in Figure 72). This analysis is appealing since it would result in the rime, as head of the syllable, carrying typically vocalic attributes and the coda consonantal ones. Since the phonetics of the rime begins earlier in time than the phonetics of the coda (Figure 72), this arrangement would make accurate predictions about phasing of gestures at least for syllable-final laterals, namely that the vocalic (rimal) dorsal gesture precedes the consonantal (coda) apical gesture.

$$\left[\text{syllable}: \left[\begin{array}{l}\text{onset}: \begin{bmatrix}\mathbf{P}\\ \mathbf{R}\end{bmatrix} \\ \text{rime}: \begin{bmatrix}\mathbf{R}\\ \text{nucleus}\\ \text{coda}: [\mathbf{P}]\end{bmatrix}\end{array}\right]\right]$$

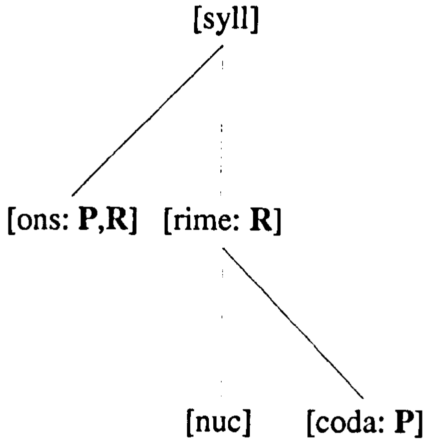


Figure 71. Location of [P] and [R] in syllable structure.

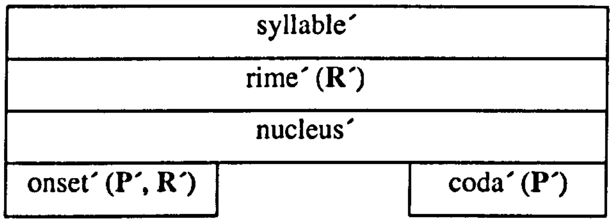


*Figure 72. Schematic temporal exponency of the structure in Figure 71. The representation **x′** indicates the exponents of **x**.*

The absence of an intermediate level in the prosodic hierarchy between the onset and the syllable, analogous to the sub-structure of the rime (with the rime intermediate between the coda and the syllable), means that no such constraints are placed on the timing of gestures in initial position, predicting variability in the phasing of gestures in syllable-initial position, which is indeed what is found cross-dialectally. Moreover, this separation of vocalic attributes from consonantal attributes also predicts the sort of ambisyllabicity data reported by Gick (to appear) in that later coda gestures would have a greater affinity for the following syllable than would earlier rimal gestures, and so would vary more under conditions of ambisyllabicity. In the phonological structure, the coda (rather than the rime *per se*) is the node which unifies with the following syllable under conditions of ambisyllabicity.

An abstract non-segmental analysis in the terms presented here makes certain predictions about the temporal phasing of phonetic parameters associated with phonological attributes which turn out to tally closely with the observed variation across varieties of English. It additionally provides a unified account of liquids and glides which does not predict more combinations of attributes than in fact occur.

A useful method for testing the validity of a phonological analysis is to see if it is capable of making accurate predictions about other closely-related areas of the phonology. The attributes [P] and [R] are effectively sub-phonemic, although no phonemic level is implied. The nature of the prosodic hierarchy allows for different kinds of bindings between these phonological atoms at different places in structure. A [P]/[R] analysis is therefore similar to analyses of other phenomena in the phonology of English such as the variation in strictness of temporal alignment of parameters between lexical and grammatical words (as described by Ogden, 1997a,b): two independent phonological items interact with different kinds of bindings. So, for example, while the [θ] in *thick* has a relatively strict binding between dentality and frication, the [ð] in a citation form *the* has a relatively lax binding. In the latter case, dentality is the only phonetic exponent which appears to be necessarily present, resulting in utterances such as *in the* [ɪn̪ːə] or *all the* [ɔl̪ːə], with no local frication.

8.5 Distribution of liquids

In Section 3.1 I discussed the distribution of liquids; here I continue the discussion of liquids in complex onsets in the light of the [P]/[R] analysis of liquids. For ease of exposition, the discussion of distribution begins at the so-called segmental level. However, I make no claims about segments somehow being pre-theoretical; they are as theoretical as any other analysis.

8.5.1 [P] and [R]: liquids in clusters

From the discussion in Section 3.1.2, it appears that neither the lateral/rhotic system nor the resonance system applies in a straightforward fashion in clusters. If anything, in clusters [l] patterns with [w] rather than with [ɹ]. This is not necessarily a problem in a variety such as Manchester English, where both [l] and [w] would in part be exponents of [**R**:*w*] (in complementary distribution), but in Sunderland English [l] is in part an exponent of [**R**:*y*] while [w] is in part an exponent of [**R**:*w*]. Overall, it appears as if clearness and darkness oppositions may have minimal phonological relevance in complex onsets, excluding the special case of the assibilated onsets, [sl] and [ʃɹ]. The clearer [s] is found with what is the clearer liquid in most varieties, in [sl] but not *[sɹ], whereas the darker (lip-rounded) [ʃ] is found with what is the darker liquid in most varieties, in [ʃɹ] but not *[ʃl].

An alternative way of viewing the state of affairs in clusters is to assume that [ɹ] does not fit into the three-way place of articulation scheme (labial, coronal, dorsal). In this way, *[pw] and *[bw] are not found because of labial place constraints and *[tl] and *[dl] are not found because of coronal place constraints. The fact that the onsets [pɹ], [bɹ], [tɹ] and [dɹ] are found would then be explained by [ɹ] not sharing the place specifications of any of the plosives. In fact, these constraints could be formulated in terms of consonantal gestures in Articulatory Phonology (following Gick, to appear) or consonantal fields in an attribute-value approach (following Coleman 1998, among others). The dorsality of [w] and [l] — which is voc(alic) — would therefore not affect the constraints (allowing [kw] and [kl], while *[pw] and *[tl] are absent). If these constraints are independent of clearness and darkness, then laterals and rhotics could still be differentiated along the dimension of resonance. This would have the added advantage of facilitating a description of [sl-], *[sɹ-], *[ʃl-], and [ʃɹ-] (at least for clear initial [l] varieties), with resonance being exponed both in the liquid and in the sibilant. There would still be a complementary distribution of [l] and [w], but the distribution would be analysed as accidental and [l] and [w] would not be counted as the same phonological object.

In summary, then, there are certain difficulties with applying the notion of clearness and darkness to the distributional constraints associated with clusters, although a number of the difficulties are eased by setting up [k^w] as a singleton consonant, although the lack of *[g^w] detracts from the analysis. Given the distribution of clearness and darkness in many (though by no means all) varieties of English, it is possible to account for the assibilated onsets which contain liquids. However, the patterns of complementary distribution in non-assibilated onsets suggest that [l] may be patterning with [w] rather than with [ɹ]. Resonance characteristics cannot straightforwardly be applied to this case, since labiovelar approximants would have to count, alongside laterals, as clear. Nevertheless, by assuming the complementary distribution of [l] and [w] to be epiphenomenal, and not indicative of a shared phonological status, it is possible to give an account of the phonotactic data in terms of primary place constraints.

8.5.2 Distribution in non-segmental terms

In order to renew a connection between a non-segmental phonology and the data it is necessary to re-evaluate the distributional data in the light of the proposed theory. What might the distribution of [P] and [R] be?

Given that the position of [s] or [ʃ] in onset clusters is predictable, the presence or absence of these sibilant fricatives could be represented by a single attribute at onset level, say, [assibilated:±]. Since (as Sprigg, ms, points out) [assibilated:+] implies [voice:-] (or, at least, an absence of voice specification), an attribute such as [assibilated] could conceivably be incorporated with another related to voicing to produce a ternary attribute with values along the lines of [breath:*v*] (associated, for example, with [b]), [breath:*h*] (associated, for example, with [p]) and [breath:*s*] (associated, for example, with [sp]). Further details of this analysis are beyond the scope of this dissertation.

The constraint on the co-occurrence of [s] and [ʃ] with [l] and [ɹ] can be accounted for by the interpretation of [assibilated] (or [breath]) in combination with [P] and [R]. However, this is not entirely satisfactory, partly because of the issues raised in Section 8.5.1, but also because [R:*w*] is associated with [ɹ], predicting [ʃɹ] and *[sɹ], and also associated with [w], making the incorrect predictions [ʃw] and *[sw].

Table 48 outlines the distribution for C_iC_j onsets, where C_i is a plosive and C_j a liquid or glide. As described in Section 8.3.2, initial sibilant fricatives are a special case and initial non-sibilant fricatives pattern with plosives in this respect.

Place of articulation	P	R	phonetic transcription	comments
labial	α	*y*	[pl] [bl]	
labial	α	*w*	[pɹ] [bɹ]	
labial	δ	*y*	[pj] [bj]	analysed as singleton C onset (/p/ + /iw/) analysed as singleton C onset (/b/ + /iw/)
labial	δ	*w*	[pw] [bw]	not found not found
alveolar	α	*y*	[tl] [dl]	not found not found
alveolar	α	*w*	[tɹ] [dɹ]	
alveolar	δ	*y*	[tj] [dj]	analysed as singleton C onset (/t/ + /iw/) analysed as singleton C onset (/d/ + /iw/)
alveolar	δ	*w*	[tw] [dw]	
velar	α	*y*	[kl] [gl]	
velar	α	*w*	[kɹ] [gɹ]	
velar	δ	*y*	[kj] [gj]	analysed as singleton C onset (/k/ + /iw/) analysed as singleton C onset (/g/ + /iw/)
velar	δ	*w*	[kw] [gw]	analysed as singleton C onset (/k^{w}/) not found

Table 48. Distribution of possible CC onsets (plosive plus liquid or glide) in terms of [P] and [R] attributes, clear initial [l] varieties.

Leaving aside the issue of how multiple consonants are represented in the onset, a possible constraint identifiable from Table 54 could be expressed as

(8.1) *[C, P:δ, R:y].

This constraint holds in combination with the analysis of /iw/ (in Coleman's terms) as a nucleus, having phonetic exponents along the lines of [ju:].

The onsets [tw] and [dw] are not as common as many of the others, but they do exist in well-established forms such as *twin*. Otherwise it would have been possible to set up a constraint

(8.2) *[C, **P**:*δ*],

ruling out glides as the second element in a complex onset if a plosive or non-sibilant fricative is present. However, if such an approach were taken, it would leave a constraint like

(8.3) *[C:[place:*alveolar*], **P**:*α*, **R**:*y*]

as a stipulation with no obvious motivation other than to rule out *[tl] and *[dl]. Given that the other absent onset clusters in Table 48 are found in loan words ([pw] in *pueblo*, [bw] in *bwana* and [gw] in *guano*, for example) but *[tl] and *[dl] are not (and, for that matter, nor is *[θl], although Sprigg, ms, claims that [θl] is possible as an adaptation of Welsh [ɬ]) are not, it is unfortunate that the least general description (8.3) is the most generally applicable constraint. Moreover, the analysis of clusters offered in Section 8.5.1 suggested that constraints might be expressed in terms of place of articulation for [l] but not for [ɹ]; this calls into question the identification of both liquids as [**P**:*α*] only if [**P**] relates directly to place of articulation, which it may not. The analysis of the phonetic data does not require that [**P**] be the phonological entity which expones place of articulation in obstruents (as opposed to liquids and glides): [**P**:*α*] would still have apicality as a phonetic exponent in liquids but apicality in obstruents would not be an exponent of [**P**].

From the point of view of purely phonological arguments of distribution, then, it seems that the [**P**]/[**R**] analysis does not contribute any further descriptive adequacy to the consonantal and vocalic field analysis used in declarative analyses of English stemming from YorkTalk. Moreover, it detracts from the general constraints possible within the [cns]/[voc] analysis, such as *[grave][grave] which Coleman (1998:295) suggests, and which can be included in an description of English onsets if $/k^w/$ is analysed as a singleton consonant, as described in Section 3.1.2. Without the $/k^w/$ analysis, distributional constraints on clusters with [l] relate to the [**P**] attribute (apicality) but distributional constraints on clusters with [w] relate to the [**R**] attribute (labiality), losing any possible generalisation regarding distributional constraints and the identity of particular attributes.

A further challenge to the [P]/[R] analysis is that if it is [R] in liquids which accounts for their distribution with sibilants, then it is unclear why [R] in glides does not behave in a similar fashion.

Despite these difficulties, the [P]/[R] analysis, unlike the [cns]/[voc] analysis, has the advantage of not predicting non-occurring combinations of attributes. Moreover, by providing a different set of attributes, there is no temptation to confound the levels of analysis by attempting to make, for instance, a [grave] vocoid somehow more [grave] in the context of a dark liquid (an intrinsically-interpreted phonology would presumably at the very least attempt to place these two features on the same autosegmental tier, running into the problem that two instances of the same feature would be barred from being associated with the same melodic slot, decreasing the explanatory adequacy of the phonological representation). Instead, the gravity of the vocoid would interact in interpretation with the *w*-ness of [R].

8.6 Variation in contemporary English

8.6.1 Another polarity

Of course, the phonetic analysis presented in this dissertation supports the hypothesis that resonance qualities are associated with different liquids in different nonrhotic varieties. Table 49 lists the values of [P] and [R] associated with the different liquids in nonrhotic and rhotic varieties. Liquids and glides are defined by the presence of [P]; this is the panlectal aspect of the phonology, with each variety having a [P] attribute with the potential for an accompanying [R]. Nonrhotic varieties have no [R] in syllable-final [l], since there is no contrast with syllable-final [ɹ]. Both rhotic varieties have the same systems of [P] and [R].

In the case of Manchester English, then, the associations of liquids and glides with phonological attributes would therefore be as in Table 50.

Variety and liquid	syllable-initial		syllable-final	
	[P]	**[R]**	**[P]**	**[R]**
Sunderland [l]	α	*y*	α	–
Sunderland [ɹ]	α	*w*	–	–
Manchester [l]	α	*w*	α	–
Manchester [ɹ]	α	*y*	–	–
Rhotic [l]	α	*y*	α	*w*
Rhotic [ɹ]	α	*w*	α	*y*

Table 49. Values of [P] and [R] associated with the different liquids in nonrhotic and rhotic varieties.

P	R	segmental phonetic exponent
α	*y*	[ɹ]
α	*w*	[l]
δ	*y*	[j]
δ	*w*	[w]

Table 50. Segmental transcriptions of liquids and glides associated with [P] and [R] phonological attributes in a dark initial [l] nonrhotic variety.

Links between [l] and [j] and between [ɹ] and [w] (Section 8.3.1) are lost in this variety. However, the alternative analysis in which [l] and [ɹ] are single items in the phonology with different resonance exponents in each variety would remove the opportunity to predict gestural phasing as in Section 8.4.3.

In the case of the Manchester variety, the phonotactic constraints for clusters do not intersect neatly with the phonological analysis required for singleton onsets, so, for example, the liquid in [sl] would be in part an exponent of [R:*w*] while the liquid in [ʃɹ] would be in part an exponent of [R:*y*]. The analysis of clusters using [P] and [R] is therefore weakened. The generalities in the association between phonetics and phonology are lost if sibilants as well as liquids have a different polarity in different varieties, since there is no phonetic evidence to support a clear [ʃ] (which is heavily lip-rounded) and a dark [s]. In an abstract phonology, [ʃ] could simply be counted as part of the exponents of [**R**:*y*] in Manchester English, but the cross-dialectal advantage in analysing liquids would then be offset by the disadvantage of analysing sibilants differently in different varieties. This is further evidence that resonance may have less of a role to play in the phonology of onset clusters than in the phonology of singleton consonants in the onset.

8.6.2 Other cross-dialectal variations

Phonetic and phonological variation and change provides a further potential testing ground for the analysis. What effects might this abstract non-segmental proposal predict in the phonetics of contemporary varieties of English? Within the liquids and glides, the following variations in contemporary English are well known:

- (non)rhoticity (see, for example, Wells, 1982:75-76, 218ff)
- l-vocalisation (see, for example, Tollfree, 1996, 1999:174)
- labiodental r (see, for example, Foulkes & Docherty, 2000)
- yod dropping (see, for example, Trudgill, 1990, 1999:133)

Given the phonetic patterns reported in Chapter 6 (with variation in the associations between resonance categories and onset liquids in the nonrhotic varieties examined, but no variation in the associations between resonance categories and onset liquids in the rhotic varieties examined), it seems as if rhoticity and nonrhoticity might be an aspect of variation which needs to be stipulated as is, since it is needed in order to state the phonetics and phonological systems of different varieties.

Of the other phenomena outlined above, l-vocalisation, labiodental r and yod dropping are then left to be accounted for.

8.6.2.1 L-vocalisation

L-vocalisation involves some sort of loss or reorganisation of the apical gesture (in more open approximation) in the relatively weak coda position, leaving a vocalic portion similar to the secondary articulation of a typical non-vocalised lateral. Under a [P]/[R] analysis, the [P] attribute is associated with the (primary) apical gesture in English [l], while the [R] attribute is associated with the (secondary) dorsal gesture. L-vocalisation therefore leaves the phonetics associated with the [R] attribute intact at the rime level; the phonetics associated with the [P] attribute (at the coda level) appears to be lost. L-vocalisation could also be analysed as a case of attributes which are at a level in the prosodic hierarchy which is a head (e.g. the rime) being more persistent than attributes found at a non-head level (e.g. the coda). However, the presence of apical closure for [l] in ambisyllabic contexts suggests that no phonological attributes are being lost; there is merely a variation in phonetic interpretation in different structural contexts.

8.6.2.2 Labiodental r

Labiodental r, [ʋ], involves a labial gesture which is different from the labial gesture in the canonical English postalveolar approximant, but a labial gesture nonetheless. The 'primary' tongue gesture seems to be in increasingly open approximation. The [P] attribute is associated with the apical gesture in English [r] (I use the broader transcription at this point in order to generalise over [ɹ] and [ʋ]), while the [R] attribute is associated with the labial gesture. In a similar fashion to the phenomenon of l-vocalisation, then, labiodental r leaves the phonetics associated with the [R] attribute intact; the phonetics associated with the [P] attribute appears to be lost, or in the process of being lost. Tantalisingly, labiodental r appears to be prevalent in nonrhotic varieties rather than in rhotic varieties, and particularly in those varieties where [l] is relatively clear and [ɹ]/[ʋ] relatively dark. Despite both l-vocalisation and labiodental r being possible instances of change in dark liquids (rather than clear liquids) it is not possible (in British English) to speculate on any possible structural explanation since the geographical distance of the rhotic varieties (north and west Britain) from the hotbed of labiodental r (and, indeed, l-vocalisation) in the south-east of England suggests a typical sociophonetic change (Foulkes & Docherty, 2000) with geographical diffusion in progress.

8.6.2.3 Yod dropping

An analysis of English yod involves a departure from the biuniqueness principle in phonetic interpretation: with the Firthians, I see no need for a one-to-one mapping between items of phonology and items of phonetics. In this precise case, it may be possible to agree with

Mitchell (1969:162) in challenging Abercrombie's (1967:62) comment that 'it would be meaningless to describe ... a *palatal* consonant as being at the same time *palatalised*'. If both the [P] attribute, [**P**:*δ*], and the [R] attribute, [**R**:*y*], are associated with a palatal gesture (which is in accord with the associations of [**P**:*δ*] — tongue body raising — and [**R**:*y*] — clearness — elsewhere) then yod-dropping could also be analysed as loss of the association with the [**P**] attribute, leaving the phonetics associated with the [**R**] attribute. If yod dropping is really the (phonetic) dropping of yod, then this analysis is problematic, since the [**R**] attribute as well as the [**P**] attribute would be left with no phonetic exponents. However, if the [**R**] attribute continues to have phonetic exponents, then this analysis would predict a continuing phonetic presence similar to yod, but perhaps more subtly present in the speech signal. This prediction is supported by Kelly & Local (1989:139-140) who discuss data from a Norfolk speaker who, instead of deleting yod, re-phases articulatory gestures so that contrasts are marked by relatively front and back resonances across the syllable, so *do* [dəʉ] versus *dew* [d̩əʉ̟] ([d̩] is the symbol Kelly & Local use for [d] with clear resonance: pp.72-74). Nevertheless, even if the [**P**]/[**R**] analysis could account for yod-dropping, it could not form part of the overall analysis as previously outlined, since the location where yod-dropping occurs is analysed as /C + iw/ rather than /Cj + uː/.

8.6.2.4 Variation in [w]

A [**P**]/[**R**]-type analysis can therefore provide a step towards an account of l-vocalisation, labiodental r and, possibly, yod dropping by the same effect: loss of phonetic exponents associated with the [**P**] attribute. No predictions have yet been made with respect to the remaining member of the set of liquids and glides: [w].

If loss of exponents associated with the [**P**] attribute is a general characteristic of variation and change in the glide and liquid system, then this analysis predicts that there should be evidence of similar effects in [w]. This would presumably involve weakening in some sense of the tongue gesture (associated with [**P**: *δ*]) leaving the lip gesture (associated with [**R**:*w*]). I am not aware of reports in the literature of change in English [w] to [β]; however, there do seem to be hints of just such a variation in a recently published corpus (Grabe *et al.*, 2000) which contains data from (amongst several others) Newcastle speakers who speak a very similar variety to the Sunderland speaker in this study. Speaker JW, for example produces the following for a turn-initial *well*:

[βɛ̞̜'lᵋ]

Similarly, speaker SB produces a token of *as well* thus:

[əzʷβᷪə̟̜'lᵊ]

Another non-velarised labial turns up with speaker EP, who produces the following as part of *[underst]and why erm*:

[a̠ˤnᷪ·dʷʊɑ̟e̠ɛ̠̜ʷmᷪˡ]

By no means do these speakers produce such tokens on every occasion; moreover, all these instances precede vowels with some front element and may therefore be assimilatory in nature. Nevertheless, all of these tokens are instances of a reduction in prominence of the dorsal gesture in [w] which the analysis presented here associates with [P:δ], and are more easily explained by a [P]/[R] analysis than a more traditional analysis with features such as [labial], since [labial] would be maintained in [w] but lost in [ɹ]. (An analysis in which labiality in [w] behaves differently from labiality in [ɹ] would be supported by Brown, 1981, who observes that lip rounding in [w] is not the same as lip rounding in [ɹ]).

Given that in contemporary English, the phonetics of the [P] attribute seems to be more susceptible to weakening than the phonetics of the [R] attribute, it might be suggested that if there is a primary aspect of these phonologies, it is the [R] attribute rather than the [P] attribute which is phonologically primary. A similar distinction between phonetically primary and secondary articulations (defined in terms of degree of stricture) and their phonological function has been suggested by Sagey (1988), following Anderson (1976): phonological values are not phonetically determined but can only be inferred through relationships.

8.7 [P], [R] and polysystems

In this section I will briefly discuss some of the consequences of an analysis incorporating abstract [P] and [R] attributes on the issue of polysystems.

8.7.1 Variability in the exponency of polysystems

The phonetic data presented in Chapters 6 and 7 do not tell a consistent story where ranges of variability in resonance quality are concerned. Across both positions in the syllable, each speaker seems to vary (Section 6.1.3). However, when more data is taken into account, it seems to be the case either that dark liquids vary more than clear liquids (Section 7.3.2), or that initial [l] coarticulates more than initial [r] (Section 7.3.1).

The issue of polysystems arises when rhotic and non-rhotic varieties are compared. Rhotic varieties have two values for [P] and [R] wherever they occur in the syllable; non-rhotic varieties only have one liquid in syllable-final position. A neo-Firthian analysis incorporating polysystems (such as Ogden, 1997a,b, 1999b) along with differentiation (Section 8.2.3) would predict greater variability where there are fewer terms in the system; that is, the liquid which coarticulates most in nonrhotic varieties should be final [l]. This does not appear to be the case in the data presented in this dissertation. More work is therefore required in this area.

8.7.2 [R]-harmony: long-domain polysystems

The motivation for this study began from observations regarding the long extent of resonance qualities associated with both laterals and rhotics in English (Kelly & Local, 1986, 1989; later extended by Tunley, 1999, West, 2000, and Heid & Hawkins, 2000). These long-extent phonetic phenomena appear to be related to acme articulations (Kelly, 1989) and the precise details of extents may vary from variety to variety.

Under a [P]/[R] analysis, such effects can be viewed as an instance of harmony: [R]-harmony, which may be found where [R] is in combination with [P:α], associated with an acme articulation which, presumably will be defined in prosodic terms (e.g. in a strong syllable).

The precise domains of these harmonic effects remain to be investigated, though they have the potential to be remarkably long (Heid & Hawkins, 2000).

Long-domain harmony of this sort is associated with both laterals and rhotics (since they are in system) and is dependent upon a phonological analysis in which attributes for resonance are separate from attributes for place. The [P]/[R] analysis is therefore well-suited to data such as these. [R] is separate from vocalic attributes (allowing, for example, a [grave] vowel to become somehow more [grave], as mentioned in Section 8.5.2). Similarly (Section 8.5.2), [P] is separate from place of articulation attributes in general.

8.7.3 How many phonologies?

In a polysystematic approach to phonology, it is legitimate to raise the question whether both [P]/[R] and [cns]/[voc] analyses might be tenable. There may be no *single* phonology of English; only a collection of subphonologies which account for phenomena from a range of viewpoints. My approach is to assume difference until similarity can be demonstrated. An analysis of English liquids in terms of cross-dialectal variation, such as [P] and [R] in singleton liquids, might not look the same as an analysis of English liquids in terms of phonotactics, such as an analysis of complex onsets. Much as the neo-Firthian declarative tradition allows for different phonologies for different word-classes (Simpson, 1992b; Ogden, 1999b) or even pieces of phonetics which have no phonology (such as certain loanwords: Kelly & Local, 1989:233), so there may be different phonologies for the same phenomenon taken from different viewpoints.

It is also possible that listeners perceive and build their own phonological analysis in this way, without necessarily having a single overarching phonology but rather having a distributed collection of phonologies appropriate for different structures.

While such a polysystematic approach may be appealing, it is also remarkably unconstrained. How is it possible to know, with so many sub-phonologies, what a coherent 'phonology of English' might look like? In fact, the analysis is tied down in renewal of connection with the data: what I have presented is part of a phonology of English because the data set analysed is English.

8.8 Conclusion

In this chapter I have endeavoured to show how a declarative and non-segmental analysis of liquids in English can account for the purely phonological data associated with distributions and systems of contrast while retaining a systematic link to the details of the phonetics in a number of varieties of English as reported in previous chapters.

The analysis involving consonantal and vocalic fields developed for YorkTalk and its successor systems is powerful and can handle the relevant phonological data, although it predicts the existence of more bundles of attributes than do in fact occur. I have proposed a more abstract analysis involving attributes which I have labelled **[P]** and **[R]**, which are characteristically associated with the phonetically primary articulation and the resonance quality of liquids and glides.

While the [P]/[R] analysis is not as appropriate as the [cns]/[voc] field analysis for the description of synchronic distributional data, particularly in the case of complex onsets, it does account for the relationships between singleton liquids and glides without predicting more combinations of attributes that actually occur; it can also account for certain contemporary phenomena in the realm of cross-dialectal variation and change (by the mechanism of loss of the [P] attribute, leaving the [R] attribute intact) and for the phonetic data relating to the phasing of gestures in liquids. It is the fundamentally abstract nature of the phonological categories which enables such an analysis.

9 Concluding remarks

9.1 Summary of the dissertation

In this dissertation, I have sketched a declarative, non-segmental and polysystemic account of cross-dialectal variation in the resonance quality associated with liquids in British English. I have argued for an abstract phonology which is related to its phonetic exponents through extrinsic phonetic interpretation, loosening the association often adopted between articulatory categories and the phonology. The cross-dialectal data suggests that there is more variability in the phonetics than a universalist intrinsically-interpreted phonology might allow: if some phonetic phenomenon is not obligatory, there must be an element of learning involved.

In examining the interface between phonetics and the phonological categories I have endeavoured to show that there is a requirement for an understanding of detailed phonetics in appropriate phonological contexts in order to make sense of individual and varietal differences.

I have aimed to produce a phonologically-informed phonetic analysis and a phonetically-informed phonological analysis based on experimental data and to relate these quantitative findings to impressionistic descriptions of clear and dark resonance.

I have demonstrated the usefulness of cluster analysis as an exploratory data technique, and of classification and regression trees as knowledge-driven statistical methods for interrogating a database. I have also developed the technique of spectral moments analysis to incorporate a dynamic spectral filter which tracks formant frequencies sample by sample in order to shed more light on the detail of analytically relevant portions of the spectrum.

Liquids are complex articulations which have some of the nature of consonants and some of the nature of vowels. Laterals in English in particular are commonly identified as having secondary articulation. Such quasi-vocalic articulation overlaid on consonantal articulation results in auditory distinctions traditionally termed resonance. Resonance in this sense is not just associated with laterals but also with rhotics. Moreover, it is differentially associated with the liquids in different varieties. The major acoustic difference between [l] and [r] is the frequency of F3, but other aspects of the acoustics contribute to the perceptual coherence of liquids. Clear and dark resonance is primarily associated with variation in F2 (with F1 acting to enhance darkness in certain circumstances). I have confirmed polarity effects across the varieties: for nonrhotic varieties, one liquid is clear and the other is dark (clear [l] and dark [r] — as in Sunderland — or dark [l] and clear [r] — as in Manchester). However, for rhotic varieties, the absolute clearness or darkness of the liquids matters less: instead, the relativities between the liquids are important. However clear or dark the initial lateral, it is clearer than the initial rhotic. In syllable-final position, the lateral is relatively dark and the rhotic relatively clear. Phonetic interpretation is therefore dependent on the (potentially nonlocal) phonological systems which obtain in the language. It is not simply structure-dependant (in an intrinsic fashion) but also variety-specific.

F2 shows the polarity effects both in the (spectral) trajectory of the formant and also in the temporal domain: transition and steady state durations vary in a similar fashion across the varieties. Darkness appears to be associated with relatively early dorsal displacement. F1 and F3, on the other hand, are employed more straightforwardly to differentiate laterals from rhotics. Where there is cross-dialectal variation in these formants, the effect is one of magnitude (one variety has a greater difference between the two liquids than the other variety) rather than one of polarity. The F2-F1 space is identified as increasing robustness with respect to F2 both across speakers and in statistical analysis. It can also be employed to explain what appears to be enhancement of extreme darkness (in laterals in appropriate varieties) where F1 is raised in a situation in which F2 has reached a minimum.

I have identified some evidence of anticipatory coarticulation in onset liquids (particularly laterals) due to the tautosyllabic vocoid. Perseveratory coarticulation from the liquid into the vocoid is identifiable in many contexts but is not statistically significant. However, given evidence from elsewhere of resonance effects extending over quite sizeable portions of the speech signal, the effect discussed in this dissertation may still contribute to the perceptual coherence of the signal. It is likely that the resonance effect's prominence is attenuated by the fact that the vocoids investigated are in strong syllables.

Some other differences in the strategy for producing liquids are identified, such as the Manchester speaker having relatively long transitions and relatively short steady states while the Sunderland speaker has relatively short transitions and relatively long steady states.

The difference between the patterns evident in rhotic varieties and those evident in nonrhotic varieties can be accounted for by a polysystemic principle of differentiation of phonological categories in the phonetic space. Where there is contrast between laterals and rhotics, the phonetic resource of resonance (which is available to the speaker in addition to the primary articulatory difference between laterals and rhotics) can be employed to enhance the distinction between members of the two categories. This has the consequence that the phonetic patterns in rhotic varieties are more restricted than those in nonrhotic varieties, since more contrastive distinctions need to be maintained.

The variation in resonance polarity is accounted for by an abstract and non-segmental phonology based around two attributes, which I have labelled **[P]** and **[R]**. **[P]** has as its exponents the primary articulation of the liquids; **[R]** has as its exponents clearness and darkness (and the articulations associated with those resonance qualities). I propose that the instances of **[P]** and **[R]** which are associated with prevocalic liquids are located at onset level. Postvocalic liquids are handled with an instance of **[R]** at rime level and an instance of **[P]** at coda level. While some generalisations pertaining to other consonants are lost in comparison to alternative declarative representations, the **[P]**/**[R]** analysis does account parsimoniously for variation data associated with liquids (and, additionally, glides) in English (particularly gestural phasing in the rime and cross-dialectal variability in phasing in the onset), and may be able to be extended to account for contemporary instances of variation and change in liquids and glides.

9.2 Some implications

9.2.1 Speech perception

Tunley (1999), West (1999) and Heid & Hawkins (2000) have demonstrated that long-extent resonance effects are important for perception, at least in standard southern British English. If resonance characteristics add to the perceptual coherence of the speech signal, then perceptual models need to be able to incorporate the phonetic dependencies which have been identified over long temporal extents and across different positions in hierarchical phonological structure.

If a perceptual model encodes the fact that resonance is used to differentiate liquids but not the direction in which that differentiation obtains (since, for example, it is one way round for Manchester English and the other way round for Sunderland English), it must be based on a phonology without intrinsic phonetic content. Phonological categories are then purely relational rather than concrete. This approach could sit well with episodic memory (Goldinger, 1997; Johnson, 1997; Pisoni, 1997), exemplar (Hintzmann, 1986, 1988; Nosofsky, 1988) or adaptive resonance (Grossberg, 1986; Boardman *et al.*, 1999; Grossberg *et al.*, 1997; Grossberg & Myers, 2000) models of perception which incorporate top-down processing, since phonetic detail is not discarded but rather is used to relate individual tokens of speech to abstract categories. Acoustic resonance characteristics increase robustness in noise (Tunley, 1999; Heid & Hawkins, 2000; Ogden *et al.*, 2000) and could contribute to reducing the search space for exemplars.

The contemporary interest in exemplar models in part arises from a dissatisfaction with traditional 'abstract' phonologies. In this dissertation I have argued for an abstract phonology, but a neo-Firthian declarative phonological approach of the sort presented here is made up of abstractness of a different order from that which is found in generative phonologies; it is ontologically distinct from the notion of abstractness in a procedural phonology. As in exemplar models of perception, the abstract categories are sets which describe linguistic objects; they are place-holders for the linguistic objects rather than the objects themselves. The polysystemic phonological representations countenanced by Firthian phonology bear a striking resemblance to the distributed multifunctional categories of exemplar models or episodic memory.

Since the aspects of acoustic resonance identified in this dissertation are spread over a relatively short extent in the speech signal while others occur over a much larger extent, questions must be raised as to the adequacy of the segment or phoneme as phonological units to be accessed in perception. Admitting phonological attributes at non-terminal node levels in the prosodic hierarchy has the consequence that perceptual models need to look to variable-domain phonology, perhaps with short-term memory interacting with activations associated with short-extent phonetics to produce virtual long-extent windows within which acoustic resonance characteristics could be detected. This conclusion complements the two-component model of liquid resonance proposed by Heid & Hawkins (2000) and the relationship between short-term events and the cumulative effect of distributed information discussed by Hawkins

& Smith (2001). See also Pöppel (1997) on the possibility of perceptual windows of up to around 3 seconds in duration.

9.2.2 The nature of phonology

Phonology in the Firthian tradition is formal and nominalist: no explicit claims are made to psychological reality; rather, phonology is a descriptive tool for the analyst. However, it does seem that recent advances in the field of speech perception mean that abstract categories with detailed phonetic exponents (exemplar models) coupled with polysystems (distributed memory) may indeed also be legitimate analytic tools for phonology in the realist sense, i.e. what users of language do in their heads.

The implications outlined in Section 9.2.1 may therefore require a clarification of precisely what is being studied in the discipline of phonology. From the perspective of speech perception, each individual perceiver has their own phonology. This is also the case if the claims of articulatory phonology are taken seriously, since the atoms of phonology are gestures: different speakers employ different gestures and hence have different phonologies. Is a panlectal phonology therefore a legitimate aim, or even possible?

I have shown in this dissertation that cross-dialectal studies can reveal important information about the relativities involved in phonological categories. If resonance is encoded in terms of difference but not with intrinsic directionality, then not only do the categories become more robust (since more phonetic information is used to aid perception) but also cross-dialectal communication is facilitated (since the phonetics associated with those categories may vary in certain structurally-definable ways). As a result, panlectal phonology continues to be a useful approach for the analyst but it also provides an insight into worthy areas of investigation in the realms of psycholinguistics and neurolinguistics.

9.3 Directions for further research

Some of the experiments carried out for this dissertation used a large number of tokens (resulting in a remarkable stability in some of the results). Nevertheless, the small number of speakers used is a weakness. A clear direction for future research is therefore to test the predictions made by my analysis on a larger number of speakers in order to ascertain whether any of the differences I have identified are idiolectal rather than dialectal in nature. Perhaps, also, a wider range of varieties of English could be investigated, such as rhotic Lancashire (which would test the claims I have made with regard to rhotic varieties since it is geographically so close to the Manchester nonrhotic variety I have discussed).

An extended data set is also possible: although the number of tokens used in these experiments was high, they come from restricted metrical contexts. Future work, particularly with ambisyllabic liquids (which are thought to share some of the nature of both onset and rime liquids) could shed further light on how the claims I make in this dissertation relate to analyses such as that provided by Tunley (1999) and Gick (to appear). Wider metrical contexts will enable refinement of the phonological analysis which uses a unified prosodo-melodic structure, with phonological attributes distributed around the hierarchy.

I have made indirect claims about the phasing of articulatory gestures based on an interpretation of acoustic data. Another extension of this research is therefore articulatory analysis. The most pressing requirement is for EMA investigations which could speak to my discussions of the work of West (2000) and Sproat & Fujimura (1993).

Future research will also clarify issues regarding language variation and change in contemporary British English. Innovating tendencies in the liquid system include loss of tongue-tip contact both in vocalised [l] and in labiodental [r]. In both these cases, what was once a secondary articulation related to consonantal resonance is now becoming the primary articulation. By achieving a greater understanding of the implication of resonance in variation and change in the liquid system, it will be possible to attempt a phonologically and phonetically-aware statement regarding these innovations.

In short, the methods and results of phonetic and phonological analysis presented in this dissertation have the potential to provide a detailed and extensive account of one of the more complex areas of phonological structure, variation and change: how resonance affects the part-consonantal and part-vocalic liquid system of British English.

Appendix 1: The bark scale

There are two main justifications for using bark scaled data (based on the critical bandwidth: Zwicker et al., 1957; Zwicker, 1961) in spectral analysis such as that presented in this dissertation: one theoretical-phonetic, and one statistical.

From a theoretical perspective, the bark scale is designed to represent the tonotopic outputs of filters in the ear and hence is a useful starting point in modelling how hearers may analyse the speech signal which they receive. Bark scale measurements (particularly bark difference) may be robust across speakers of differing ages and sexes (Syrdal & Gopal, 1986; Traunmüller, 1988), and therefore provides a motivated distance metric suitable for statistical exploration.

However, there must be a small note of caution: we cannot be absolutely sure that the bark scale is an accurate representation of what goes on on each person's basilar membrane.

Equivalent rectangular bandwidth (ERB) representations (Moore & Glasberg, 1983) take into account temporal analyses performed on the speech signal by the brain at low frequencies. For this reason, they may give a more accurate reflection of the ear's activity but, for dynamic analyses, they introduce possible errors in that time is modelled twice (effectively once on each axis for a frequency/time plot): see Traunmüller (1990). Temporal analyses are important for hearing up to around 500 Hz; above this level, the bark scale and ERB rate are proportional to one another.

The standard rounded bark scale is based on empirical observations from loudness summation experiments. A number of equations have been proposed which produce approximations to the bark/Hertz curve. The most prominent of them are laid out in Table 51. The equation in Fourcin *et al.* (1977) — equation A2 — is credited in that text to unpublished work by Schroeder. Equation A3 (Schroeder *et al.*, 1979) has been referenced to Fourcin *et al.* (1977) but is, in fact, not found there.

Traunmüller's (1983, 1988, 1990) approximation (equation A8) is accompanied by low and high frequency corrections. The low frequency correction ensures that the curve more closely approximates the standard rounded values, although Traunmüller (1990:99) claims that the uncorrected form more closely approximates the actual empirical data at low frequencies. The high frequency correction simply corrects inaccuracies in the general equation above bark values of $z = 20.1$. Both corrections are included in the comparisons in Table 56 and the plot in Figure 124.

In Table 52, each of the equations in Table 51 is used to provide approximations to each reference point on the standard bark/Hertz curve. These standard reference points are reproduced in the first column of Table 52. The figures in the remaining columns of Table 52 allow comparison between the approximation equations and justify the selection of Traunmüller's (1983, 1988, 1990) equation (A8) for Hertz to bark conversion.

Author		**Equation**
Tjomov (1971)	(A1)	$z = 6\cdot 7\sinh^{-1}\left(\frac{f-20}{600}\right)$
Fourcin *et al.* (1977):	(A2)	$z = 6\sinh^{-1}\left(\frac{f}{600}\right)$
Schroeder *et al.* (1979):	(A3)	$z = 7\sinh^{-1}\left(\frac{f}{650}\right)$
Terhardt (1979):	(A4)	$z = 13\cdot 3\tan^{-1}\left(\frac{0\cdot 75f}{1000}\right)$
	(A5)	$z = 12\cdot 82\tan^{-1}\left(\frac{0\cdot 78f}{1000}\right) + 0\cdot 17\left(\frac{f}{1000}\right)^{1\cdot 4}$
Zwicker & Terhardt (1980):	(A6)	$z = 13\tan^{-1}\left(\frac{0\cdot 76f}{1000}\right) + 3\cdot 5\tan^{-1}\left(\frac{f}{7500}\right)^{2}$
	(A7)	$z = 8\cdot 7 + 14\cdot 2\log_{10}\left(\frac{f}{1000}\right)$
Traunmüller (1983, 1988, 1990):	(A8)	$z = \frac{26\cdot 81f}{1960+f} - 0\cdot 53$
low frequency correction:		*if* $z < 2,\ z' = z + 0\cdot 15(2 - z)$
high frequency correction:		*if* $z > 20\cdot 1,\ z' = z + 0\cdot 22(z - 20\cdot 1)$

Table 51. Equations for approximation to the bark/Hertz curve (z in bark, f in Hertz and angles in radians).

From the figures in Table 52, it is clear that Traunmüller's approximation (equation A8) is the most suitable for speech analysis applications. From 100 Hz upwards, Table 52 shows that equation A8 is accurate to within ±0.1 bark. In fact, it is accurate to ±0.05 bark within that range. For most values, equation A8 provides the closest approximation of any of the equations and the pattern of shading in Table 52 shows that it is evidently the most consistently good performer across the full range of frequencies.

Equation A8 loses a small amount of accuracy around the low F1 range and the low F2 range, but otherwise the F1 - F4 region is very well represented. Difficulties at very low frequencies are more apparent than real, since formants are not found at such low frequencies in speech.

In the low F1 and F2 region, the closest challengers to equation A8 are equations A1 (Tjomov, 1971), A3 (Schroeder *et al.*, 1979) and A5 (Terhardt, 1979). None of these are as accurate as A8 from the high F2 region upwards.

It is therefore Traunmüller's approximation (equation A8) which is used in this dissertation.

Figure 73 plots Bark-transformed frequency (as approximated by Traunmüller's equation) against frequency in Hertz. The correlation between the set of rounded empirical values and Traunmüller's approximation of those values is above 0.9999.

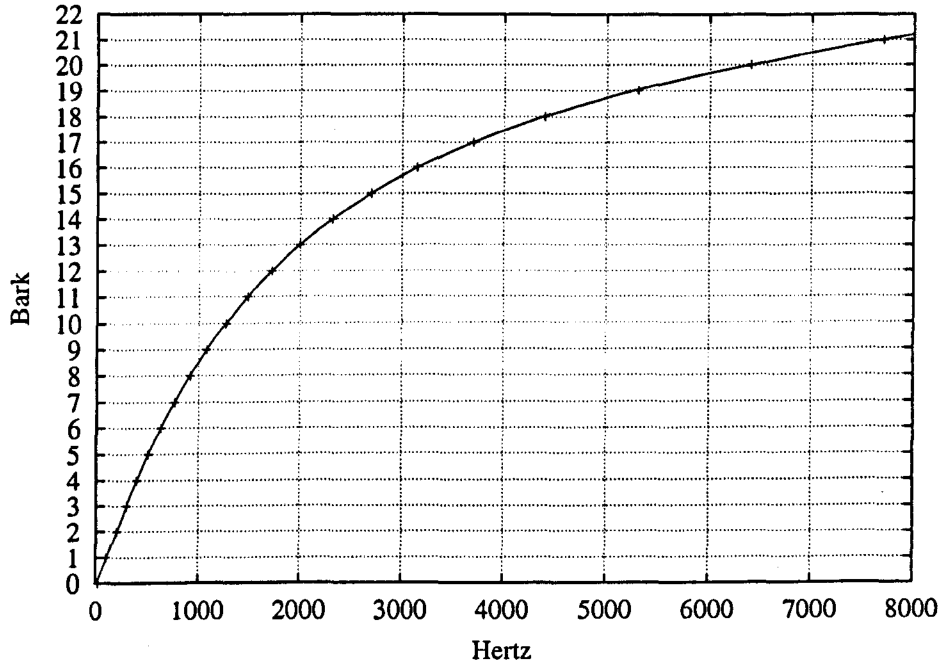


Figure 73. Plot of bark-transformed frequency against frequency in Hertz. Crosses represent points on the empirical rounded Bark scale.

Bark scale (rounded)	**Frequency (Hertz)**	**Approximations**							
		(A1)	(A2)	(A3)	(A4)	(A5)	(A6)	(A7)	(A8)
0	0	-0.223	**0**	**0**	**0**	**0**	**0**	—	-0.151
1	100	0.891	0.995	1.073	**0.996**	1.005	0.987	-5.500	0.956
2	200	1.981	1.965	2.121	1.980	**2.002**	1.963	-1.225	1.960
3	300	3.023	2.887	3.126	2.943	**2.978**	2.920	1.275	3.029
4	400	**4.001**	3.751	4.074	3.876	3.924	3.847	3.049	4.014
5	510	**4.996**	4.627	5.044	4.859	4.920	4.823	4.547	5.006
6	630	5.984	5.498	6.016	5.871	5.944	5.830	5.851	**5.991**
7	770	**7.019**	6.409	7.043	6.965	7.052	6.920	7.088	7.032
8	920	**8.005**	7.279	8.028	8.033	8.131	7.985	8.186	8.034
9	1080	8.939	8.103	8.968	9.055	9.164	9.007	9.175	**8.995**
10	1270	9.918	8.968	9.960	10.122	10.246	10.080	10.174	**10.011**
11	1480	10.869	9.809	10.927	11.139	11.280	11.109	11.118	**11.005**
12	1720	11.821	10.653	11.901	12.121	12.289	12.115	12.045	**12.001**
13	2000	12.792	11.513	12.897	13.071	13.278	13.104	12.975	**13.010**
14	2320	13.758	12.371	13.892	13.954	14.218	14.047	13.890	**14.003**
15	2700	14.754	13.256	14.920	14.791	15.137	14.976	14.825	**15.004**
16	3150	15.772	14.162	15.973	15.566	16.030	15.888	15.776	**15.997**
17	3700	16.840	15.113	17.079	16.291	16.923	16.814	16.768	**16.996**
18	4400	**17.994**	16.141	18.277	16.978	17.856	17.803	17.837	18.018
19	5300	19.236	17.249	19.568	17.614	18.851	18.878	**18.985**	19.042
20	6400	20.498	18.375	20.880	18.160	19.889	19.987	20.148	**19.994**
21	7700	21.736	19.480	22.168	18.611	20.984	21.061	21.288	**21.003**
22	9500	23.143	20.738	23.635	19.037	22.392	22.178	22.584	**22.046**
23	12000	24.709	22.137	25.267	19.420	24.285	23.195	24.024	**23.047**
24	15500	26.424	23.671	27.056	19.750	26.967	**24.012**	25.603	23.968

Table 52. Comparison of the performance of the Hertz to bark approximation equations in Table 51. 10% grey shading indicates a value within 0.2 bark of the rounded bark scale values; 20% grey shading indicates a value within 0.1 bark of the rounded bark scale. Bold type identifies the equation which best approximates the rounded bark scale value at each point.

Appendix 2: Dummy lexemes

	front vowel context		**back vowel context**	
high vowel context	beam deem Eve heath heave Keith knee need neep niece sheaf thieve	Mick mitt nib nick Nidd nip sift sing sink wish	moon muse shoes spoof spoon tomb tooth	nook
mid vowel context	men said send sent when	mace maid make mane mate may name nave	fluff mug numb some sung gong knock knot mob moss song	cove gnome know moan node note poach probe shoal soap
low vowel context	hang mac mad map mash Max nags nap Pam pan sag sang swam	knife mice might mine my nice sighed sighs	fawn gnaw pawn paws sauce sawn tawn	

Table 53. Dummy lexemes used in recordings.

Appendix 3: Dendrograms

In the dendrograms below, clusters may be identified by drawing a horizontal line at any level, cutting through the vertical lines projected from the clusters. Tokens are listed horizontally at the bottom edge of the graph. The dissimilarity of the clusters is proportional to the length of the vertical lines projecting from each cluster.

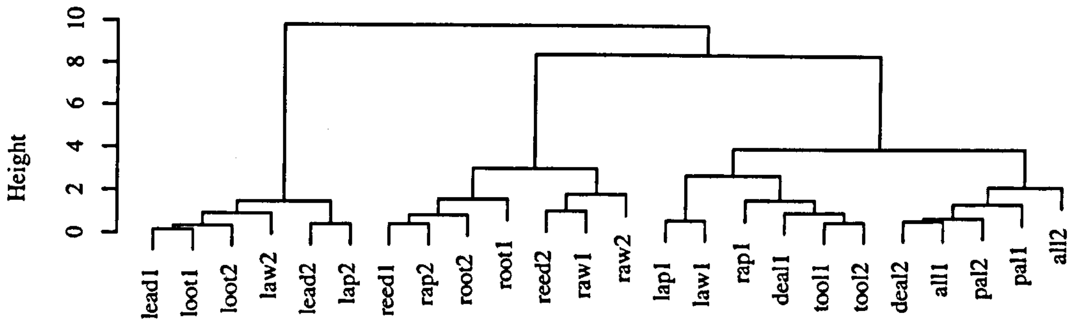


Figure 74. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Sunderland liquids (dimensions: F1, F2, F3).

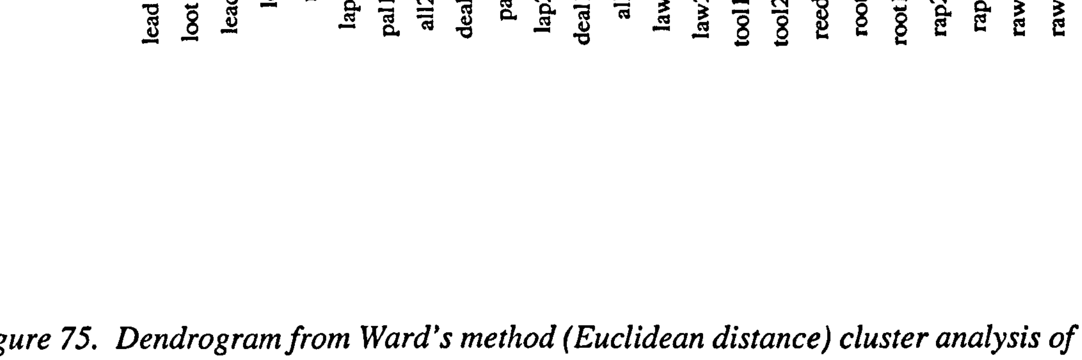


Figure 75. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Manchester liquids (dimensions: F1, F2, F3).

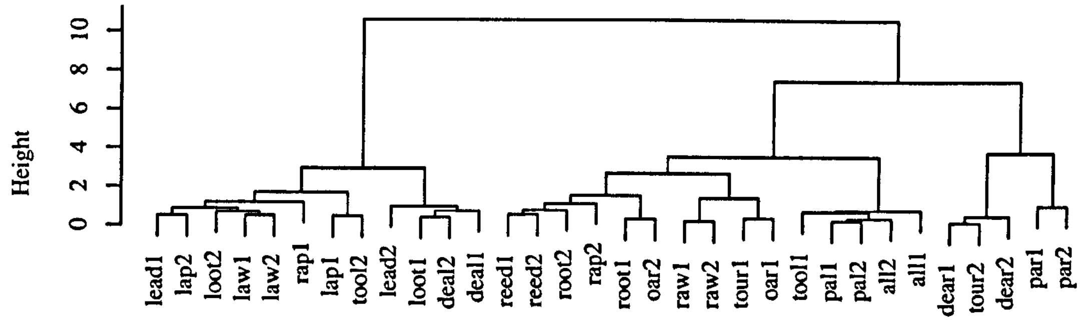


Figure 76. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Tyrone liquids (dimensions: F1, F2, F3).

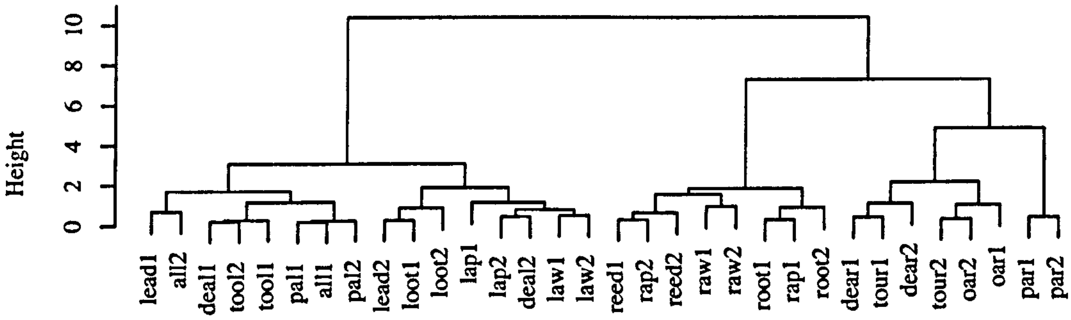


Figure 77. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Fife liquids (dimensions: F1, F2, F3).

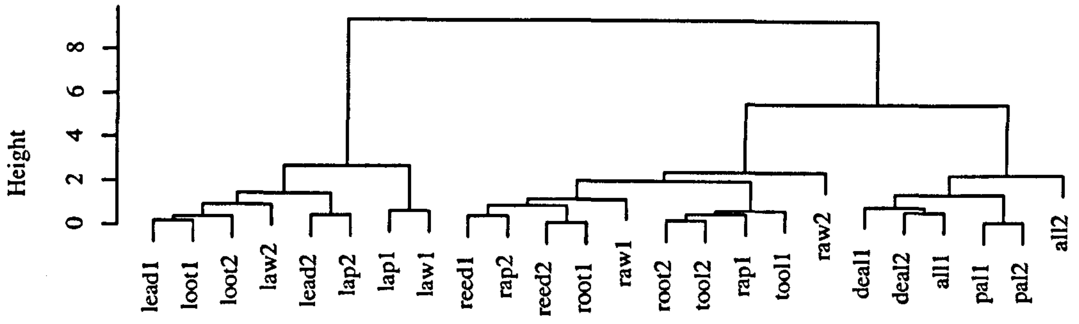


Figure 78. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Sunderland liquids (dimensions: F1, F2).

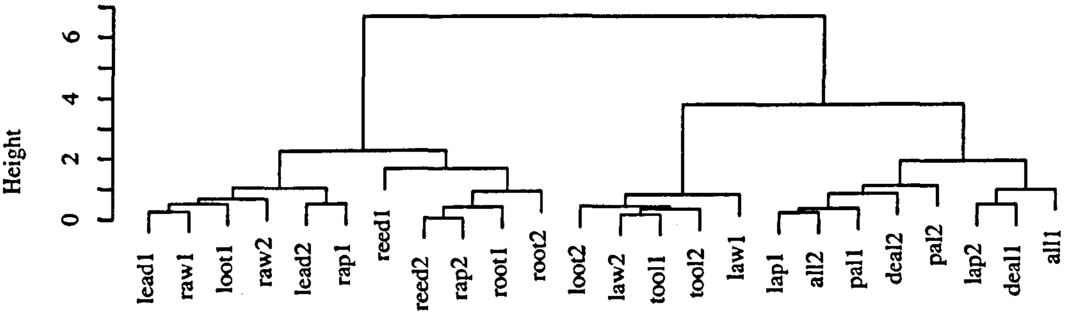


Figure 79. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Manchester liquids (dimensions: F1, F2).

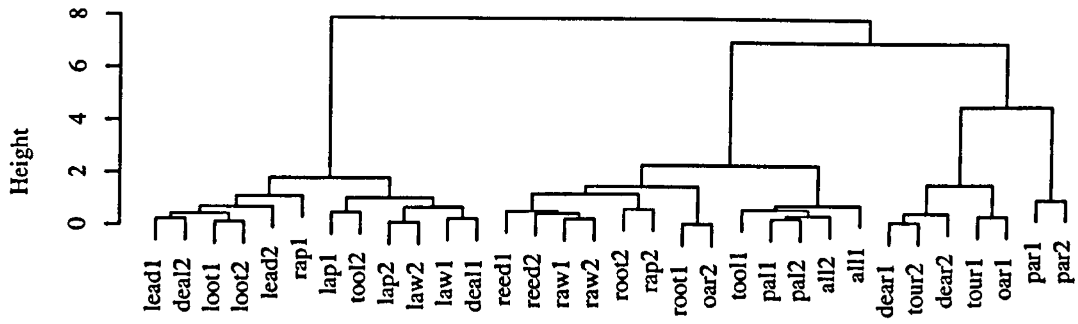


Figure 80. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Tyrone liquids (dimensions: F1, F2).

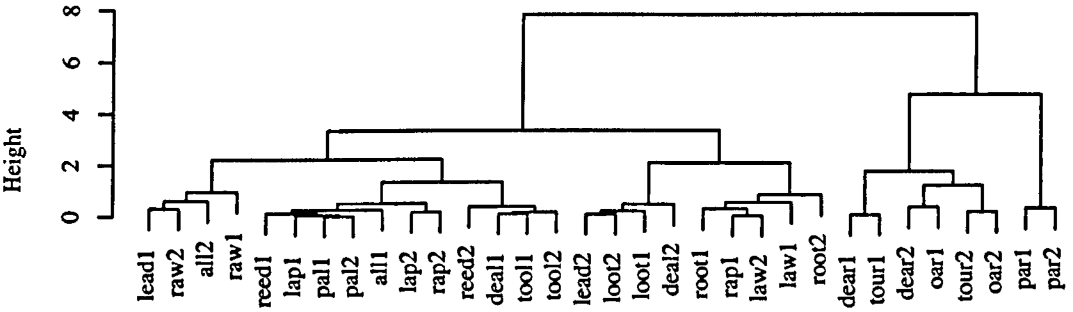


Figure 81. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Fife liquids (dimensions: F1, F2).

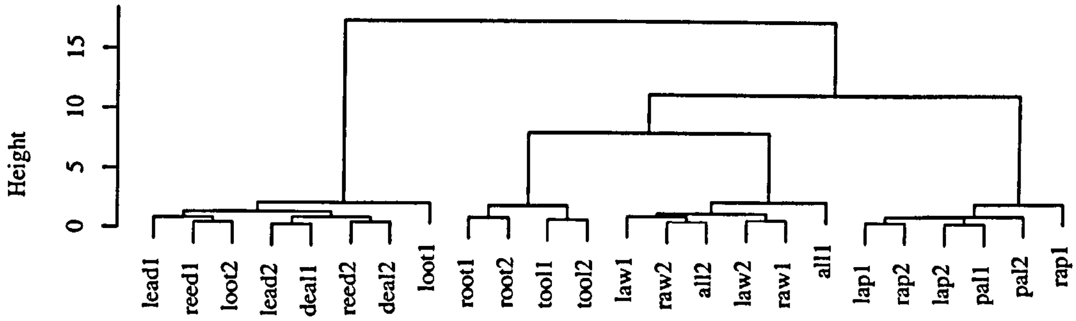


Figure 82. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Sunderland vocoids (dimensions: F1, F2, F3).

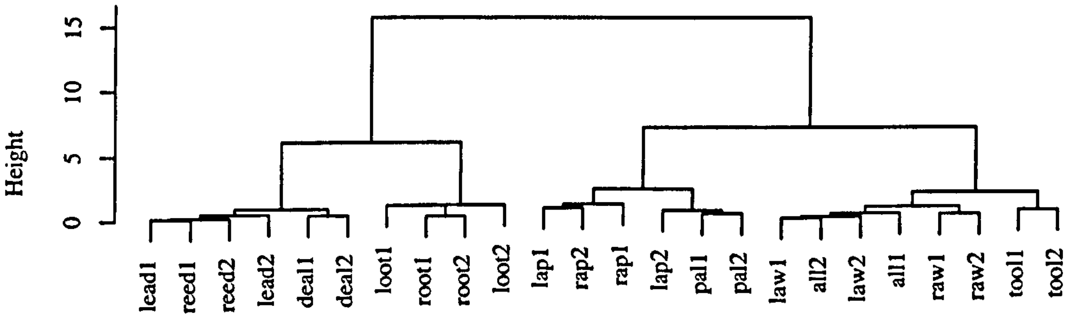


Figure 83. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Manchester vocoids (dimensions: F1, F2, F3).

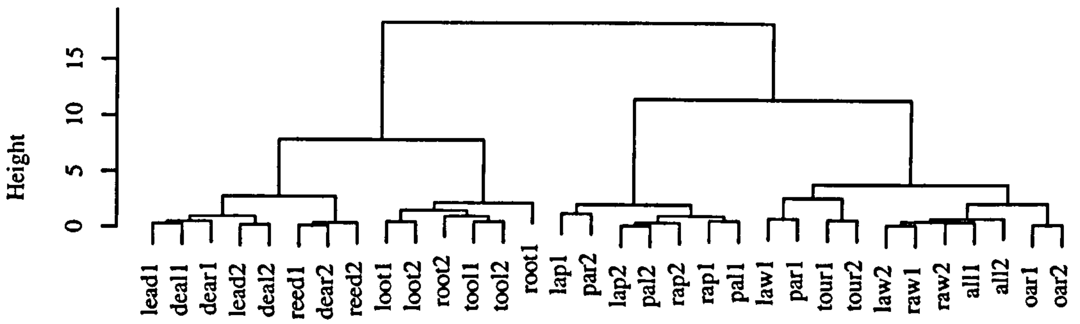


Figure 84. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Tyrone vocoids (dimensions: F1, F2, F3).

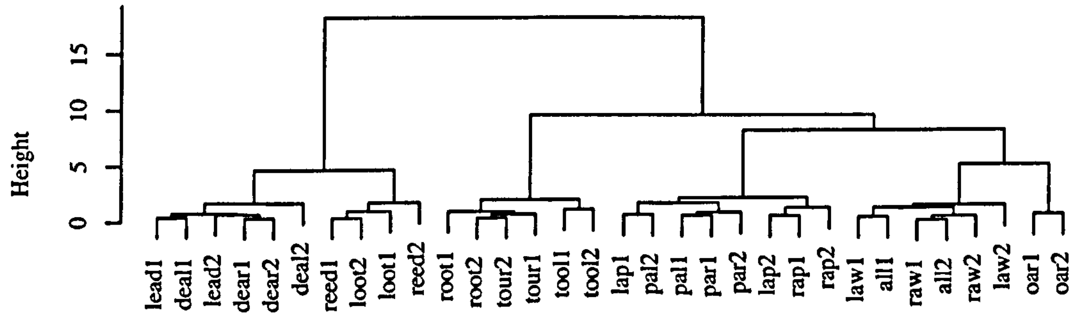


Figure 85. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Fife vocoids (dimensions: F1, F2, F3).

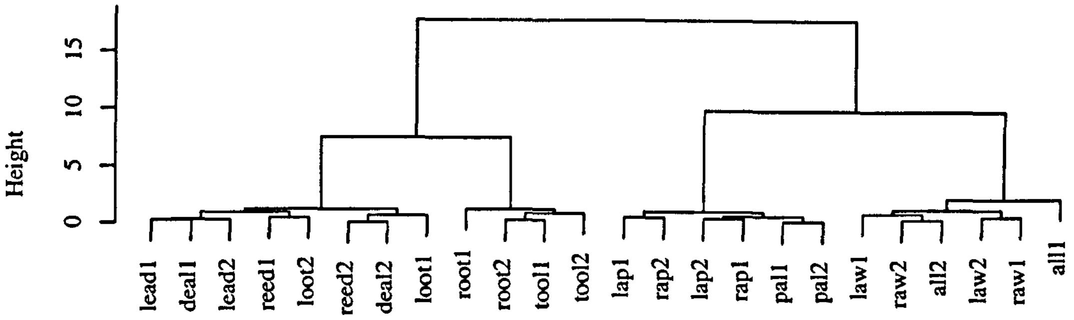


Figure 86. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Sunderland vocoids (dimensions: F1, F2).

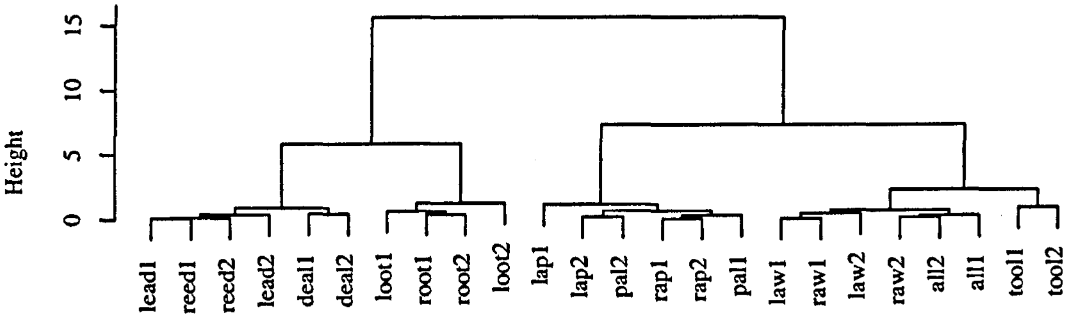


Figure 87. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Manchester vocoids (dimensions: F1, F2).

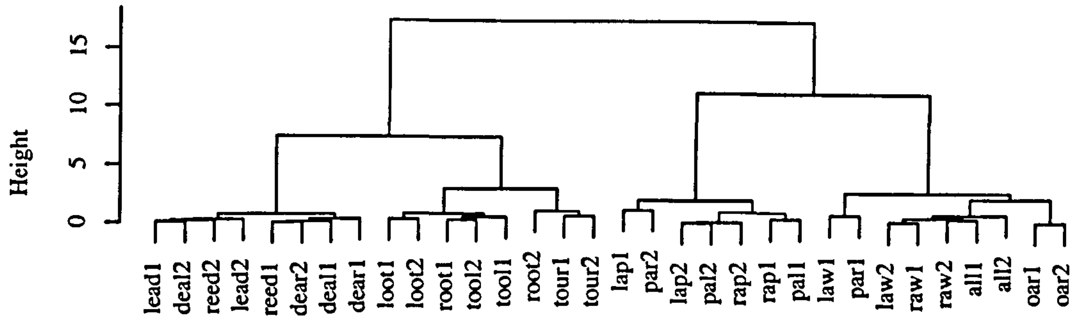


Figure 88. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Tyrone vocoids (dimensions: F1, F2).

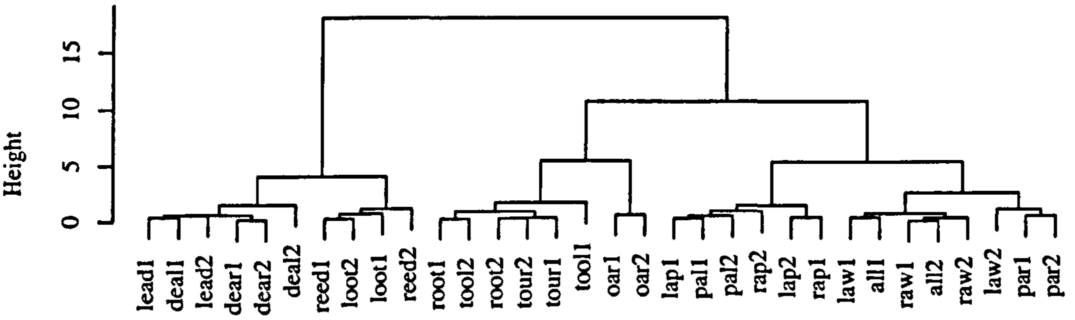


Figure 89. Dendrogram from Ward's method (Euclidean distance) cluster analysis of Fife vocoids (dimensions: F1, F2).

Appendix 4: Classification and regression trees

In each line of the classification tree, the first number identifies a node in the tree. Then follows text which identifies the split at that node (a value or range of values for the variable in question). Then comes the number of tokens identified by that decision, the deviance (a measure of node heterogeneity) and a value predicted for the response variable. Finally, there is a set of probability values. The four values for *p* give the probability that the node represents a Manchester [l], a Manchester [r], a Sunderland [l] or a Sunderland [r], respectively. A final asterisk indicates a terminal node.

Classification tree; midpoint of liquid steady state — see Figure 31 (p.173).

```
1) root 676 1874.00 Man.l ( 0.261834 0.245562 0.251479 0.241124 )
   2) f3 < 14.171 332  503.50 Man.r ( 0.006024 0.500000 0.006024 0.487952 )
     4) f2 < 8.786 121   59.23 Sun.r ( 0.008264 0.049587 0.000000 0.942149 ) *
     5) f2 > 8.786 211  260.00 Man.r ( 0.004739 0.758294 0.009479 0.227488 )
      10) f1 < 2.8615 72  107.30 Sun.r ( 0.013889 0.416667 0.000000 0.569444 )
        20) f2 < 9.5235 37   29.31 Sun.r ( 0.000000 0.135135 0.000000 0.864865 ) *
        21) f2 > 9.5235 35   48.38 Man.r ( 0.028571 0.714286 0.000000 0.257143 ) *
      11) f1 > 2.8615 139   76.21 Man.r ( 0.000000 0.935252 0.014388 0.050360 )
        22) f2 < 9.3435 35   35.03 Man.r ( 0.000000 0.800000 0.000000 0.200000 ) *
        23) f2 > 9.3435 104   19.77 Man.r ( 0.000000 0.980769 0.019231 0.000000 ) *
   3) f3 > 14.171 344  489.00 Man.l ( 0.508721 0.000000 0.488372 0.002907 )
     6) f2 < 9.5775 183   89.88 Man.l ( 0.939891 0.000000 0.054645 0.005464 )
      12) f3 < 14.947 23   38.54 Man.l ( 0.521739 0.000000 0.434783 0.043478 ) *
      13) f3 > 14.947 160    0.00 Man.l ( 1.000000 0.000000 0.000000 0.000000 ) *
     7) f2 > 9.5775 161   29.84 Sun.l ( 0.018634 0.000000 0.981366 0.000000 ) *
```

In the following regression trees, the lines follow a pattern similar to the classification tree above, with the exception that there are no probability representations. In their place, after each regression tree I give the results of unpaired two-tailed t-tests carried out on each of the binary splits identified in the tree.

Regression tree for F2 (bark); midpoint of liquid steady state — see Figure 32 (p.175).

```
1) root 676 1006.00  9.249
   2) Variety: Manchester 343  273.20  8.975
     4) Liquid: l 177   63.94  8.297
       8) height: low,mid 116   21.50  8.018 *
       9) height: high 61   16.20  8.828 *
     5) Liquid: r 166   41.28  9.697 *
   3) Variety: Sunderland 333  680.50  9.532
     6) Liquid: l 170   87.49 10.690
      12) height: low,mid 110   58.76 10.490 *
      13) height: high 60   16.62 11.050 *
     7) Liquid: r 163  131.30  8.330
      14) length: long 86   62.05  8.569 *
       15) length: short 77   58.82  8.063 *
```

nodes tested	t	df	*p*
2 & 3	6.0937	674	<0.0001
4 & 5	23.3362	341	<0.0001
6 & 7	26.4319	331	<0.0001
8 & 9	11.0365	175	<0.0001
12 & 13	5.1954	168	<0.0001
14 & 15	3.7204	161	0.0003

Regression tree for F2-F1 (bark); midpoint of liquid steady state — see Figure 33 (p.176).

```
1) root 676 1409.00 6.118
   2) Variety: Manchester 343  582.60 5.572
     4) Liquid: l 177  159.40 4.561
       8) height: low,mid 116   46.20 4.034 *
       9) height: high 61   20.05 5.561 *
     5) Liquid: r 166   49.40 6.650 *
   3) Variety: Sunderland 333  618.70 6.681
     6) Liquid: l 170  169.50 7.590
      12) height: low 43   55.95 6.792 *
      13) height: high,mid 127   76.95 7.860 *
     7) Liquid: r 163  162.10 5.733 *
```

nodes tested	t	df	*p*
2 & 3	10.8014	674	<0.0001
4 & 5	24.7064	341	<0.0001
6 & 7	16.9257	331	<0.0001
8 & 9	15.6879	175	<0.0001
12 & 13	6.8057	168	<0.0001

Regression tree for F2 (bark); midpoint of vocoid — see Figure 34 (p.178).

```
1) root 676 2386.00 11.040
   2) backness: back 218  284.00  9.081
     4) height: high 51  116.90 10.230
       8) Liquid: l 20   52.74 11.120 *
       9) Liquid: r 31   38.58  9.664 *
     5) height: mid 167   78.73  8.730 *
   3) backness: front 458  866.10 11.970
     6) height: low 166  101.90 10.510 *
     7) height: high,mid 292  204.80 12.810
      14) phthongness: . 128   90.41 12.200 *
       15) phthongness: di,mono 164   31.14 13.280 *
```

nodes tested	t	df	*p*
2 & 3	11.8314	674	<0.0001
4 & 5	12.2389	216	<0.0001
6 & 7	31.5171	456	<0.0001
8 & 9	3.1922	49	0.0025
14 & 15	13.3692	290	<0.0001

Regression tree for F2-F1 (bark); midpoint of vocoid — see Figure 35 (p.179).

```
1) root 676 5436.000  6.511
   2) height: low,mid 434 1930.000  5.063
     4) phthongness: .,mono 228  545.200  4.207 *
     5) phthongness: di 206 1034.000  6.010
      10) height: low 80  211.000  4.747 *
      11) height: mid 126  614.000  6.811
        22) backness: back 62   11.790  4.678 *
        23) backness: front 64   46.530  8.878 *
   3) height: high 242  961.100  9.109
     6) backness: back 51  210.100  6.875
      12) phthongness: . 9   7.737  4.507 *
      13) phthongness: mono 42  141.100  7.383 *
     7) backness: front 191  428.500  9.706
      14) length: long 100  14.200 10.790 *
       15) length: short 91  165.600  8.510 *
```

nodes tested	t	df	*p*
2 & 3	24.3523	674	<0.0001
4 & 5	9.8087	432	<0.0001
6 & 7	11.0103	240	<0.0001
10 & 11	7.1807	204	<0.0001
12 & 13	4.4926	49	<0.0001
14 & 15	16.1686	189	<0.0001
22 & 23	34.3737	124	<0.0001

Appendix 5: ANOVA tables

This appendix contains ANOVA tables referred to in Chapter 7. The following abbreviations are used in the factors:

V	Variety main effect
L	Liquid main effect
B	Backness main effect
V:L	interaction between Variety and Liquid
V:B	interaction between Variety and Backness
L:B	interaction between Liquid and Backness
V:L:B	interaction between Variety, Liquid and Backness
Resid	Residuals.

The following codes are used for significance levels:

***	p<0.001
**	p<0.01
*	p<0.05
.	p<0.1

F1

```
######################################################
ANOVA for F1 at point 0
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  2.829   2.829 42.9248 1.137e-10 ***
L       1  1.530   1.530 23.2197 1.790e-06 ***
B       1  0.025   0.025  0.3868   0.53420
V:L     1  0.591   0.591  8.9674   0.00285 **
V:B     1  0.089   0.089  1.3465   0.24630
L:B     1  0.028   0.028  0.4242   0.51509
V:L:B   1  0.007   0.007  0.1113   0.73880
Resid 668 44.028   0.066
```

```
######################################################
ANOVA for F1 at point 1
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  3.443   3.443 47.4690 1.294e-11 ***
L       1  2.764   2.764 38.0999 1.166e-09 ***
B       1  0.004   0.004  0.0557 0.8135253
V:L     1  1.073   1.073 14.7918 0.0001315 ***
V:B     1  0.103   0.103  1.4191 0.2339715
L:B     1  0.045   0.045  0.6147 0.4333096
V:L:B   1  0.035   0.035  0.4824 0.4875746
Resid 668 48.453   0.073
```

```
######################################################
ANOVA for F1 at point 2
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  2.106   2.106 23.8879 1.280e-06 ***
L       1  4.966   4.966 56.3315 1.963e-13 ***
B       1  0.105   0.105  1.1923 0.2752641
V:L     1  1.134   1.134 12.8637 0.0003595 ***
V:B     1  0.128   0.128  1.4489 0.2291316
L:B     1  0.118   0.118  1.3440 0.2467492
V:L:B   1  0.155   0.155  1.7576 0.1853729
Resid 668 58.884   0.088
```

```
######################################################
ANOVA for F1 at point 3
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  2.185   2.185 18.4094 2.045e-05 ***
L       1  5.005   5.005 42.1780 1.627e-10 ***
B       1  0.361   0.361  3.0432   0.08154 .
V:L     1  0.681   0.681  5.7394   0.01686 *
V:B     1  0.633   0.633  5.3360   0.02119 *
L:B     1  0.419   0.419  3.5316   0.06065 .
V:L:B   1  0.421   0.421  3.5505   0.05996 .
Resid 668 79.274   0.119
```

```
######################################################
ANOVA for F1 at point 4
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   2.703   2.703 16.4501 5.584e-05 ***
L       1   3.136   3.136 19.0881 1.447e-05 ***
B       1   0.874   0.874  5.3173   0.02142 *
V:L     1   0.043   0.043  0.2634   0.60794
V:B     1   0.974   0.974  5.9305   0.01514 *
L:B     1   0.807   0.807  4.9102   0.02703 *
V:L:B   1   0.598   0.598  3.6380   0.05690 .
Resid 668 109.760   0.164
```

```
######################################################
ANOVA for F1 at point 5
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   3.736   3.736 19.6001 1.115e-05 ***
L       1   1.620   1.620  8.5020  0.003667 **
B       1   1.256   1.256  6.5901  0.010471 *
V:L     1   0.236   0.236  1.2403  0.265822
V:B     1   0.568   0.568  2.9782  0.084855 .
L:B     1   0.726   0.726  3.8095  0.051380 .
V:L:B   1   0.251   0.251  1.3158  0.251763
Resid 668 127.312   0.191
```

```
######################################################
ANOVA for F1 at point 6
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   1.300   1.300  6.5744   0.01056 *
L       1   5.266   5.266 26.6290 3.255e-07 ***
B       1   0.706   0.706  3.5683   0.05933 .
V:L     1   0.312   0.312  1.5802   0.20918
V:B     1   0.135   0.135  0.6831   0.40880
L:B     1   0.239   0.239  1.2095   0.27183
V:L:B   1   0.006   0.006  0.0297   0.86324
Resid 668 132.099   0.198
```

```
######################################################
ANOVA for F1 at point 7
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   0.194   0.194  0.9354  0.333817
L       1  12.393  12.393 59.6962 4.063e-14 ***
B       1   1.387   1.387  6.6827  0.009946 **
V:L     1   0.117   0.117  0.5624  0.453570
V:B     1   0.182   0.182  0.8746  0.350034
L:B     1   0.097   0.097  0.4656  0.495264
V:L:B   1   0.018   0.018  0.0881  0.766707
Resid 668 138.677   0.208
```

```
######################################################
ANOVA for F1 at point 8
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   3.365   3.365  18.3684 2.088e-05 ***
L       1  22.305  22.305 121.7548 < 2.2e-16 ***
B       1   2.132   2.132  11.6356  0.000686 ***
V:L     1   0.535   0.535   2.9226  0.087810 .
V:B     1   0.150   0.150   0.8161  0.366643
L:B     1   0.050   0.050   0.2721  0.602077
V:L:B   1   0.021   0.021   0.1150  0.734628
Resid 668 122.375   0.183
```

```
######################################################
ANOVA for F1 at point 9
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 10.211  10.211  68.3078 7.772e-16 ***
L       1 37.377  37.377 250.0484 < 2.2e-16 ***
B       1  3.341   3.341  22.3516 2.770e-06 ***
V:L     1  0.397   0.397   2.6585    0.1035
V:B     1  0.030   0.030   0.2020    0.6533
L:B     1  0.158   0.158   1.0556    0.3046
V:L:B   1  0.081   0.081   0.5417    0.4620
Resid 668 99.853   0.149
```

```
######################################################
ANOVA for F1 at point 10
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 19.378  19.378 134.9022 < 2.2e-16 ***
L       1 46.531  46.531 323.9240 < 2.2e-16 ***
B       1  3.240   3.240  22.5579 2.497e-06 ***
V:L     1  0.486   0.486   3.3863   0.06619 .
V:B     1  0.014   0.014   0.0987   0.75349
L:B     1  0.123   0.123   0.8547   0.35557
V:L:B   1  0.093   0.093   0.6484   0.42099
Resid 668 95.957   0.144
```

```
######################################################
ANOVA for F1 at point 11
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 29.432  29.432 214.0986 < 2.2e-16 ***
L       1 45.196  45.196 328.7657 < 2.2e-16 ***
B       1  3.506   3.506  25.5050 5.699e-07 ***
V:L     1  1.169   1.169   8.5044  0.003662 **
V:B     1  0.036   0.036   0.2614  0.609342
L:B     1  0.059   0.059   0.4302  0.512122
V:L:B   1  0.023   0.023   0.1691  0.681073
Resid 668 91.831   0.137
```

```
######################################################
ANOVA for F1 at point 12
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 33.873  33.873 241.9948 < 2.2e-16 ***
L       1 55.296  55.296 395.0433 < 2.2e-16 ***
B       1  2.936   2.936  20.9780 5.543e-06 ***
V:L     1  0.731   0.731   5.2229   0.02260 *
V:B     1  0.042   0.042   0.3034   0.58196
L:B     1  0.072   0.072   0.5134   0.47394
V:L:B   1  0.005   0.005   0.0351   0.85148
Resid 668 93.503   0.140
```

```
######################################################
ANOVA for F1 at point 13
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  40.402  40.402 265.7624 < 2.2e-16 ***
L       1  58.716  58.716 386.2277 < 2.2e-16 ***
B       1   3.064   3.064  20.1556 8.408e-06 ***
V:L     1   0.691   0.691   4.5445   0.03339 *
V:B     1   0.002   0.002   0.0114   0.91516
L:B     1   0.077   0.077   0.5062   0.47703
V:L:B   1   0.011   0.011   0.0730   0.78711
Resid 668 101.552   0.152
```

```
######################################################
ANOVA for F1 at point 14
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 46.196  46.196 321.6899 < 2.2e-16 ***
L       1 60.208  60.208 419.2636 < 2.2e-16 ***
B       1  3.184   3.184  22.1708 3.035e-06 ***
V:L     1  1.024   1.024   7.1334   0.00775 **
V:B     1  0.003   0.003   0.0229   0.87978
L:B     1  0.007   0.007   0.0473   0.82796
V:L:B   1  0.008   0.008   0.0565   0.81214
Resid 668 95.928   0.144
```

```
######################################################
ANOVA for F1 at point 15
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  51.777  51.777 344.3650 < 2.2e-16 ***
L       1  60.104  60.104 399.7457 < 2.2e-16 ***
B       1   3.761   3.761  25.0117 7.291e-07 ***
V:L     1   1.345   1.345   8.9426  0.002889 **
V:B     1   0.064   0.064   0.4238  0.515264
L:B     1   0.010   0.010   0.0633  0.801451
V:L:B   1   0.006   0.006   0.0385  0.844569
Resid 668 100.437   0.150
```

```
######################################################
ANOVA for F1 at point 16
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  60.347  60.347 380.5340 < 2.2e-16 ***
L       1  57.336  57.336 361.5450 < 2.2e-16 ***
B       1   3.571   3.571  22.5170 2.549e-06 ***
V:L     1   1.850   1.850  11.6649 0.0006755 ***
V:B     1   0.148   0.148   0.9321 0.3346661
L:B     1   0.017   0.017   0.1075 0.7431221
V:L:B   1   0.243   0.243   1.5350 0.2157990
Resid 668 105.936   0.159
```

```
######################################################
ANOVA for F1 at point 17
       Df    Sum Sq   Mean Sq  F value    Pr(>F)
V       1    70.951    70.951 405.5993 < 2.2e-16 ***
L       1    56.133    56.133 320.8899 < 2.2e-16 ***
B       1     2.671     2.671  15.2665 0.0001029 ***
V:L     1     2.610     2.610  14.9204 0.0001231 ***
V:B     1     0.164     0.164   0.9367 0.3334791
L:B     1 0.0001224 0.0001224   0.0007 0.9789020
V:L:B   1     0.716     0.716   4.0954 0.0433967 *
Resid 668   116.853     0.175
```

```
######################################################
ANOVA for F1 at point 18
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  69.147  69.147 276.1140 < 2.2e-16 ***
L       1  63.630  63.630 254.0826 < 2.2e-16 ***
B       1   1.205   1.205   4.8106  0.028630 *
V:L     1   2.123   2.123   8.4778  0.003715 **
V:B     1   0.116   0.116   0.4613  0.497233
L:B     1   0.207   0.207   0.8257  0.363855
V:L:B   1   0.658   0.658   2.6255  0.105630
Resid 668 167.287   0.250
```

```
######################################################
ANOVA for F1 at point 19
       Df  Sum Sq Mean Sq  F value  Pr(>F)
V       1  55.940  55.940 144.3782 < 2e-16 ***
L       1  79.827  79.827 206.0303 < 2e-16 ***
B       1   0.002   0.002   0.0056 0.94060
V:L     1   0.799   0.799   2.0629 0.15139
V:B     1   0.074   0.074   0.1916 0.66170
L:B     1   1.633   1.633   4.2146 0.04047 *
V:L:B   1   0.022   0.022   0.0563 0.81249
Resid 668 258.818   0.387
```

```
######################################################
ANOVA for F1 at point 20
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    32.67    32.67  58.1766 8.271e-14 ***
L       1   115.72   115.72 206.0776 < 2.2e-16 ***
B       1     0.02     0.02   0.0343    0.8532
V:L     1     0.13     0.13   0.2307    0.6312
V:B     1 0.004493 0.004493   0.0080    0.9287
L:B     1     1.04     1.04   1.8495    0.1743
V:L:B   1     0.26     0.26   0.4713    0.4926
Resid 668   375.11     0.56
```

```
######################################################
ANOVA for F1 at point 21
       Df   Sum Sq  Mean Sq  F value    Pr(>F)    
V       1    43.50    43.50  70.7256 2.220e-16 ***
L       1   143.70   143.70 233.6560 < 2.2e-16 ***
B       1     0.90     0.90   1.4674    0.2262    
V:L     1 0.003456 0.003456   0.0056    0.9403    
V:B     1 0.001939 0.001939   0.0032    0.9552    
L:B     1     0.14     0.14   0.2252    0.6353    
V:L:B   1     0.20     0.20   0.3177    0.5732    
Resid 668   410.84     0.62                       

######################################################
ANOVA for F1 at point 22
       Df    Sum Sq   Mean Sq   F value  Pr(>F)    
V       1     62.59     62.59   99.8501 < 2e-16 ***
L       1    180.65    180.65  288.2009 < 2e-16 ***
B       1      3.93      3.93    6.2661 0.01254 *  
V:L     1      0.53      0.53    0.8401 0.35969    
V:B     1      0.03      0.03    0.0540 0.81636    
L:B     1      0.18      0.18    0.2879 0.59172    
V:L:B   1 1.073e-07 1.073e-07 1.712e-07 0.99967    
Resid 668    418.71      0.63                      

######################################################
ANOVA for F1 at point 23
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1  75.47   75.47 117.9478 < 2.2e-16 ***
L       1 201.10  201.10 314.2930 < 2.2e-16 ***
B       1   8.12    8.12  12.6927 0.0003932 ***
V:L     1   0.88    0.88   1.3715 0.2419793    
V:B     1   0.01    0.01   0.0205 0.8862135    
L:B     1   0.71    0.71   1.1124 0.2919481    
V:L:B   1   0.08    0.08   0.1198 0.7293554    
Resid 668 427.42    0.64                       

######################################################
ANOVA for F1 at point 24
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1  80.38   80.38 121.1957 < 2.2e-16 ***
L       1 197.57  197.57 297.8782 < 2.2e-16 ***
B       1  12.45   12.45  18.7763 1.696e-05 ***
V:L     1   0.84    0.84   1.2657    0.2610    
V:B     1   0.02    0.02   0.0254    0.8734    
L:B     1   1.01    1.01   1.5248    0.2173    
V:L:B   1   0.10    0.10   0.1486    0.7000    
Resid 668 443.06    0.66                       

######################################################
ANOVA for F1 at point 25
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1  77.86   77.86 110.7983 < 2.2e-16 ***
L       1 174.80  174.80 248.7427 < 2.2e-16 ***
B       1  14.40   14.40  20.4911 7.093e-06 ***
V:L     1   0.50    0.50   0.7119    0.3991    
V:B     1   0.34    0.34   0.4797    0.4888    
L:B     1   0.86    0.86   1.2249    0.2688    
V:L:B   1   0.11    0.11   0.1610    0.6884    
Resid 668 469.44    0.70                       

######################################################
ANOVA for F1 at point 26
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1  69.87   69.87  91.7294 < 2.2e-16 ***
L       1 147.15  147.15 193.1756 < 2.2e-16 ***
B       1  14.80   14.80  19.4237 1.220e-05 ***
V:L     1   0.07    0.07   0.0882    0.7665    
V:B     1   1.14    1.14   1.4922    0.2223    
L:B     1   0.61    0.61   0.7952    0.3728    
V:L:B   1   0.06    0.06   0.0848    0.7710    
Resid 668 508.83    0.76                       

######################################################
ANOVA for F1 at point 27
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1  56.87   56.87  70.3411 3.331e-16 ***
L       1 117.73  117.73 145.6166 < 2.2e-16 ***
B       1  13.71   13.71  16.9523 4.313e-05 ***
V:L     1   0.13    0.13   0.1632    0.6864    
V:B     1   2.18    2.18   2.7004    0.1008    
L:B     1   0.13    0.13   0.1567    0.6924    
V:L:B   1   0.02    0.02   0.0200    0.8875    
Resid 668 540.07    0.81                       

######################################################
ANOVA for F1 at point 28
       Df    Sum Sq   Mean Sq   F value    Pr(>F)    
V       1     45.41     45.41   52.3945 1.252e-12 ***
L       1     93.50     93.50  107.8830 < 2.2e-16 ***
B       1     12.27     12.27   14.1572 0.0001829 ***
V:L     1      0.77      0.77    0.8861 0.3468868    
V:B     1      3.16      3.16    3.6433 0.0567251 .  
L:B     1 1.840e-06 1.840e-06 2.123e-06 0.9988380    
V:L:B   1 3.570e-05 3.570e-05 4.119e-05 0.9948815    
Resid 668    578.97      0.87                        

######################################################
ANOVA for F1 at point 29
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1  33.31   33.31 35.7002 3.743e-09 ***
L       1  74.11   74.11 79.4220 < 2.2e-16 ***
B       1  10.48   10.48 11.2348  0.000848 ***
V:L     1   2.24    2.24  2.3952  0.122179    
V:B     1   4.71    4.71  5.0513  0.024933 *  
L:B     1   0.10    0.10  0.1065  0.744255    
V:L:B   1   0.07    0.07  0.0701  0.791300    
Resid 668 623.33    0.93                      

######################################################
ANOVA for F1 at point 30
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1  24.25   24.25 24.0869 1.158e-06 ***
L       1  55.49   55.49 55.1141 3.476e-13 ***
B       1   8.43    8.43  8.3739  0.003930 ** 
V:L     1   3.59    3.59  3.5673  0.059362 .  
V:B     1   5.91    5.91  5.8727  0.015643 *  
L:B     1   0.22    0.22  0.2144  0.643468    
V:L:B   1   0.19    0.19  0.1851  0.667143    
Resid 668 672.57    1.01                      

######################################################
ANOVA for F1 at point 31
       Df Sum Sq Mean Sq F value   Pr(>F)    
V       1   8.75    8.75  7.0199 0.008251 ** 
L       1  25.73   25.73 20.6480 6.55e-06 ***
B       1  10.27   10.27  8.2426 0.004221 ** 
V:L     1   6.57    6.57  5.2755 0.021935 *  
V:B     1   5.70    5.70  4.5730 0.032841 *  
L:B     1   0.35    0.35  0.2792 0.597378    
V:L:B   1   0.51    0.51  0.4112 0.521561    
Resid 668 832.36    1.25                     

######################################################
ANOVA for F1 at point 32
       Df  Sum Sq Mean Sq F value   Pr(>F)   
V       1    2.59    2.59  1.6459 0.199964   
L       1    6.36    6.36  4.0477 0.044631 * 
B       1   15.92   15.92 10.1279 0.001528 **
V:L     1    8.44    8.44  5.3685 0.020806 * 
V:B     1    8.55    8.55  5.4390 0.019988 * 
L:B     1    0.67    0.67  0.4282 0.513122   
V:L:B   1    1.00    1.00  0.6340 0.426162   
Resid 668 1050.27    1.57                    

######################################################
ANOVA for F1 at point 33
       Df  Sum Sq Mean Sq F value   Pr(>F)   
V       1    0.33    0.33  0.1760 0.675012   
L       1    0.33    0.33  0.1775 0.673658   
B       1   18.27   18.27  9.8332 0.001789 **
V:L     1    8.47    8.47  4.5586 0.033117 * 
V:B     1   11.22   11.22  6.0400 0.014238 * 
L:B     1    0.84    0.84  0.4546 0.500383   
V:L:B   1    0.52    0.52  0.2784 0.597896   
Resid 668 1241.00    1.86                    

######################################################
ANOVA for F1 at point 34
       Df    Sum Sq   Mean Sq F value   Pr(>F)    
V       1      0.02      0.02  0.0117 0.914033    
L       1 0.0003852 0.0003852  0.0002 0.989141    
B       1     22.88     22.88 11.0088 0.000956 ***
V:L     1      6.14      6.14  2.9522 0.086223 .  
V:B     1     13.49     13.49  6.4889 0.011078 *  
L:B     1      0.58      0.58  0.2771 0.598788    
V:L:B   1      0.25      0.25  0.1223 0.726711    
Resid 668   1388.22      2.08                     

######################################################
ANOVA for F1 at point 35
       Df   Sum Sq  Mean Sq F value   Pr(>F)   
V       1     0.43     0.43  0.1979 0.656564   
L       1 0.001260 0.001260  0.0006 0.980730   
B       1    20.93    20.93  9.6998 0.001922 **
V:L     1     4.78     4.78  2.2159 0.137071   
V:B     1    15.47    15.47  7.1679 0.007604 **
L:B     1     0.12     0.12  0.0536 0.816908   
V:L:B   1     0.21     0.21  0.0988 0.753326   
Resid 668  1441.27     2.16                    

######################################################
ANOVA for F1 at point 36
       Df  Sum Sq Mean Sq F value  Pr(>F)  
V       1    0.02    0.02  0.0112 0.91579  
L       1    0.66    0.66  0.3142 0.57531  
B       1   13.76   13.76  6.5353 0.01080 *
V:L     1    2.53    2.53  1.2002 0.27368  
V:B     1    9.40    9.40  4.4653 0.03496 *
L:B     1    0.28    0.28  0.1309 0.71763  
V:L:B   1    0.01    0.01  0.0048 0.94458  
Resid 668 1406.22    2.11                  
```

```
#########################################################
ANOVA for F1 at point 37
      Df   Sum Sq  Mean Sq F value  Pr(>F)
V      1     0.12     0.12  0.0580 0.80982
L      1     0.38     0.38  0.1862 0.66620
B      1     8.52     8.52  4.1900 0.04105 *
V:L    1     1.50     1.50  0.7386 0.39042
V:B    1     5.76     5.76  2.8293 0.09303 .
L:B    1     0.22     0.22  0.1076 0.74301
V:L:B  1 0.004876 0.004876  0.0024 0.96097
Resid 668  1359.02     2.03
```

```
#########################################################
ANOVA for F1 at point 38
      Df Sum Sq Mean Sq F value Pr(>F)
V      1   0.45    0.45  0.3243 0.5692
L      1   0.02    0.02  0.0131 0.9091
B      1   1.21    1.21  0.8727 0.3505
V:L    1   2.09    2.09  1.5085 0.2198
V:B    1   1.98    1.98  1.4249 0.2330
L:B    1   0.09    0.09  0.0642 0.8000
V:L:B  1   0.33    0.33  0.2400 0.6244
Resid 668 926.81   1.39
```

```
#########################################################
ANOVA for F1 at point 39
      Df   Sum Sq  Mean Sq F value  Pr(>F)
V      1     0.40     0.40  0.2970 0.58595
L      1     0.06     0.06  0.0452 0.83179
B      1     0.56     0.56  0.4179 0.51823
V:L    1     1.63     1.63  1.2102 0.27170
V:B    1     4.34     4.34  3.2317 0.07268 .
L:B    1 0.002253 0.002253  0.0017 0.96736
V:L:B  1     0.21     0.21  0.1596 0.68968
Resid 668   898.11     1.34
```

```
#########################################################
ANOVA for F1 at point 40
      Df    Sum Sq   Mean Sq F value  Pr(>F)
V      1      0.81      0.81  0.4742 0.49131
L      1      0.65      0.65  0.3841 0.53560
B      1      1.43      1.43  0.8406 0.35954
V:L    1 0.0004448 0.0004448  0.0003 0.98711
V:B    1      9.35      9.35  5.4950 0.01936 *
L:B    1      0.06      0.06  0.0358 0.84989
V:L:B  1      0.51      0.51  0.3026 0.58244
Resid 668   1136.82      1.70
```

```
#########################################################
```

F2

```
#########################################################
ANOVA for F2 at point 0
      Df Sum Sq Mean Sq F value    Pr(>F)
V      1  1.097   1.097  8.2751 0.0041474 **
L      1  1.945   1.945 14.6671 0.0001403 ***
B      1  0.507   0.507  3.8201 0.0510591 .
V:L    1  0.083   0.083  0.6267 0.4288641
V:B    1  0.209   0.209  1.5789 0.2093571
L:B    1  0.157   0.157  1.1835 0.2770469
V:L:B  1  0.067   0.067  0.5040 0.4779744
Resid 668 88.572   0.133
```

```
#########################################################
ANOVA for F2 at point 1
      Df  Sum Sq Mean Sq F value    Pr(>F)
V      1   0.080   0.080  0.4999   0.47979
L      1   3.384   3.384 21.1848 4.992e-06 ***
B      1   1.025   1.025  6.4143   0.01155 *
V:L    1   4.857   4.857 30.4028 5.020e-08 ***
V:B    1   0.588   0.588  3.6798   0.05550 .
L:B    1   0.203   0.203  1.2678   0.26058
V:L:B  1   0.261   0.261  1.6307   0.20204
Resid 668 106.720   0.160
```

```
#########################################################
ANOVA for F2 at point 2
      Df  Sum Sq Mean Sq  F value    Pr(>F)
V      1   0.060   0.060   0.3050   0.58092
L      1   3.821   3.821  19.4100 1.228e-05 ***
B      1   1.053   1.053   5.3483   0.02105 *
V:L    1  27.073  27.073 137.5180 < 2.2e-16 ***
V:B    1   0.552   0.552   2.8049   0.09445 .
L:B    1   0.129   0.129   0.6534   0.41917
V:L:B  1   0.093   0.093   0.4712   0.49269
Resid 668 131.508   0.197
```

```
#########################################################
ANOVA for F2 at point 3
      Df  Sum Sq Mean Sq  F value    Pr(>F)
V      1   1.683   1.683   7.5866 0.0060404 **
L      1   2.575   2.575  11.6039 0.0006976 ***
B      1   0.819   0.819   3.6924 0.0550853 .
V:L    1  65.801  65.801 296.5609 < 2.2e-16 ***
V:B    1   0.593   0.593   2.6708 0.1026738
L:B    1   0.007   0.007   0.0319 0.8582646
V:L:B  1   0.608   0.608   2.7382 0.0984432 .
Resid 668 148.216   0.222
```

```
#########################################################
ANOVA for F2 at point 4
      Df  Sum Sq Mean Sq  F value    Pr(>F)
V      1   4.758   4.758  18.7131 1.752e-05 ***
L      1   0.156   0.156   0.6127   0.43404
B      1   0.424   0.424   1.6690   0.19684
V:L    1 109.746 109.746 431.6183 < 2.2e-16 ***
V:B    1   1.163   1.163   4.5731   0.03284 *
L:B    1   0.014   0.014   0.0550   0.81469
V:L:B  1   0.709   0.709   2.7898   0.09534 .
Resid 668 169.850   0.254
```

```
#########################################################
ANOVA for F2 at point 5
      Df  Sum Sq Mean Sq  F value    Pr(>F)
V      1  11.280  11.280  37.3022 1.717e-09 ***
L      1   0.425   0.425   1.4063   0.23609
B      1   0.224   0.224   0.7411   0.38962
V:L    1 163.229 163.229 539.7976 < 2.2e-16 ***
V:B    1   1.957   1.957   6.4728   0.01118 *
L:B    1   0.003   0.003   0.0105   0.91848
V:L:B  1   0.181   0.181   0.5995   0.43906
Resid 668 201.996   0.302
```

```
#########################################################
ANOVA for F2 at point 6
      Df  Sum Sq Mean Sq  F value    Pr(>F)
V      1  26.819  26.819  74.2104 < 2.2e-16 ***
L      1   4.228   4.228  11.7005 0.0006629 ***
B      1   0.527   0.527   1.4575 0.2277628
V:L    1 231.317 231.317 640.0821 < 2.2e-16 ***
V:B    1   2.162   2.162   5.9830 0.0147013 *
L:B    1   0.014   0.014   0.0376 0.8463435
V:L:B  1   0.001   0.001   0.0020 0.9645337
Resid 668 241.406   0.361
```

```
#########################################################
ANOVA for F2 at point 7
      Df Sum Sq Mean Sq  F value    Pr(>F)
V      1  52.80   52.80 131.8158 < 2.2e-16 ***
L      1   9.76    9.76  24.3569 1.012e-06 ***
B      1   0.86    0.86   2.1520   0.14286
V:L    1 327.65  327.65 817.9431 < 2.2e-16 ***
V:B    1   2.44    2.44   6.0864   0.01387 *
L:B    1   0.10    0.10   0.2476   0.61892
V:L:B  1   0.04    0.04   0.1080   0.74249
Resid 668 267.58    0.40
```

```
#########################################################
ANOVA for F2 at point 8
      Df   Sum Sq  Mean Sq  F value    Pr(>F)
V      1    77.87    77.87 182.5849 < 2.2e-16 ***
L      1    14.29    14.29  33.5045 1.094e-08 ***
B      1     1.79     1.79   4.1960   0.04091 *
V:L    1   394.83   394.83 925.8022 < 2.2e-16 ***
V:B    1     1.62     1.62   3.7923   0.05191 .
L:B    1 0.002681 0.002681   0.0063   0.93683
V:L:B  1 0.004624 0.004624   0.0108   0.91710
Resid 668   284.88     0.43
```

```
#########################################################
ANOVA for F2 at point 9
      Df Sum Sq Mean Sq   F value    Pr(>F)
V      1  80.54   80.54  179.8108 < 2.2e-16 ***
L      1  20.86   20.86   46.5781 1.978e-11 ***
B      1   2.12    2.12    4.7390   0.02983 *
V:L    1 455.69  455.69 1017.3044 < 2.2e-16 ***
V:B    1   0.38    0.38    0.8584   0.35451
L:B    1   0.09    0.09    0.2071   0.64916
V:L:B  1   0.11    0.11    0.2354   0.62772
Resid 668 299.22    0.45
```

```
#########################################################
ANOVA for F2 at point 10
      Df Sum Sq Mean Sq   F value Pr(>F)
V      1  79.98   79.98  181.9744 <2e-16 ***
L      1  34.65   34.65   78.8409 <2e-16 ***
B      1   0.62    0.62    1.4198 0.2339
V:L    1 531.39  531.39 1208.9938 <2e-16 ***
V:B    1   0.76    0.76    1.7265 0.1893
L:B    1   0.03    0.03    0.0730 0.7871
V:L:B  1   0.05    0.05    0.1226 0.7264
Resid 668 293.61    0.44
```

```
#########################################################
ANOVA for F2 at point 11
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  47.36   47.36  113.8564 < 2e-16 ***
L       1  38.37   38.37   92.2443 < 2e-16 ***
B       1   2.06    2.06    4.9433 0.02653 *
V:L     1 592.94  592.94 1425.6001 < 2e-16 ***
V:B     1   0.27    0.27    0.6436 0.42268
L:B     1   0.05    0.05    0.1146 0.73506
V:L:B   1   0.03    0.03    0.0804 0.77691
Resid 668 277.84    0.42
```

```
#########################################################
ANOVA for F2 at point 12
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  42.17   42.17  109.6953 < 2e-16 ***
L       1  36.20   36.20   94.1721 < 2e-16 ***
B       1   1.92    1.92    4.9861 0.02588 *
V:L     1 610.92  610.92 1589.0688 < 2e-16 ***
V:B     1   1.33    1.33    3.4712 0.06288 .
L:B     1   0.26    0.26    0.6732 0.41225
V:L:B   1   0.12    0.12    0.3051 0.58087
Resid 668 256.81    0.38
```

```
#########################################################
ANOVA for F2 at point 13
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  40.04   40.04  101.8271 < 2e-16 ***
L       1  42.22   42.22  107.3922 < 2e-16 ***
B       1   1.05    1.05    2.6647 0.10307
V:L     1 625.93  625.93 1592.0040 < 2e-16 ***
V:B     1   1.61    1.61    4.1023 0.04322 *
L:B     1   0.20    0.20    0.5206 0.47082
V:L:B   1   0.47    0.47    1.1861 0.27652
Resid 668 262.64    0.39
```

```
#########################################################
ANOVA for F2 at point 14
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  47.90   47.90  112.5688 < 2e-16 ***
L       1  34.14   34.14   80.2320 < 2e-16 ***
B       1   1.29    1.29    3.0434 0.08152 .
V:L     1 601.14  601.14 1412.8169 < 2e-16 ***
V:B     1   1.04    1.04    2.4398 0.11876
L:B     1   1.46    1.46    3.4381 0.06415 .
V:L:B   1   1.12    1.12    2.6408 0.10462
Resid 668 284.23    0.43
```

```
#########################################################
ANOVA for F2 at point 15
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  52.52   52.52  111.2624 < 2e-16 ***
L       1  34.21   34.21   72.4699 < 2e-16 ***
B       1   1.82    1.82    3.8564 0.04997 *
V:L     1 597.90  597.90 1266.7413 < 2e-16 ***
V:B     1   0.70    0.70    1.4871 0.22310
L:B     1   2.18    2.18    4.6224 0.03191 *
V:L:B   1   1.57    1.57    3.3307 0.06844 .
Resid 668 315.30    0.47
```

```
#########################################################
ANOVA for F2 at point 16
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1  61.40   61.40  132.6372 < 2.2e-16 ***
L       1  23.81   23.81   51.4319 1.972e-12 ***
B       1   3.41    3.41    7.3732  0.006791 **
V:L     1 551.12  551.12 1190.6243 < 2.2e-16 ***
V:B     1   0.04    0.04    0.0765  0.782149
L:B     1   1.64    1.64    3.5538  0.059845 .
V:L:B   1   1.15    1.15    2.4868  0.115282
Resid 668 309.21    0.46
```

```
#########################################################
ANOVA for F2 at point 17
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1  62.79   62.79  132.4950 < 2.2e-16 ***
L       1  20.10   20.10   42.4172 1.451e-10 ***
B       1   2.85    2.85    6.0034   0.01453 *
V:L     1 535.89  535.89 1130.7690 < 2.2e-16 ***
V:B     1   0.03    0.03    0.0625   0.80260
L:B     1   2.97    2.97    6.2620   0.01257 *
V:L:B   1   1.58    1.58    3.3346   0.06828 .
Resid 668 316.58    0.47
```

```
#########################################################
ANOVA for F2 at point 18
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1  68.94   68.94  156.2378 < 2.2e-16 ***
L       1  14.88   14.88   33.7251 9.819e-09 ***
B       1   4.73    4.73   10.7165  0.001117 **
V:L     1 485.35  485.35 1099.8950 < 2.2e-16 ***
V:B     1   0.36    0.36    0.8123  0.367755
L:B     1   4.00    4.00    9.0753  0.002689 **
V:L:B   1   2.63    2.63    5.9675  0.014830 *
Resid 668 294.77    0.44
```

```
#########################################################
ANOVA for F2 at point 19
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  82.57   82.57 185.4525 < 2.2e-16 ***
L       1  12.03   12.03  27.0260 2.671e-07 ***
B       1   6.88    6.88  15.4451 9.379e-05 ***
V:L     1 435.58  435.58 978.2696 < 2.2e-16 ***
V:B     1   0.62    0.62   1.3912  0.238629
L:B     1   3.45    3.45   7.7476  0.005531 **
V:L:B   1   1.95    1.95   4.3789  0.036763 *
Resid 668 297.43    0.45
```

```
#########################################################
ANOVA for F2 at point 20
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 126.65  126.65 233.4327 < 2.2e-16 ***
L       1  13.28   13.28  24.4813 9.507e-07 ***
B       1  17.35   17.35  31.9845 2.305e-08 ***
V:L     1 409.87  409.87 755.4570 < 2.2e-16 ***
V:B     1   2.90    2.90   5.3499 0.0210265 *
L:B     1   6.03    6.03  11.1085 0.0009068 ***
V:L:B   1   3.54    3.54   6.5308 0.0108227 *
Resid 668 362.42    0.54
```

```
#########################################################
ANOVA for F2 at point 21
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 112.09  112.09 188.6684 < 2.2e-16 ***
L       1  13.26   13.26  22.3138 2.824e-06 ***
B       1  40.23   40.23  67.7176 9.992e-16 ***
V:L     1 360.10  360.10 606.1332 < 2.2e-16 ***
V:B     1   1.65    1.65   2.7829  0.095746 .
L:B     1   5.97    5.97  10.0482  0.001595 **
V:L:B   1   2.66    2.66   4.4767  0.034730 *
Resid 668 396.86    0.59
```

```
#########################################################
ANOVA for F2 at point 22
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  91.66   91.66 136.0295 < 2.2e-16 ***
L       1  12.08   12.08  17.9217 2.624e-05 ***
B       1  68.39   68.39 101.4951 < 2.2e-16 ***
V:L     1 287.52  287.52 426.6887 < 2.2e-16 ***
V:B     1   0.80    0.80   1.1918  0.275356
L:B     1   5.45    5.45   8.0899  0.004587 **
V:L:B   1   0.45    0.45   0.6732  0.412231
Resid 668 450.13    0.67
```

```
#########################################################
ANOVA for F2 at point 23
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    81.72    81.72 107.9365 < 2.2e-16 ***
L       1    10.98    10.98  14.4984 0.0001532 ***
B       1   116.54   116.54 153.9157 < 2.2e-16 ***
V:L     1   223.96   223.96 295.8041 < 2.2e-16 ***
V:B     1     0.56     0.56   0.7382 0.3905360
L:B     1     3.81     3.81   5.0387 0.0251139 *
V:L:B   1 0.002971 0.002971   0.0039 0.9500743
Resid 668   505.77     0.76
```

```
#########################################################
ANOVA for F2 at point 24
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  74.95   74.95  82.6790 < 2.2e-16 ***
L       1   7.07    7.07   7.8034  0.005364 **
B       1 185.53  185.53 204.6731 < 2.2e-16 ***
V:L     1 159.24  159.24 175.6768 < 2.2e-16 ***
V:B     1   0.41    0.41   0.4570  0.499269
L:B     1   1.63    1.63   1.8032  0.179780
V:L:B   1   0.32    0.32   0.3533  0.552471
Resid 668 605.52    0.91
```

```
#########################################################
ANOVA for F2 at point 25
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  69.79   69.79  66.1105 2.109e-15 ***
L       1   4.78    4.78   4.5244   0.03378 *
B       1 264.84  264.84 250.8621 < 2.2e-16 ***
V:L     1 108.97  108.97 103.2161 < 2.2e-16 ***
V:B     1   0.38    0.38   0.3565   0.55067
L:B     1   0.80    0.80   0.7597   0.38375
V:L:B   1   0.97    0.97   0.9215   0.33742
Resid 668 705.21    1.06
```

```
#########################################################
ANOVA for F2 at point 26
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  62.63   62.63  50.5075 3.055e-12 ***
L       1   3.26    3.26   2.6260    0.1056
B       1 351.41  351.41 283.3835 < 2.2e-16 ***
V:L     1  65.51   65.51  52.8270 1.021e-12 ***
V:B     1   0.12    0.12   0.0999    0.7521
L:B     1   0.13    0.13   0.1035    0.7478
V:L:B   1   2.78    2.78   2.2416    0.1348
Resid 668 828.35    1.24
```

```
#######################################################
ANOVA for F2 at point 27
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  48.47   48.47  33.0118 1.392e-08 ***
L       1   4.08    4.08   2.7813   0.09584 .
B       1 441.73  441.73 300.8392 < 2.2e-16 ***
V:L     1  36.06   36.06  24.5580 9.149e-07 ***
V:B     1   0.02    0.02   0.0112   0.91587
L:B     1   0.05    0.05   0.0354   0.85072
V:L:B   1   4.83    4.83   3.2904   0.07014 .
Resid 668 980.84    1.47
```

```
#######################################################
ANOVA for F2 at point 28
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   36.44   36.44  22.2977 2.847e-06 ***
L       1    4.60    4.60   2.8171 0.0937347 .
B       1  516.64  516.64 316.1012 < 2.2e-16 ***
V:L     1   19.45   19.45  11.8983 0.0005972 ***
V:B     1    0.38    0.38   0.2319 0.6303019
L:B     1    0.02    0.02   0.0094 0.9226997
V:L:B   1    6.19    6.19   3.7869 0.0520733 .
Resid 668 1091.78    1.63
```

```
#######################################################
ANOVA for F2 at point 29
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    33.00    33.00  18.5779 1.877e-05 ***
L       1     4.81     4.81   2.7105   0.10016
B       1   581.03   581.03 327.0730 < 2.2e-16 ***
V:L     1     8.69     8.69   4.8915   0.02733 *
V:B     1     1.00     1.00   0.5603   0.45442
L:B     1 0.004856 0.004856   0.0027   0.95832
V:L:B   1     7.17     7.17   4.0335   0.04501 *
Resid 668  1186.66     1.78
```

```
#######################################################
ANOVA for F2 at point 30
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    31.09    31.09  16.3865  5.77e-05 ***
L       1     5.83     5.83   3.0737   0.08002 .
B       1   636.90   636.90 335.7131 < 2.2e-16 ***
V:L     1     3.26     3.26   1.7168   0.19056
V:B     1     1.33     1.33   0.7010   0.40276
L:B     1 0.002455 0.002455   0.0013   0.97131
V:L:B   1     6.57     6.57   3.4624   0.06322 .
Resid 668  1267.30     1.90
```

```
#######################################################
ANOVA for F2 at point 31
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   33.33   33.33  17.0260 4.153e-05 ***
L       1    5.64    5.64   2.8831   0.08998 .
B       1  683.23  683.23 348.9907 < 2.2e-16 ***
V:L     1    1.01    1.01   0.5165   0.47257
V:B     1    1.02    1.02   0.5215   0.47046
L:B     1    0.09    0.09   0.0474   0.82777
V:L:B   1    4.26    4.26   2.1748   0.14076
Resid 668 1307.77    1.96
```

```
#######################################################
ANOVA for F2 at point 32
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   27.25   27.25  13.6959 0.0002326 ***
L       1    8.01    8.01   4.0245 0.0452469 *
B       1  750.80  750.80 377.3793 < 2.2e-16 ***
V:L     1    0.82    0.82   0.4130 0.5206531
V:B     1    0.56    0.56   0.2839 0.5943636
L:B     1    0.48    0.48   0.2425 0.6225373
V:L:B   1    2.21    2.21   1.1106 0.2923394
Resid 668 1329.00    1.99
```

```
#######################################################
ANOVA for F2 at point 33
       Df  Sum Sq Mean Sq  F value  Pr(>F)
V       1   22.02   22.02  10.9622 0.00098 ***
L       1    9.70    9.70   4.8279 0.02835 *
B       1  853.51  853.51 424.8097 < 2e-16 ***
V:L     1    1.22    1.22   0.6077 0.43594
V:B     1    0.15    0.15   0.0724 0.78797
L:B     1    0.52    0.52   0.2571 0.61230
V:L:B   1    1.71    1.71   0.8524 0.35622
Resid 668 1342.12    2.01
```

```
#######################################################
ANOVA for F2 at point 34
       Df    Sum Sq   Mean Sq  F value    Pr(>F)
V       1     20.19     20.19  10.7782  0.001081 **
L       1     11.88     11.88   6.3444  0.012008 *
B       1   1022.23   1022.23 545.8019 < 2.2e-16 ***
V:L     1      1.64      1.64   0.8772  0.349297
V:B     1 0.0002716 0.0002716   0.0001  0.990396
L:B     1      0.39      0.39   0.2057  0.650315
V:L:B   1      1.30      1.30   0.6919  0.405829
Resid 668   1251.09      1.87
```

```
#######################################################
ANOVA for F2 at point 35
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   19.29   19.29  11.4062 0.0007745 ***
L       1   11.20   11.20   6.6218 0.0102882 *
B       1 1222.76 1222.76 723.1850 < 2.2e-16 ***
V:L     1    1.65    1.65   0.9774 0.3231940
V:B     1    0.13    0.13   0.0764 0.7822594
L:B     1    0.36    0.36   0.2133 0.6443337
V:L:B   1    0.93    0.93   0.5502 0.4585167
Resid 668 1129.45    1.69
```

```
#######################################################
ANOVA for F2 at point 36
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   21.25   21.25  13.7822 0.0002224 ***
L       1   12.16   12.16   7.8863 0.0051266 **
B       1 1446.80 1446.80 938.4468 < 2.2e-16 ***
V:L     1    1.40    1.40   0.9095 0.3406021
V:B     1    0.12    0.12   0.0758 0.7831211
L:B     1    0.07    0.07   0.0434 0.8350407
V:L:B   1    0.54    0.54   0.3491 0.5548414
Resid 668 1029.85    1.54
```

```
#######################################################
ANOVA for F2 at point 37
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   24.72   24.72   17.5179 3.227e-05 ***
L       1   10.83   10.83    7.6751  0.005754 **
B       1 1648.10 1648.10 1168.0378 < 2.2e-16 ***
V:L     1    0.40    0.40    0.2856  0.593204
V:B     1    0.34    0.34    0.2416  0.623223
L:B     1    0.15    0.15    0.1033  0.748019
V:L:B   1    0.76    0.76    0.5372  0.463865
Resid 668  942.55    1.41
```

```
#######################################################
ANOVA for F2 at point 38
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   23.08   23.08   16.6551 5.025e-05 ***
L       1   11.25   11.25    8.1162  0.004522 **
B       1 1703.59 1703.59 1229.3352 < 2.2e-16 ***
V:L     1    1.03    1.03    0.7448  0.388445
V:B     1    0.21    0.21    0.1518  0.696898
L:B     1    0.04    0.04    0.0316  0.858931
V:L:B   1    0.41    0.41    0.2979  0.585406
Resid 668  925.70    1.39
```

```
#######################################################
ANOVA for F2 at point 39
       Df    Sum Sq   Mean Sq   F value    Pr(>F)
V       1     22.19     22.19   15.8323 7.678e-05 ***
L       1      9.84      9.84    7.0203   0.00825 **
B       1   1634.45   1634.45 1166.0696 < 2.2e-16 ***
V:L     1      1.79      1.79    1.2792   0.25846
V:B     1      0.52      0.52    0.3717   0.54228
L:B     1 0.0003628 0.0003628    0.0003   0.98717
V:L:B   1      0.33      0.33    0.2370   0.62652
Resid 668    936.32      1.40
```

```
#######################################################
ANOVA for F2 at point 40
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   29.77   29.77   21.6281  3.99e-06 ***
L       1    6.56    6.56    4.7645    0.0294 *
B       1 1477.34 1477.34 1073.2669 < 2.2e-16 ***
V:L     1    0.80    0.80    0.5804    0.4464
V:B     1    2.65    2.65    1.9249    0.1658
L:B     1    1.64    1.64    1.1888    0.2760
V:L:B   1    0.96    0.96    0.6963    0.4043
Resid 668  919.49    1.38
```

```
#######################################################
```

F3

```
#######################################################
ANOVA for F3 at point 0
       Df    Sum Sq   Mean Sq  F value    Pr(>F)
V       1     9.832     9.832 124.5000 < 2.2e-16 ***
L       1    28.948    28.948 366.5527 < 2.2e-16 ***
B       1 0.0001629 0.0001629   0.0021 0.9637873
V:L     1     1.105     1.105  13.9924 0.0001993 ***
V:B     1     0.019     0.019   0.2382 0.6257028
L:B     1     0.106     0.106   1.3447 0.2466137
V:L:B   1     0.223     0.223   2.8266 0.0931812 .
Resid 668    52.754     0.079
```

```
#########################################################
ANOVA for F3 at point 1
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  6.046   6.046  73.3665 < 2.2e-16 ***
L       1 61.809  61.809 750.0282 < 2.2e-16 ***
B       1  0.026   0.026   0.3201    0.5717
V:L     1  1.870   1.870  22.6974 2.328e-06 ***
V:B     1  0.001   0.001   0.0085    0.9265
L:B     1  0.054   0.054   0.6500    0.4204
V:L:B   1  0.036   0.036   0.4403    0.5072
Resid 668 55.049   0.082
```

```
#########################################################
ANOVA for F3 at point 2
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   2.135   2.135   26.7325 3.091e-07 ***
L       1 112.373 112.373 1407.1207 < 2.2e-16 ***
B       1   0.012   0.012    0.1547    0.6942
V:L     1   2.493   2.493   31.2220 3.353e-08 ***
V:B     1   0.182   0.182    2.2740    0.1320
L:B     1   0.001   0.001    0.0087    0.9256
V:L:B   1   0.118   0.118    1.4759    0.2248
Resid 668  53.346   0.080
```

```
#########################################################
ANOVA for F3 at point 3
       Df    Sum Sq   Mean Sq   F value    Pr(>F)
V       1     0.621     0.621    7.6271  0.005908 **
L       1   178.344   178.344 2191.6311 < 2.2e-16 ***
B       1     0.012     0.012    0.1437  0.704789
V:L     1     3.514     3.514   43.1795 1.006e-10 ***
V:B     1     0.234     0.234    2.8721  0.090591 .
L:B     1     0.068     0.068    0.8345  0.361314
V:L:B   1 0.0001094 0.0001094    0.0013  0.970769
Resid 668    54.358     0.081
```

```
#########################################################
ANOVA for F3 at point 4
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   0.475   0.475    4.1217  0.042732 *
L       1 254.948 254.948 2210.7861 < 2.2e-16 ***
B       1   0.043   0.043    0.3689  0.543832
V:L     1   1.138   1.138    9.8690  0.001755 **
V:B     1   0.743   0.743    6.4392  0.011389 *
L:B     1   0.281   0.281    2.4365  0.119011
V:L:B   1   0.007   0.007    0.0615  0.804254
Resid 668  77.034   0.115
```

```
#########################################################
ANOVA for F3 at point 5
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   1.03    1.03    7.1605  0.007635 **
L       1 365.68  365.68 2551.0362 < 2.2e-16 ***
B       1   0.13    0.13    0.8729  0.350497
V:L     1   0.01    0.01    0.0629  0.802108
V:B     1   0.34    0.34    2.4048  0.121439
L:B     1   0.14    0.14    1.0013  0.317367
V:L:B   1   0.08    0.08    0.5769  0.447780
Resid 668  95.75    0.14
```

```
#########################################################
ANOVA for F3 at point 6
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   2.72    2.72   16.2395 6.224e-05 ***
L       1 490.95  490.95 2936.3100 < 2.2e-16 ***
B       1   0.06    0.06    0.3663   0.54525
V:L     1   3.46    3.46   20.6781 6.451e-06 ***
V:B     1   0.38    0.38    2.2716   0.13224
L:B     1   0.13    0.13    0.7529   0.38586
V:L:B   1   0.73    0.73    4.3682   0.03699 *
Resid 668 111.69    0.17
```

```
#########################################################
ANOVA for F3 at point 7
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   3.86    3.86   21.6799 3.887e-06 ***
L       1 654.36  654.36 3674.4001 < 2.2e-16 ***
B       1   0.02    0.02    0.0962   0.75656
V:L     1  11.91   11.91   66.8997 1.443e-15 ***
V:B     1   0.06    0.06    0.3550   0.55150
L:B     1   0.18    0.18    1.0096   0.31537
V:L:B   1   0.87    0.87    4.8936   0.02729 *
Resid 668 118.96    0.18
```

```
#########################################################
ANOVA for F3 at point 8
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   2.00    2.00   10.0992  0.001552 **
L       1 784.38  784.38 3953.2451 < 2.2e-16 ***
B       1   0.02    0.02    0.1083  0.742197
V:L     1  19.92   19.92  100.3987 < 2.2e-16 ***
V:B     1   0.01    0.01    0.0741  0.785508
L:B     1   0.94    0.94    4.7357  0.029893 *
V:L:B   1   0.97    0.97    4.8909  0.027337 *
Resid 668 132.54    0.20
```

```
#########################################################
ANOVA for F3 at point 9
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   0.49    0.49    2.1113  0.146689
L       1 929.60  929.60 3989.5222 < 2.2e-16 ***
B       1   0.10    0.10    0.4276  0.513411
V:L     1  27.77   27.77  119.1807 < 2.2e-16 ***
V:B     1   0.01    0.01    0.0328  0.856257
L:B     1   1.59    1.59    6.8050  0.009293 **
V:L:B   1   0.73    0.73    3.1511  0.076333 .
Resid 668 155.65    0.23
```

```
#########################################################
ANOVA for F3 at point 10
       Df   Sum Sq  Mean Sq   F value Pr(>F)
V       1 0.001511 0.001511    0.0065 0.93561
L       1  1070.31  1070.31 4628.5398 < 2e-16 ***
B       1 0.001506 0.001506    0.0065 0.93570
V:L     1    28.65    28.65  123.8787 < 2e-16 ***
V:B     1     0.15     0.15    0.6344 0.42603
L:B     1     0.93     0.93    4.0005 0.04589 *
V:L:B   1     1.03     1.03    4.4658 0.03495 *
Resid 668   154.47     0.23
```

```
#########################################################
ANOVA for F3 at point 11
       Df    Sum Sq   Mean Sq   F value Pr(>F)
V       1 0.0031872 0.0031872    0.0141 0.90562
L       1   1161.33   1161.33 5125.6527 < 2e-16 ***
B       1 0.0004558 0.0004558    0.0020 0.96424
V:L     1     26.95     26.95  118.9343 < 2e-16 ***
V:B     1 0.0039293 0.0039293    0.0173 0.89527
L:B     1      0.43      0.43    1.9006 0.16847
V:L:B   1      1.50      1.50    6.6225 0.01028 *
Resid 668    151.35      0.23
```

```
#########################################################
ANOVA for F3 at point 12
       Df  Sum Sq Mean Sq   F value Pr(>F)
V       1    0.02    0.02    0.0963 0.7565
L       1 1213.89 1213.89 4940.4725 <2e-16 ***
B       1    0.02    0.02    0.0685 0.7935
V:L     1   33.79   33.79  137.5145 <2e-16 ***
V:B     1    0.20    0.20    0.7991 0.3717
L:B     1    1.09    1.09    4.4390 0.0355 *
V:L:B   1    0.22    0.22    0.9131 0.3396
Resid 668  164.13    0.25
```

```
#########################################################
ANOVA for F3 at point 13
       Df  Sum Sq Mean Sq   F value  Pr(>F)
V       1    0.07    0.07    0.2948 0.58733
L       1 1294.89 1294.89 5457.8916 < 2e-16 ***
B       1    0.02    0.02    0.0987 0.75344
V:L     1   35.55   35.55  149.8248 < 2e-16 ***
V:B     1    0.52    0.52    2.1725 0.14097
L:B     1    1.39    1.39    5.8553 0.01580 *
V:L:B   1    0.07    0.07    0.2776 0.59842
Resid 668  158.48    0.24
```

```
#########################################################
ANOVA for F3 at point 14
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1    0.01    0.01    0.0581  0.809647
L       1 1324.35 1324.35 5220.1774 < 2.2e-16 ***
B       1    0.23    0.23    0.9185  0.338210
V:L     1   40.67   40.67  160.2966 < 2.2e-16 ***
V:B     1    0.35    0.35    1.3782  0.240823
L:B     1    2.09    2.09    8.2454  0.004215 **
V:L:B   1    0.15    0.15    0.5910  0.442288
Resid 668  169.47    0.25
```

```
#########################################################
ANOVA for F3 at point 15
       Df  Sum Sq Mean Sq   F value Pr(>F)
V       1    0.23    0.23    0.9017 0.3427
L       1 1309.50 1309.50 5177.9512 <2e-16 ***
B       1    0.70    0.70    2.7701 0.0965 .
V:L     1   40.14   40.14  158.7166 <2e-16 ***
V:B     1    0.60    0.60    2.3856 0.1229
L:B     1    1.55    1.55    6.1482 0.0134 *
V:L:B   1    0.15    0.15    0.5957 0.4405
Resid 668  168.94    0.25
```

```
#########################################################
ANOVA for F3 at point 16
       Df  Sum Sq Mean Sq   F value  Pr(>F)
V       1    0.23    0.23    0.8748 0.34998
L       1 1298.41 1298.41 4885.9785 < 2e-16 ***
B       1    0.24    0.24    0.9036 0.34216
V:L     1   45.13   45.13  169.8398 < 2e-16 ***
V:B     1    0.45    0.45    1.6751 0.19602
L:B     1    1.10    1.10    4.1377 0.04233 *
V:L:B   1    0.19    0.19    0.7009 0.40279
Resid 668  177.52    0.27
```

```
#####################################################
ANOVA for F3 at point 17
        Df  Sum Sq Mean Sq   F value  Pr(>F)    
V        1    0.31    0.31    1.1822 0.27730    
L        1 1319.31 1319.31 5090.2566 < 2e-16 ***
B        1    0.23    0.23    0.8734 0.35035    
V:L      1   43.35   43.35  167.2610 < 2e-16 ***
V:B      1    0.38    0.38    1.4525 0.22856    
L:B      1    1.14    1.14    4.3990 0.03634 *  
V:L:B    1    0.23    0.23    0.8949 0.34450    
Resid  668  173.13    0.26                      
```

```
#####################################################
ANOVA for F3 at point 18
        Df  Sum Sq Mean Sq   F value  Pr(>F)    
V        1    0.60    0.60    2.1997 0.13851    
L        1 1340.70 1340.70 4929.2295 < 2e-16 ***
B        1    0.51    0.51    1.8829 0.17046    
V:L      1   42.15   42.15  154.9566 < 2e-16 ***
V:B      1    0.45    0.45    1.6658 0.19727    
L:B      1    1.55    1.55    5.6864 0.01738 *  
V:L:B    1    0.74    0.74    2.7178 0.09970 .  
Resid  668  181.69    0.27                      
```

```
#####################################################
ANOVA for F3 at point 19
        Df  Sum Sq Mean Sq   F value  Pr(>F)    
V        1    1.32    1.32    4.6101 0.03214 *  
L        1 1335.99 1335.99 4662.6968 < 2e-16 ***
B        1    0.69    0.69    2.4158 0.12059    
V:L      1   46.71   46.71  163.0191 < 2e-16 ***
V:B      1    0.63    0.63    2.1916 0.13924    
L:B      1    1.52    1.52    5.3063 0.02155 *  
V:L:B    1    0.54    0.54    1.8993 0.16862    
Resid  668  191.40    0.29                      
```

```
#####################################################
ANOVA for F3 at point 20
        Df  Sum Sq Mean Sq   F value    Pr(>F)    
V        1    2.08    2.08    6.6865  0.009925 ** 
L        1 1333.99 1333.99 4293.1087 < 2.2e-16 ***
B        1    0.62    0.62    1.9802  0.159833    
V:L      1   50.21   50.21  161.6005 < 2.2e-16 ***
V:B      1    0.47    0.47    1.5092  0.219694    
L:B      1    1.10    1.10    3.5276  0.060790 .  
V:L:B    1    0.75    0.75    2.4161  0.120565    
Resid  668  207.57    0.31                        
```

```
#####################################################
ANOVA for F3 at point 21
        Df  Sum Sq Mean Sq   F value    Pr(>F)    
V        1    2.81    2.81    9.1584  0.002571 ** 
L        1 1336.08 1336.08 4358.3261 < 2.2e-16 ***
B        1    0.73    0.73    2.3885  0.122705    
V:L      1   47.22   47.22  154.0415 < 2.2e-16 ***
V:B      1    0.12    0.12    0.3874  0.533858    
L:B      1    0.76    0.76    2.4720  0.116366    
V:L:B    1    1.16    1.16    3.7837  0.052173 .  
Resid  668  204.78    0.31                        
```

```
#####################################################
ANOVA for F3 at point 22
        Df  Sum Sq Mean Sq   F value    Pr(>F)    
V        1    4.63    4.63   14.8286 0.0001291 ***
L        1 1261.22 1261.22 4042.0888 < 2.2e-16 ***
B        1    0.36    0.36    1.1695 0.2799022    
V:L      1   38.33   38.33  122.8408 < 2.2e-16 ***
V:B      1    0.33    0.33    1.0634 0.3028131    
L:B      1    0.51    0.51    1.6199 0.2035496    
V:L:B    1    0.88    0.88    2.8106 0.0941096 .  
Resid  668  208.43    0.31                        
```

```
#####################################################
ANOVA for F3 at point 23
        Df  Sum Sq Mean Sq   F value    Pr(>F)    
V        1    4.99    4.99   14.3761 0.0001632 ***
L        1 1145.53 1145.53 3302.7790 < 2.2e-16 ***
B        1    1.29    1.29    3.7154 0.0543354 .  
V:L      1   32.20   32.20   92.8486 < 2.2e-16 ***
V:B      1    0.87    0.87    2.4954 0.1146549    
L:B      1    1.42    1.42    4.0902 0.0435303 *  
V:L:B    1    0.45    0.45    1.2919 0.2561021    
Resid  668  231.69    0.35                        
```

```
#####################################################
ANOVA for F3 at point 24
        Df  Sum Sq Mean Sq   F value    Pr(>F)    
V        1    6.05    6.05   14.0929 0.0001891 ***
L        1 1018.38 1018.38 2371.5542 < 2.2e-16 ***
B        1    3.46    3.46    8.0657 0.0046484 ** 
V:L      1   26.88   26.88   62.6082 1.055e-14 ***
V:B      1    2.00    2.00    4.6504 0.0314024 *  
L:B      1    3.15    3.15    7.3458 0.0068945 ** 
V:L:B    1    0.12    0.12    0.2852 0.5934916    
Resid  668  286.85    0.43                        
```

```
#####################################################
ANOVA for F3 at point 25
       Df Sum Sq Mean Sq   F value    Pr(>F)    
V       1   6.24    6.24   12.3437 0.0004723 ***
L       1 876.28  876.28 1733.6149 < 2.2e-16 ***
B       1   5.92    5.92   11.7053 0.0006612 ***
V:L     1  20.28   20.28   40.1173 4.393e-10 ***
V:B     1   4.81    4.81    9.5234 0.0021126 ** 
L:B     1   4.60    4.60    9.1074 0.0026426 ** 
V:L:B   1   0.01    0.01    0.0240 0.8768792    
Resid 668 337.65    0.51                        
```

```
#####################################################
ANOVA for F3 at point 26
       Df Sum Sq Mean Sq   F value    Pr(>F)    
V       1   7.19    7.19   12.8774 0.0003569 ***
L       1 754.75  754.75 1351.9227 < 2.2e-16 ***
B       1   9.94    9.94   17.7979 2.796e-05 ***
V:L     1  15.72   15.72   28.1618 1.520e-07 ***
V:B     1   7.02    7.02   12.5728 0.0004187 ***
L:B     1   6.54    6.54   11.7168 0.0006572 ***
V:L:B   1   0.18    0.18    0.3298 0.5659793    
Resid 668 372.93    0.56                        
```

```
#####################################################
ANOVA for F3 at point 27
       Df Sum Sq Mean Sq   F value    Pr(>F)    
V       1   6.34    6.34   10.4380 0.0012951 ** 
L       1 648.98  648.98 1068.9689 < 2.2e-16 ***
B       1  14.67   14.67   24.1651 1.114e-06 ***
V:L     1  11.28   11.28   18.5728 1.882e-05 ***
V:B     1   8.32    8.32   13.7050 0.0002315 ***
L:B     1   9.46    9.46   15.5829 8.734e-05 ***
V:L:B   1   0.65    0.65    1.0651 0.3024282    
Resid 668 405.55    0.61                        
```

```
#####################################################
ANOVA for F3 at point 28
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1   5.32    5.32   8.1749 0.0043799 ** 
L       1 551.17  551.17 847.2111 < 2.2e-16 ***
B       1  21.14   21.14  32.4913 1.797e-08 ***
V:L     1   8.64    8.64  13.2820 0.0002888 ***
V:B     1  10.44   10.44  16.0543 6.847e-05 ***
L:B     1  12.83   12.83  19.7188 1.050e-05 ***
V:L:B   1   1.45    1.45   2.2340 0.1354805    
Resid 668 434.58    0.65                       
```

```
#####################################################
ANOVA for F3 at point 29
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1   5.08    5.08   7.7121  0.005639 ** 
L       1 467.89  467.89 709.9205 < 2.2e-16 ***
B       1  26.03   26.03  39.4944 5.936e-10 ***
V:L     1   6.35    6.35   9.6376  0.001987 ** 
V:B     1  11.56   11.56  17.5428 3.186e-05 ***
L:B     1  14.10   14.10  21.3991 4.480e-06 ***
V:L:B   1   2.50    2.50   3.7998  0.051677 .  
Resid 668 440.26    0.66                       
```

```
#####################################################
ANOVA for F3 at point 30
       Df Sum Sq Mean Sq  F value    Pr(>F)    
V       1   4.18    4.18   6.2797  0.012450 *  
L       1 389.68  389.68 585.5549 < 2.2e-16 ***
B       1  29.69   29.69  44.6129 5.059e-11 ***
V:L     1   5.02    5.02   7.5446  0.006181 ** 
V:B     1  12.73   12.73  19.1344 1.413e-05 ***
L:B     1  14.08   14.08  21.1573 5.062e-06 ***
V:L:B   1   2.96    2.96   4.4466  0.035342 *  
Resid 668 444.55    0.67                       
```

```
#####################################################
ANOVA for F3 at point 31
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1   2.978   2.978   6.3448  0.012005 *  
L       1 218.830 218.830 466.2543 < 2.2e-16 ***
B       1  37.876  37.876  80.7016 < 2.2e-16 ***
V:L     1   4.785   4.785  10.1952  0.001474 ** 
V:B     1  14.013  14.013  29.8576 6.569e-08 ***
L:B     1  10.986  10.986  23.4082 1.628e-06 ***
V:L:B   1   4.372   4.372   9.3155  0.002362 ** 
Resid 668 313.517   0.469                       
```

```
#####################################################
ANOVA for F3 at point 32
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1   1.791   1.791   5.0522  0.024920 *  
L       1 118.617 118.617 334.5478 < 2.2e-16 ***
B       1  38.790  38.790 109.4029 < 2.2e-16 ***
V:L     1   3.066   3.066   8.6486  0.003386 ** 
V:B     1  13.478  13.478  38.0128 1.216e-09 ***
L:B     1   6.250   6.250  17.6267 3.052e-05 ***
V:L:B   1   3.552   3.552  10.0180  0.001621 ** 
Resid 668 236.846   0.355                       
```

```
#########################################################
ANOVA for F3 at point 33
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.263   0.263   0.8196 0.3656108
L       1  65.227  65.227 202.9284 < 2.2e-16 ***
B       1  35.599  35.599 110.7520 < 2.2e-16 ***
V:L     1   2.918   2.918   9.0777 0.0026853 **
V:B     1  10.731  10.731  33.3858 1.159e-08 ***
L:B     1   3.934   3.934  12.2376 0.0004994 ***
V:L:B   1   2.901   2.901   9.0242 0.0027640 **
Resid 668 214.714   0.321
```

```
#########################################################
ANOVA for F3 at point 34
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.148   0.148   0.4646  0.495729
L       1  38.378  38.378 120.0956 < 2.2e-16 ***
B       1  34.495  34.495 107.9458 < 2.2e-16 ***
V:L     1   2.161   2.161   6.7634  0.009511 **
V:B     1   9.510   9.510  29.7593 6.896e-08 ***
L:B     1   2.915   2.915   9.1207  0.002624 **
V:L:B   1   3.387   3.387  10.6000  0.001188 **
Resid 668 213.466   0.320
```

```
#########################################################
ANOVA for F3 at point 35
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.001   0.001   0.0042  0.948360
L       1  27.503  27.503  95.0408 < 2.2e-16 ***
B       1  34.822  34.822 120.3344 < 2.2e-16 ***
V:L     1   0.942   0.942   3.2566  0.071589 .
V:B     1  12.954  12.954  44.7650 4.704e-11 ***
L:B     1   2.515   2.515   8.6918  0.003308 **
V:L:B   1   1.856   1.856   6.4126  0.011560 *
Resid 668 193.307   0.289
```

```
#########################################################
ANOVA for F3 at point 36
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.096   0.096   0.3150  0.574828
L       1  19.848  19.848  65.4535 2.776e-15 ***
B       1  31.201  31.201 102.8943 < 2.2e-16 ***
V:L     1   0.325   0.325   1.0706  0.301184
V:B     1  10.846  10.846  35.7661 3.625e-09 ***
L:B     1   2.913   2.913   9.6053  0.002022 **
V:L:B   1   2.113   2.113   6.9687  0.008489 **
Resid 668 202.562   0.303
```

```
#########################################################
ANOVA for F3 at point 37
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.230   0.230   0.7203  0.396364
L       1  11.043  11.043  34.6310 6.306e-09 ***
B       1  33.458  33.458 104.9213 < 2.2e-16 ***
V:L     1   0.579   0.579   1.8152  0.178337
V:B     1  12.684  12.684  39.7752 5.182e-10 ***
L:B     1   3.247   3.247  10.1818  0.001485 **
V:L:B   1   1.949   1.949   6.1113  0.013680 *
Resid 668 213.017   0.319
```

```
#########################################################
ANOVA for F3 at point 38
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   0.149   0.149  0.4454  0.504750
L       1   8.794   8.794 26.3272 3.782e-07 ***
B       1  32.746  32.746 98.0299 < 2.2e-16 ***
V:L     1   0.487   0.487  1.4577  0.227727
V:B     1  13.842  13.842 41.4393 2.322e-10 ***
L:B     1   3.533   3.533 10.5771  0.001203 **
V:L:B   1   1.520   1.520  4.5512  0.033259 *
Resid 668 223.140   0.334
```

```
#########################################################
ANOVA for F3 at point 39
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   0.109   0.109  0.2977  0.585480
L       1   7.293   7.293 19.9961 9.117e-06 ***
B       1  31.722  31.722 86.9769 < 2.2e-16 ***
V:L     1   0.215   0.215  0.5889  0.443125
V:B     1  13.965  13.965 38.2894 1.064e-09 ***
L:B     1   2.734   2.734  7.4970  0.006345 **
V:L:B   1   1.959   1.959  5.3713  0.020772 *
Resid 668 243.629   0.365
```

```
#########################################################
ANOVA for F3 at point 40
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   0.001   0.001  0.0014    0.9704
L       1   6.227   6.227 16.4820 5.493e-05 ***
B       1  27.821  27.821 73.6364 < 2.2e-16 ***
V:L     1   0.037   0.037  0.0986    0.7536
V:B     1  22.725  22.725 60.1489 3.297e-14 ***
L:B     1   0.731   0.731  1.9358    0.1646
V:L:B   1   0.742   0.742  1.9652    0.1614
Resid 668 252.380   0.378
```

```
#########################################################
```

F2-F1

```
#########################################################
ANOVA for F2-F1 at point 0
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   7.450   7.450 32.6313 1.678e-08 ***
L       1   6.926   6.926 30.3335 5.194e-08 ***
B       1   0.759   0.759  3.3256   0.06866 .
V:L     1   1.117   1.117  4.8939   0.02729 *
V:B     1   0.025   0.025  0.1116   0.73841
L:B     1   0.052   0.052  0.2295   0.63203
V:L:B   1   0.030   0.030  0.1309   0.71761
Resid 668 152.513   0.228
```

```
#########################################################
ANOVA for F2-F1 at point 1
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1   4.572   4.572 17.8201 2.764e-05 ***
L       1  12.265  12.265 47.8055 1.102e-11 ***
B       1   1.157   1.157  4.5116   0.03403 *
V:L     1  10.496  10.496 40.9105 2.996e-10 ***
V:B     1   0.199   0.199  0.7750   0.37899
L:B     1   0.057   0.057  0.2225   0.63733
V:L:B   1   0.105   0.105  0.4076   0.52343
Resid 668 171.378   0.257
```

```
#########################################################
ANOVA for F2-F1 at point 2
       Df     Sum Sq    Mean Sq  F value    Pr(>F)
V       1      1.455      1.455   5.0235   0.02533 *
L       1     17.499     17.499  60.4338 2.887e-14 ***
B       1      0.493      0.493   1.7016   0.19253
V:L     1     39.288     39.288 135.6852 < 2.2e-16 ***
V:B     1      0.149      0.149   0.5138   0.47374
L:B     1 0.0002094 0.0002094   0.0007   0.97855
V:L:B   1      0.008      0.008   0.0274   0.86860
Resid 668    193.423      0.290
```

```
#########################################################
ANOVA for F2-F1 at point 3
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.033   0.033   0.1046    0.7465
L       1  14.760  14.760  47.2902 1.409e-11 ***
B       1   0.093   0.093   0.2965    0.5863
V:L     1  79.872  79.872 255.9053 < 2.2e-16 ***
V:B     1   0.001   0.001   0.0022    0.9630
L:B     1   0.317   0.317   1.0164    0.3137
V:L:B   1   0.017   0.017   0.0544    0.8156
Resid 668 208.492   0.312
```

```
#########################################################
ANOVA for F2-F1 at point 4
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.289   0.289   0.7543 0.3854410
L       1   4.690   4.690  12.2564 0.0004945 ***
B       1   0.080   0.080   0.2097 0.6471549
V:L     1 114.148 114.148 298.2899 < 2.2e-16 ***
V:B     1   0.008   0.008   0.0217 0.8828567
L:B     1   1.033   1.033   2.6999 0.1008266
V:L:B   1   0.005   0.005   0.0125 0.9111239
Resid 668 255.627   0.383
```

```
#########################################################
ANOVA for F2-F1 at point 5
       Df  Sum Sq Mean Sq  F value  Pr(>F)
V       1   2.033   2.033   4.4964 0.03433 *
L       1   0.385   0.385   0.8525 0.35618
B       1   0.419   0.419   0.9268 0.33604
V:L     1 151.043 151.043 334.0815 < 2e-16 ***
V:B     1   0.417   0.417   0.9220 0.33730
L:B     1   0.825   0.825   1.8251 0.17716
V:L:B   1   0.006   0.006   0.0124 0.91121
Resid 668 302.011   0.452
```

```
#########################################################
ANOVA for F2-F1 at point 6
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  16.31   16.31  30.9016 3.926e-08 ***
L       1   0.06    0.06   0.1077    0.7428
B       1   0.01    0.01   0.0247    0.8751
V:L     1 214.63  214.63 406.6627 < 2.2e-16 ***
V:B     1   1.22    1.22   2.3047    0.1295
L:B     1   0.14    0.14   0.2629    0.6083
V:L:B   1   0.01    0.01   0.0202    0.8869
Resid 668 352.55    0.53
```

```
#####################################################
ANOVA for F2-F1 at point 7
       Df    Sum Sq   Mean Sq   F value Pr(>F)
V       1     59.40     59.40   98.5753 <2e-16 ***
L       1      0.16      0.16    0.2613 0.6094
B       1      0.06      0.06    0.1032 0.7481
V:L     1    340.13    340.13  564.4530 <2e-16 ***
V:B     1      1.29      1.29    2.1390 0.1441
L:B     1 1.643e-05 1.643e-05 2.726e-05 0.9958
V:L:B   1      0.12      0.12    0.1955 0.6585
Resid 668    402.53      0.60
```

```
#####################################################
ANOVA for F2-F1 at point 8
       Df Sum Sq Mean Sq  F value Pr(>F)
V       1 113.61  113.61 175.4826 <2e-16 ***
L       1   0.89    0.89   1.3729 0.2417
B       1   0.01    0.01   0.0231 0.8792
V:L     1 424.44  424.44 655.6154 <2e-16 ***
V:B     1   0.78    0.78   1.2100 0.2717
L:B     1   0.03    0.03   0.0454 0.8313
V:L:B   1   0.01    0.01   0.0092 0.9236
Resid 668 432.46    0.65
```

```
#####################################################
ANOVA for F2-F1 at point 9
       Df   Sum Sq  Mean Sq  F value  Pr(>F)
V       1   148.11   148.11 232.9199 < 2e-16 ***
L       1     2.39     2.39   3.7587 0.05295 .
B       1     0.14     0.14   0.2163 0.64200
V:L     1   483.00   483.00 759.5721 < 2e-16 ***
V:B     1     0.20     0.20   0.3133 0.57586
L:B     1     0.01     0.01   0.0135 0.90758
V:L:B   1 0.001611 0.001611   0.0025 0.95987
Resid 668   424.77     0.64
```

```
#####################################################
ANOVA for F2-F1 at point 10
       Df Sum Sq Mean Sq  F value Pr(>F)
V       1 178.10  178.10 288.4651 <2e-16 ***
L       1   0.87    0.87   1.4151 0.2346
B       1   1.02    1.02   1.6527 0.1990
V:L     1 564.03  564.03 913.5456 <2e-16 ***
V:B     1   0.57    0.57   0.9160 0.3389
L:B     1   0.03    0.03   0.0475 0.8275
V:L:B   1   0.01    0.01   0.0086 0.9259
Resid 668 412.43    0.62
```

```
#####################################################
ANOVA for F2-F1 at point 11
       Df    Sum Sq   Mean Sq  F value Pr(>F)
V       1    151.45    151.45 233.1673 <2e-16 ***
L       1      0.28      0.28   0.4304 0.5120
B       1      0.19      0.19   0.2962 0.5865
V:L     1    646.77    646.77 995.7080 <2e-16 ***
V:B     1      0.11      0.11   0.1655 0.6843
L:B     1      0.21      0.21   0.3279 0.5671
V:L:B   1 0.0009217 0.0009217   0.0014 0.9700
Resid 668    433.90      0.65
```

```
#####################################################
ANOVA for F2-F1 at point 12
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1 151.64  151.64  242.0090 < 2e-16 ***
L       1   2.01    2.01    3.2140 0.07346 .
B       1   0.11    0.11    0.1728 0.67776
V:L     1 653.92  653.92 1043.6401 < 2e-16 ***
V:B     1   0.90    0.90    1.4378 0.23093
L:B     1   0.60    0.60    0.9630 0.32679
V:L:B   1   0.07    0.07    0.1184 0.73084
Resid 668 418.55    0.63
```

```
#####################################################
ANOVA for F2-F1 at point 13
       Df Sum Sq Mean Sq  F value Pr(>F)
V       1 160.87  160.87 238.0672 <2e-16 ***
L       1   1.36    1.36   2.0072 0.1570
B       1   0.53    0.53   0.7819 0.3769
V:L     1 668.21  668.21 988.8419 <2e-16 ***
V:B     1   1.51    1.51   2.2332 0.1355
L:B     1   0.03    0.03   0.0453 0.8315
V:L:B   1   0.33    0.33   0.4936 0.4826
Resid 668 451.40    0.68
```

```
#####################################################
ANOVA for F2-F1 at point 14
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1 188.17  188.17 257.3989 < 2e-16 ***
L       1   3.67    3.67   5.0249 0.02531 *
B       1   0.42    0.42   0.5715 0.44993
V:L     1 651.79  651.79 891.5911 < 2e-16 ***
V:B     1   0.92    0.92   1.2647 0.26116
L:B     1   1.27    1.27   1.7378 0.18787
V:L:B   1   1.32    1.32   1.8094 0.17903
Resid 668 488.34    0.73
```

```
#####################################################
ANOVA for F2-F1 at point 15
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1 208.58  208.58 258.6758 < 2e-16 ***
L       1   3.63    3.63   4.4962 0.03434 *
B       1   0.35    0.35   0.4318 0.51132
V:L     1 655.95  655.95 813.4863 < 2e-16 ***
V:B     1   1.19    1.19   1.4741 0.22513
L:B     1   1.90    1.90   2.3602 0.12494
V:L:B   1   1.39    1.39   1.7203 0.19010
Resid 668 538.64    0.81
```

```
#####################################################
ANOVA for F2-F1 at point 16
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1   243.48   243.48 295.3205 < 2.2e-16 ***
L       1     7.25     7.25   8.7951  0.003128 **
B       1 0.001786 0.001786   0.0022  0.962890
V:L     1   616.83   616.83 748.1579 < 2.2e-16 ***
V:B     1     0.33     0.33   0.3978  0.528450
L:B     1     1.33     1.33   1.6097  0.204981
V:L:B   1     0.34     0.34   0.4073  0.523553
Resid 668   550.74     0.82
```

```
#####################################################
ANOVA for F2-F1 at point 17
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1   267.24   267.24 309.4489 < 2.2e-16 ***
L       1     9.05     9.05  10.4818  0.001265 **
B       1 0.002762 0.002762   0.0032  0.954915
V:L     1   613.30   613.30 710.1741 < 2.2e-16 ***
V:B     1     0.05     0.05   0.0627  0.802407
L:B     1     3.01     3.01   3.4807  0.062525 .
V:L:B   1     0.17     0.17   0.1953  0.658677
Resid 668   576.88     0.86
```

```
#####################################################
ANOVA for F2-F1 at point 18
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 276.18  276.18 291.2137 < 2.2e-16 ***
L       1  16.97   16.97  17.8910 2.666e-05 ***
B       1   1.16    1.16   1.2231   0.26916
V:L     1 551.67  551.67 581.7030 < 2.2e-16 ***
V:B     1   0.07    0.07   0.0706   0.79050
L:B     1   6.03    6.03   6.3597   0.01191 *
V:L:B   1   0.66    0.66   0.6950   0.40477
Resid 668 633.51    0.95
```

```
#####################################################
ANOVA for F2-F1 at point 19
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 274.44  274.44 241.6660 < 2.2e-16 ***
L       1  29.87   29.87  26.3054 3.823e-07 ***
B       1   6.64    6.64   5.8434  0.015903 *
V:L     1 473.70  473.70 417.1258 < 2.2e-16 ***
V:B     1   1.12    1.12   0.9885  0.320464
L:B     1   9.83    9.83   8.6556  0.003374 **
V:L:B   1   1.56    1.56   1.3729  0.241739
Resid 668 758.60    1.14
```

```
#####################################################
ANOVA for F2-F1 at point 20
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 287.96  287.96 194.6007 < 2.2e-16 ***
L       1  50.59   50.59  34.1913 7.817e-09 ***
B       1  16.22   16.22  10.9590 0.0009816 ***
V:L     1 395.42  395.42 267.2213 < 2.2e-16 ***
V:B     1   2.68    2.68   1.8102 0.1789436
L:B     1  12.07   12.07   8.1561 0.0044249 **
V:L:B   1   1.87    1.87   1.2645 0.2612093
Resid 668 988.47    1.48
```

```
#####################################################
ANOVA for F2-F1 at point 21
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  295.24  295.24 179.3358 < 2.2e-16 ***
L       1   69.67   69.67  42.3181 1.521e-10 ***
B       1   29.08   29.08  17.6655 2.992e-05 ***
V:L     1  362.34  362.34 220.0954 < 2.2e-16 ***
V:B     1    1.54    1.54   0.9367   0.33349
L:B     1    7.93    7.93   4.8149   0.02856 *
V:L:B   1    1.41    1.41   0.8584   0.35452
Resid 668 1099.71    1.65
```

```
#####################################################
ANOVA for F2-F1 at point 22
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  305.74  305.74 173.6493 < 2.2e-16 ***
L       1   99.31   99.31  56.4055 1.896e-13 ***
B       1   39.54   39.54  22.4576 2.626e-06 ***
V:L     1  312.66  312.66 177.5810 < 2.2e-16 ***
V:B     1    1.17    1.17   0.6626    0.4159
L:B     1    3.65    3.65   2.0720    0.1505
V:L:B   1    0.45    0.45   0.2574    0.6121
Resid 668 1176.12    1.76
```

```
####################################################
ANOVA for F2-F1 at point 23
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  314.26  314.26 163.7168 < 2.2e-16 ***
L       1  118.11  118.11  61.5304 1.732e-14 ***
B       1   63.13   63.13  32.8873 1.480e-08 ***
V:L     1  252.88  252.88 131.7404 < 2.2e-16 ***
V:B     1    0.74    0.74   0.3872    0.5340
L:B     1    1.23    1.23   0.6413    0.4235
V:L:B   1    0.11    0.11   0.0572    0.8110
Resid 668 1282.25    1.92
```

```
####################################################
ANOVA for F2-F1 at point 24
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  310.57  310.57 140.9797 < 2.2e-16 ***
L       1  129.88  129.88  58.9578 5.740e-14 ***
B       1  101.85  101.85  46.2328 2.332e-11 ***
V:L     1  183.21  183.21  83.1664 < 2.2e-16 ***
V:B     1    0.26    0.26   0.1198    0.7293
L:B     1    0.07    0.07   0.0338    0.8542
V:L:B   1    0.06    0.06   0.0288    0.8653
Resid 668 1471.54    2.20
```

```
####################################################
ANOVA for F2-F1 at point 25
       Df    Sum Sq  Mean Sq  F value    Pr(>F)
V       1    295.09   295.09 115.5603 < 2.2e-16 ***
L       1    121.79   121.79  47.6937 1.162e-11 ***
B       1    155.73   155.73  60.9835 2.232e-14 ***
V:L     1    124.23   124.23  48.6505 7.374e-12 ***
V:B     1 0.001080 0.001080    0.0004    0.9836
L:B     1 0.001041 0.001041    0.0004    0.9839
V:L:B   1      0.42     0.42   0.1655    0.6843
Resid 668  1705.79     2.55
```

```
####################################################
ANOVA for F2-F1 at point 26
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  264.81  264.81 88.4418 < 2.2e-16 ***
L       1  106.62  106.62 35.6102 3.911e-09 ***
B       1  221.99  221.99 74.1417 < 2.2e-16 ***
V:L     1   69.77   69.77 23.3025 1.717e-06 ***
V:B     1    0.51    0.51  0.1704    0.6799
L:B     1    0.18    0.18  0.0589    0.8083
V:L:B   1    2.00    2.00  0.6669    0.4144
Resid 668 2000.10    2.99
```

```
####################################################
ANOVA for F2-F1 at point 27
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  210.35  210.35 59.7850 3.908e-14 ***
L       1   77.96   77.96 22.1576 3.055e-06 ***
B       1  299.82  299.82 85.2136 < 2.2e-16 ***
V:L     1   31.83   31.83  9.0463  0.002731 **
V:B     1    2.58    2.58  0.7327  0.392303
L:B     1    0.02    0.02  0.0046  0.945710
V:L:B   1    4.29    4.29  1.2187  0.270006
Resid 668 2350.31    3.52
```

```
####################################################
ANOVA for F2-F1 at point 28
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  163.22  163.22 41.1179 2.711e-10 ***
L       1   56.61   56.61 14.2615 0.0001733 ***
B       1  369.67  369.67 93.1273 < 2.2e-16 ***
V:L     1   12.49   12.49  3.1454 0.0765967 .
V:B     1    5.72    5.72  1.4421 0.2302226
L:B     1    0.02    0.02  0.0038 0.9508947
V:L:B   1    6.16    6.16  1.5518 0.2133130
Resid 668 2651.62    3.97
```

```
####################################################
ANOVA for F2-F1 at point 29
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  132.63  132.63 29.9839 6.172e-08 ***
L       1   41.15   41.15  9.3018   0.00238 **
B       1  435.42  435.42 98.4353 < 2.2e-16 ***
V:L     1    2.11    2.11  0.4771   0.48997
V:B     1   10.04   10.04  2.2699   0.13238
L:B     1    0.06    0.06  0.0136   0.90708
V:L:B   1    8.60    8.60  1.9442   0.16368
Resid 668 2954.82    4.42
```

```
####################################################
ANOVA for F2-F1 at point 30
       Df    Sum Sq  Mean Sq  F value    Pr(>F)
V       1     110.3    110.3  22.7713 2.243e-06 ***
L       1      25.3     25.3   5.2347   0.02245 *
B       1     498.8    498.8 103.0124 < 2.2e-16 ***
V:L     1 0.008183 0.008183   0.0017   0.96722
V:B     1      12.9     12.9   2.6541   0.10375
L:B     1       0.3      0.3   0.0546   0.81530
V:L:B   1       9.0      9.0   1.8522   0.17399
Resid 668    3234.4      4.8
```

```
####################################################
ANOVA for F2-F1 at point 31
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1   76.2    76.2 13.5331 0.0002533 ***
L       1    7.3     7.3  1.2909 0.2562913
B       1  526.0   526.0 93.3741 < 2.2e-16 ***
V:L     1    2.4     2.4  0.4311 0.5116795
V:B     1   11.5    11.5  2.0492 0.1527516
L:B     1    0.8     0.8  0.1420 0.7064049
V:L:B   1    7.7     7.7  1.3713 0.2420080
Resid 668 3762.8     5.6
```

```
####################################################
ANOVA for F2-F1 at point 32
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1   46.6    46.6  7.2740  0.007172 **
L       1    0.1     0.1  0.0147  0.903555
B       1  548.0   548.0 85.4907 < 2.2e-16 ***
V:L     1    4.0     4.0  0.6232  0.430140
V:B     1   13.5    13.5  2.1077  0.147031
L:B     1    2.3     2.3  0.3581  0.549769
V:L:B   1    6.2     6.2  0.9632  0.326741
Resid 668 4282.3     6.4
```

```
####################################################
ANOVA for F2-F1 at point 33
       Df Sum Sq Mean Sq F value Pr(>F)
V       1   27.7    27.7  3.9781 0.0465 *
L       1    6.5     6.5  0.9261 0.3362
B       1  622.0   622.0 89.2750 <2e-16 ***
V:L     1    3.3     3.3  0.4677 0.4943
V:B     1   13.9    13.9  1.9980 0.1580
L:B     1    2.7     2.7  0.3849 0.5352
V:L:B   1    4.1     4.1  0.5902 0.4426
Resid 668 4654.4     7.0
```

```
####################################################
ANOVA for F2-F1 at point 34
       Df Sum Sq Mean Sq  F value Pr(>F)
V       1   18.8    18.8   2.6823 0.1019
L       1   11.7    11.7   1.6750 0.1960
B       1  739.3   739.3 105.4080 <2e-16 ***
V:L     1    1.4     1.4   0.2037 0.6519
V:B     1   13.4    13.4   1.9056 0.1679
L:B     1    1.9     1.9   0.2714 0.6026
V:L:B   1    2.7     2.7   0.3846 0.5354
Resid 668 4684.8     7.0
```

```
####################################################
ANOVA for F2-F1 at point 35
       Df Sum Sq Mean Sq  F value Pr(>F)
V       1   14.0    14.0   2.0880 0.1489
L       1   11.4    11.4   1.7087 0.1916
B       1  923.7   923.7 138.0341 <2e-16 ***
V:L     1    0.8     0.8   0.1213 0.7277
V:B     1   12.8    12.8   1.9077 0.1677
L:B     1    0.9     0.9   0.1323 0.7162
V:L:B   1    2.0     2.0   0.3040 0.5816
Resid 668 4470.4     6.7
```

```
####################################################
ANOVA for F2-F1 at point 36
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1   19.9    19.9   3.2405 0.07229 .
L       1   18.5    18.5   3.0176 0.08282 .
B       1 1178.4  1178.4 192.3066 < 2e-16 ***
V:L     1    0.2     0.2   0.0268 0.86996
V:B     1    7.4     7.4   1.2110 0.27154
L:B     1    0.6     0.6   0.1002 0.75169
V:L:B   1    0.7     0.7   0.1136 0.73614
Resid 668 4093.3     6.1
```

```
####################################################
ANOVA for F2-F1 at point 37
       Df    Sum Sq  Mean Sq  F value  Pr(>F)
V       1      21.4     21.4   3.7778 0.05236 .
L       1      15.3     15.3   2.6912 0.10137
B       1    1419.6   1419.6 250.3555 < 2e-16 ***
V:L     1       0.3      0.3   0.0616 0.80408
V:B     1       3.3      3.3   0.5812 0.44612
L:B     1 0.007412 0.007412   0.0013 0.97117
V:L:B   1       0.6      0.6   0.1131 0.73676
Resid 668    3787.7      5.7
```

```
####################################################
ANOVA for F2-F1 at point 38
       Df  Sum Sq Mean Sq  F value  Pr(>F)
V       1   29.98   29.98   6.7298 0.00969 **
L       1   12.17   12.17   2.7319 0.09883 .
B       1 1613.96 1613.96 362.3493 < 2e-16 ***
V:L     1    0.19    0.19   0.0417 0.83833
V:B     1    0.90    0.90   0.2015 0.65367
L:B     1    0.26    0.26   0.0579 0.80991
V:L:B   1    1.49    1.49   0.3339 0.56356
Resid 668 2975.38    4.45
```

```
########################################################
ANOVA for F2-Fl at point 39
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    28.54    28.54   6.8417  0.009107 **
L       1    11.45    11.45   2.7436  0.098114 .
B       1  1574.41  1574.41 377.3615 < 2.2e-16 ***
V:L     1 0.004027 0.004027   0.0010  0.975224
V:B     1     1.86     1.86   0.4450  0.504933
L:B     1 0.004424 0.004424   0.0011  0.974034
V:L:B   1     1.08     1.08   0.2590  0.610952
Resid 668  2786.99     4.17
```

```
########################################################
ANOVA for F2-Fl at point 40
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   40.38   40.38   9.8793  0.001745 **
L       1    3.07    3.07   0.7513  0.386382
B       1 1386.82 1386.82 339.2919 < 2.2e-16 ***
V:L     1    0.84    0.84   0.2048  0.651016
V:B     1    2.05    2.05   0.5005  0.479538
L:B     1    1.07    1.07   0.2607  0.609824
V:L:B   1    2.88    2.88   0.7042  0.401667
Resid 668 2730.39    4.09
```

```
########################################################
```

F3-F2

```
########################################################
ANOVA for F3-F2 at point 0
       Df  Sum Sq Mean Sq  F value  Pr(>F)
V       1  17.498  17.498 104.8701 < 2e-16 ***
L       1  45.899  45.899 275.0767 < 2e-16 ***
B       1   0.525   0.525   3.1455 0.07659 .
V:L     1   0.582   0.582   3.4885 0.06223 .
V:B     1   0.103   0.103   0.6153 0.43309
L:B     1   0.521   0.521   3.1242 0.07759 .
V:L:B   1   0.534   0.534   3.2024 0.07398 .
Resid 668 111.461   0.167
```

```
########################################################
ANOVA for F3-F2 at point 1
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   7.516   7.516  40.8217 3.127e-10 ***
L       1  94.120  94.120 511.2185 < 2.2e-16 ***
B       1   0.722   0.722   3.9232   0.04803 *
V:L     1   0.699   0.699   3.7983   0.05172 .
V:B     1   0.629   0.629   3.4175   0.06495 .
L:B     1   0.464   0.464   2.5226   0.11270
V:L:B   1   0.491   0.491   2.6683   0.10284
Resid 668 122.985   0.184
```

```
########################################################
ANOVA for F3-F2 at point 2
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   1.479   1.479   7.5117  0.006294 **
L       1 157.638 157.638 800.7439 < 2.2e-16 ***
B       1   1.293   1.293   6.5697  0.010591 *
V:L     1  13.134  13.134  66.7174 1.554e-15 ***
V:B     1   0.100   0.100   0.5103  0.475267
L:B     1   0.110   0.110   0.5608  0.454217
V:L:B   1   0.420   0.420   2.1321  0.144709
Resid 668 131.505   0.197
```

```
########################################################
ANOVA for F3-F2 at point 3
       Df  Sum Sq Mean Sq   F value  Pr(>F)
V       1   0.260   0.260    1.1704 0.27971
L       1 223.775 223.775 1008.4610 < 2e-16 ***
B       1   1.027   1.027    4.6269 0.03183 *
V:L     1  38.904  38.904  175.3236 < 2e-16 ***
V:B     1   0.082   0.082    0.3696 0.54345
L:B     1   0.031   0.031    0.1403 0.70812
V:L:B   1   0.624   0.624    2.8120 0.09403 .
Resid 668 148.228   0.222
```

```
########################################################
ANOVA for F3-F2 at point 4
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   2.226   2.226   8.2807  0.004135 **
L       1 267.709 267.709 996.0033 < 2.2e-16 ***
B       1   0.736   0.736   2.7369  0.098527 .
V:L     1  88.532  88.532 329.3823 < 2.2e-16 ***
V:B     1   0.047   0.047   0.1745  0.676236
L:B     1   0.420   0.420   1.5637  0.211557
V:L:B   1   0.575   0.575   2.1378  0.144178
Resid 668 179.547   0.269
```

```
########################################################
ANOVA for F3-F2 at point 5
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1   5.50    5.50  14.9883 0.0001188 ***
L       1 341.16  341.16 929.5433 < 2.2e-16 ***
B       1   0.68    0.68   1.8640 0.1726266
V:L     1 165.66  165.66 451.3753 < 2.2e-16 ***
V:B     1   0.66    0.66   1.7961 0.1806386
L:B     1   0.19    0.19   0.5159 0.4728366
V:L:B   1   0.51    0.51   1.3864 0.2394263
Resid 668 245.17    0.37
```

```
########################################################
ANOVA for F3-F2 at point 6
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  12.47   12.47  29.5058 7.816e-08 ***
L       1 404.05  404.05 956.2764 < 2.2e-16 ***
B       1   0.95    0.95   2.2416    0.1348
V:L     1 291.33  291.33 689.5022 < 2.2e-16 ***
V:B     1   0.73    0.73   1.7267    0.1893
L:B     1   0.22    0.22   0.5258    0.4686
V:L:B   1   0.78    0.78   1.8384    0.1756
Resid 668 282.25    0.42
```

```
########################################################
ANOVA for F3-F2 at point 7
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  28.11   28.11  55.3174  3.16e-13 ***
L       1 504.32  504.32 992.5626 < 2.2e-16 ***
B       1   1.12    1.12   2.2086   0.13772
V:L     1 464.52  464.52 914.2308 < 2.2e-16 ***
V:B     1   1.72    1.72   3.3774   0.06654 .
L:B     1   0.55    0.55   1.0747   0.30025
V:L:B   1   1.30    1.30   2.5649   0.10973
Resid 668 339.41    0.51
```

```
########################################################
ANOVA for F3-F2 at point 8
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  54.89   54.89   97.7862 < 2e-16 ***
L       1 586.94  586.94 1045.6563 < 2e-16 ***
B       1   1.42    1.42    2.5276 0.11234
V:L     1 592.12  592.12 1054.8899 < 2e-16 ***
V:B     1   1.94    1.94    3.4570 0.06342 .
L:B     1   1.04    1.04    1.8576 0.17336
V:L:B   1   0.84    0.84    1.4984 0.22135
Resid 668 374.96    0.56
```

```
########################################################
ANOVA for F3-F2 at point 9
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  68.45   68.45  120.3083 < 2e-16 ***
L       1 671.93  671.93 1181.0594 < 2e-16 ***
B       1   1.30    1.30    2.2897 0.13071
V:L     1 708.44  708.44 1245.2331 < 2e-16 ***
V:B     1   0.50    0.50    0.8800 0.34854
L:B     1   2.45    2.45    4.2986 0.03853 *
V:L:B   1   0.28    0.28    0.4978 0.48072
Resid 668 380.04    0.57
```

```
########################################################
ANOVA for F3-F2 at point 10
       Df Sum Sq Mean Sq   F value Pr(>F)
V       1  80.68   80.68  143.0564 <2e-16 ***
L       1 719.79  719.79 1276.2895 <2e-16 ***
B       1   0.56    0.56    1.0004 0.3176
V:L     1 806.79  806.79 1430.5499 <2e-16 ***
V:B     1   0.24    0.24    0.4224 0.5159
L:B     1   1.30    1.30    2.3082 0.1292
V:L:B   1   0.61    0.61    1.0901 0.2968
Resid 668 376.73    0.56
```

```
########################################################
ANOVA for F3-F2 at point 11
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  48.14   48.14   89.0995 < 2e-16 ***
L       1 777.53  777.53 1439.2229 < 2e-16 ***
B       1   2.12    2.12    3.9199 0.04813 *
V:L     1 872.69  872.69 1615.3681 < 2e-16 ***
V:B     1   0.21    0.21    0.3827 0.53636
L:B     1   0.19    0.19    0.3549 0.55154
V:L:B   1   1.09    1.09    2.0103 0.15670
Resid 668 360.88    0.54
```

```
########################################################
ANOVA for F3-F2 at point 12
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  44.19   44.19   83.2101 < 2e-16 ***
L       1 830.81  830.81 1564.2932 < 2e-16 ***
B       1   1.57    1.57    2.9643 0.08558 .
V:L     1 932.05  932.05 1754.9140 < 2e-16 ***
V:B     1   2.55    2.55    4.8100 0.02864 *
L:B     1   0.29    0.29    0.5402 0.46261
V:L:B   1   0.02    0.02    0.0324 0.85724
Resid 668 354.78    0.53
```

```
#######################################################
ANOVA for F3-F2 at point 13
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1  43.45   43.45   72.6963 < 2e-16 ***
L       1 869.46  869.46 1454.6123 < 2e-16 ***
B       1   0.76    0.76    1.2678 0.26059
V:L     1 959.80  959.80 1605.7620 < 2e-16 ***
V:B     1   3.95    3.95    6.6116 0.01035 *
L:B     1   2.66    2.66    4.4509 0.03525 *
V:L:B   1   0.18    0.18    0.3039 0.58161
Resid 668 399.28    0.60
```

```
#######################################################
ANOVA for F3-F2 at point 14
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1  49.59   49.59   77.9309 < 2.2e-16 ***
L       1 933.23  933.23 1466.5274 < 2.2e-16 ***
B       1   0.43    0.43    0.6747 0.4117231
V:L     1 954.51  954.51 1499.9729 < 2.2e-16 ***
V:B     1   2.59    2.59    4.0744 0.0439379 *
L:B     1   7.05    7.05   11.0840 0.0009186 ***
V:L:B   1   0.45    0.45    0.7113 0.3993075
Resid 668 425.08    0.64
```

```
#######################################################
ANOVA for F3-F2 at point 15
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1  59.67   59.67   86.9344 < 2.2e-16 ***
L       1 920.42  920.42 1341.0929 < 2.2e-16 ***
B       1   0.26    0.26    0.3822  0.536647
V:L     1 947.88  947.88 1381.0918 < 2.2e-16 ***
V:B     1   2.61    2.61    3.7982  0.051727 .
L:B     1   7.42    7.42   10.8118  0.001061 **
V:L:B   1   0.75    0.75    1.0919  0.296418
Resid 668 458.46    0.69
```

```
#######################################################
ANOVA for F3-F2 at point 16
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1  69.18   69.18  103.1474 < 2.2e-16 ***
L       1 970.58  970.58 1447.0590 < 2.2e-16 ***
B       1   1.84    1.84    2.7470  0.097906 .
V:L     1 911.69  911.69 1359.2466 < 2.2e-16 ***
V:B     1   0.73    0.73    1.0909  0.296645
L:B     1   5.43    5.43    8.1021  0.004557 **
V:L:B   1   0.41    0.41    0.6132  0.433864
Resid 668 448.05    0.67
```

```
#######################################################
ANOVA for F3-F2 at point 17
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   71.87   71.87  107.7712 < 2.2e-16 ***
L       1 1013.70 1013.70 1520.0690 < 2.2e-16 ***
B       1    1.47    1.47    2.1989 0.1385787
V:L     1  884.08  884.08 1325.6927 < 2.2e-16 ***
V:B     1    0.19    0.19    0.2922 0.5890177
L:B     1    7.79    7.79   11.6763 0.0006714 ***
V:L:B   1    0.60    0.60    0.9018 0.3426410
Resid 668  445.48    0.67
```

```
#######################################################
ANOVA for F3-F2 at point 18
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   82.39   82.39  127.5336 < 2.2e-16 ***
L       1 1073.08 1073.08 1661.1367 < 2.2e-16 ***
B       1    2.13    2.13    3.2950   0.06994 .
V:L     1  813.54  813.54 1259.3669 < 2.2e-16 ***
V:B     1    0.01    0.01    0.0086   0.92628
L:B     1   10.53   10.53   16.2985 6.037e-05 ***
V:L:B   1    0.58    0.58    0.9011   0.34283
Resid 668  431.52    0.65
```

```
#######################################################
ANOVA for F3-F2 at point 19
       Df    Sum Sq   Mean Sq   F value    Pr(>F)
V       1    104.78    104.78  151.8296 < 2.2e-16 ***
L       1   1094.43   1094.43 1585.8172 < 2.2e-16 ***
B       1      3.21      3.21    4.6450 0.0315014 *
V:L     1    767.57    767.57 1112.2008 < 2.2e-16 ***
V:B     1 2.912e-05 2.912e-05 4.219e-05 0.9948194
L:B     1      9.55      9.55   13.8384 0.0002160 ***
V:L:B   1      0.43      0.43    0.6286 0.4281567
Resid 668    461.01      0.69
```

```
#######################################################
ANOVA for F3-F2 at point 20
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1  161.17  161.17  206.4719 < 2.2e-16 ***
L       1 1081.05 1081.05 1384.9465 < 2.2e-16 ***
B       1   11.43   11.43   14.6468 0.0001418 ***
V:L     1  747.00  747.00  956.9879 < 2.2e-16 ***
V:B     1    1.04    1.04    1.3299 0.2492284
L:B     1   12.26   12.26   15.7107 8.176e-05 ***
V:L:B   1    1.03    1.03    1.3221 0.2506247
Resid 668  521.42    0.78
```

```
#######################################################
ANOVA for F3-F2 at point 21
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1  150.37  150.37  190.7855 < 2.2e-16 ***
L       1 1083.17 1083.17 1374.2537 < 2.2e-16 ***
B       1   30.11   30.11   38.1992 1.111e-09 ***
V:L     1  668.13  668.13  847.6831 < 2.2e-16 ***
V:B     1    0.89    0.89    1.1238 0.2894761
L:B     1   10.98   10.98   13.9323 0.0002057 ***
V:L:B   1    0.31    0.31    0.3892 0.5329593
Resid 668  526.51    0.79
```

```
#######################################################
ANOVA for F3-F2 at point 22
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1  137.48  137.48  161.3579 < 2.2e-16 ***
L       1 1026.47 1026.47 1204.7671 < 2.2e-16 ***
B       1   58.77   58.77   68.9735 5.551e-16 ***
V:L     1  535.81  535.81  628.8795 < 2.2e-16 ***
V:B     1    0.10    0.10    0.1203  0.728830
L:B     1    9.28    9.28   10.8881  0.001019 **
V:L:B   1    0.07    0.07    0.0812  0.775831
Resid 668  569.14    0.85
```

```
#######################################################
ANOVA for F3-F2 at point 23
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 127.08  127.08 133.4072 < 2.2e-16 ***
L       1 932.24  932.24 978.6373 < 2.2e-16 ***
B       1  93.31   93.31  97.9598 < 2.2e-16 ***
V:L     1 426.02  426.02 447.2258 < 2.2e-16 ***
V:B     1   0.03    0.03   0.0350  0.851573
L:B     1   9.89    9.89  10.3785  0.001337 **
V:L:B   1   0.38    0.38   0.3969  0.528904
Resid 668 636.33    0.95
```

```
#######################################################
ANOVA for F3-F2 at point 24
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 123.59  123.59 110.7771 < 2.2e-16 ***
L       1 855.71  855.71 766.9909 < 2.2e-16 ***
B       1 138.29  138.29 123.9559 < 2.2e-16 ***
V:L     1 316.99  316.99 284.1277 < 2.2e-16 ***
V:B     1   0.59    0.59   0.5308  0.466540
L:B     1   9.33    9.33   8.3630  0.003954 **
V:L:B   1   0.84    0.84   0.7518  0.386219
Resid 668 745.27    1.12
```

```
#######################################################
ANOVA for F3-F2 at point 25
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 117.77  117.77  90.9066 < 2.2e-16 ***
L       1 751.66  751.66 580.2198 < 2.2e-16 ***
B       1 191.58  191.58 147.8863 < 2.2e-16 ***
V:L     1 223.26  223.26 172.3345 < 2.2e-16 ***
V:B     1   2.50    2.50   1.9284  0.165401
L:B     1   9.25    9.25   7.1389  0.007727 **
V:L:B   1   0.77    0.77   0.5926  0.441706
Resid 668 865.38    1.30
```

```
#######################################################
ANOVA for F3-F2 at point 26
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1 112.26  112.26  77.0376 < 2e-16 ***
L       1 658.85  658.85 452.1358 < 2e-16 ***
B       1 243.16  243.16 166.8698 < 2e-16 ***
V:L     1 145.41  145.41  99.7900 < 2e-16 ***
V:B     1   5.28    5.28   3.6221 0.05745 .
L:B     1   8.50    8.50   5.8344 0.01598 *
V:L:B   1   1.53    1.53   1.0520 0.30541
Resid 668 973.41    1.46
```

```
#######################################################
ANOVA for F3-F2 at point 27
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   89.86   89.86  53.5166 7.372e-13 ***
L       1  550.10  550.10 327.6111 < 2.2e-16 ***
B       1  295.40  295.40 175.9225 < 2.2e-16 ***
V:L     1   87.66   87.66  52.2074 1.367e-12 ***
V:B     1    9.08    9.08   5.4050   0.02038 *
L:B     1   10.92   10.92   6.5010   0.01100 *
V:L:B   1    1.94    1.94   1.1571   0.28246
Resid 668 1121.66    1.68
```

```
#######################################################
ANOVA for F3-F2 at point 28
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   69.61   69.61  37.4311 1.613e-09 ***
L       1  455.02  455.02 244.6917 < 2.2e-16 ***
B       1  328.77  328.77 176.8014 < 2.2e-16 ***
V:L     1   54.01   54.01  29.0462 9.809e-08 ***
V:B     1   14.80   14.80   7.9601  0.004924 **
L:B     1   13.73   13.73   7.3849  0.006748 **
V:L:B   1    1.64    1.64   0.8842  0.347381
Resid 668 1242.19    1.86
```

```
#######################################################
ANOVA for F3-F2 at point 29
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   63.99   63.99  31.7571 2.577e-08 ***
L       1  377.78  377.78 187.4881 < 2.2e-16 ***
B       1  361.10  361.10 179.2095 < 2.2e-16 ***
V:L     1   29.90   29.90  14.8391 0.0001284 ***
V:B     1   19.34   19.34   9.5992 0.0020283 **
L:B     1   13.59   13.59   6.7422 0.0096231 **
V:L:B   1    1.20    1.20   0.5943 0.4410294
Resid 668 1345.98    2.01
```

```
#######################################################
ANOVA for F3-F2 at point 30
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   58.06   58.06  26.6885 3.160e-07 ***
L       1  300.18  300.18 137.9747 < 2.2e-16 ***
B       1  391.57  391.57 179.9825 < 2.2e-16 ***
V:L     1   16.37   16.37   7.5224  0.006257 **
V:B     1   22.29   22.29  10.2473  0.001434 **
L:B     1   14.45   14.45   6.6439  0.010163 *
V:L:B   1    0.71    0.71   0.3264  0.567959
Resid 668 1453.29    2.18
```

```
#######################################################
ANOVA for F3-F2 at point 31
       Df    Sum Sq   Mean Sq  F value    Pr(>F)
V       1     56.24     56.24  25.3519 6.152e-07 ***
L       1    154.19    154.19  69.5087 4.441e-16 ***
B       1    399.37    399.37 180.0431 < 2.2e-16 ***
V:L     1     10.20     10.20   4.5963   0.03240 *
V:B     1     22.60     22.60  10.1879   0.00148 **
L:B     1     13.10     13.10   5.9047   0.01536 *
V:L:B   1 0.0007582 0.0007582   0.0003   0.98525
Resid 668   1481.77      2.22
```

```
#######################################################
ANOVA for F3-F2 at point 32
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   43.01   43.01  19.4796 1.185e-05 ***
L       1   64.99   64.99  29.4321 8.106e-08 ***
B       1  448.28  448.28 203.0184 < 2.2e-16 ***
V:L     1    7.06    7.06   3.1987  0.074149 .
V:B     1   19.56   19.56   8.8585  0.003023 **
L:B     1   10.21   10.21   4.6219  0.031925 *
V:L:B   1    0.16    0.16   0.0718  0.788786
Resid 668 1474.99    2.21
```

```
#######################################################
ANOVA for F3-F2 at point 33
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   27.11   27.11  12.0301 0.0005571 ***
L       1   24.62   24.62  10.9267 0.0009986 ***
B       1  540.49  540.49 239.8789 < 2.2e-16 ***
V:L     1    7.91    7.91   3.5122 0.0613550 .
V:B     1   13.38   13.38   5.9362 0.0150935 *
L:B     1    7.30    7.30   3.2402 0.0723018 .
V:L:B   1    0.16    0.16   0.0691 0.7927820
Resid 668 1505.12    2.25
```

```
#######################################################
ANOVA for F3-F2 at point 34
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   23.80   23.80  11.2956 0.0008212 ***
L       1    7.55    7.55   3.5841 0.0587655 .
B       1  681.16  681.16 323.3193 < 2.2e-16 ***
V:L     1    7.57    7.57   3.5946 0.0583973 .
V:B     1    9.41    9.41   4.4659 0.0349489 *
L:B     1    5.42    5.42   2.5722 0.1092276
V:L:B   1    0.49    0.49   0.2340 0.6287214
Resid 668 1407.32    2.11
```

```
#######################################################
ANOVA for F3-F2 at point 35
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   19.59   19.59  10.2082  0.001464 **
L       1    3.60    3.60   1.8774  0.171085
B       1  844.88  844.88 440.2001 < 2.2e-16 ***
V:L     1    5.09    5.09   2.6525  0.103861
V:B     1   10.50   10.50   5.4683  0.019658 *
L:B     1    4.78    4.78   2.4909  0.114981
V:L:B   1    0.16    0.16   0.0824  0.774114
Resid 668 1282.10    1.92
```

```
#######################################################
ANOVA for F3-F2 at point 36
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   18.49   18.49  10.6164  0.001178 **
L       1    0.94    0.94   0.5382  0.463454
B       1 1053.06 1053.06 604.5000 < 2.2e-16 ***
V:L     1    3.08    3.08   1.7658  0.184355
V:B     1    8.71    8.71   5.0002  0.025674 *
L:B     1    3.86    3.86   2.2172  0.136951
V:L:B   1    0.52    0.52   0.2976  0.585542
Resid 668 1163.68    1.74
```

```
#######################################################
ANOVA for F3-F2 at point 37
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    20.18    20.18  12.2924 0.0004852 ***
L       1 0.001045 0.001045   0.0006 0.9798754
B       1  1211.91  1211.91 738.1471 < 2.2e-16 ***
V:L     1     1.95     1.95   1.1864 0.2764408
V:B     1     8.87     8.87   5.4001 0.0204347 *
L:B     1     2.02     2.02   1.2284 0.2681177
V:L:B   1     0.28     0.28   0.1681 0.6819098
Resid 668  1096.74     1.64
```

```
#######################################################
ANOVA for F3-F2 at point 38
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   19.52   19.52  11.8000  0.000629 ***
L       1    0.15    0.15   0.0911  0.762917
B       1 1263.96 1263.96 763.9590 < 2.2e-16 ***
V:L     1    2.94    2.94   1.7751  0.183208
V:B     1   10.64   10.64   6.4307  0.011443 *
L:B     1    2.79    2.79   1.6864  0.194523
V:L:B   1    0.35    0.35   0.2108  0.646311
Resid 668 1105.19    1.65
```

```
#######################################################
ANOVA for F3-F2 at point 39
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   19.20   19.20  11.4433 0.0007594 ***
L       1    0.19    0.19   0.1135 0.7362788
B       1 1210.77 1210.77 721.7902 < 2.2e-16 ***
V:L     1    3.25    3.25   1.9368 0.1644845
V:B     1    9.09    9.09   5.4195 0.0202110 *
L:B     1    2.80    2.80   1.6678 0.1970028
V:L:B   1    0.68    0.68   0.4040 0.5252381
Resid 668 1120.54    1.68
```

```
#######################################################
ANOVA for F3-F2 at point 40
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   29.52   29.52  18.3847 2.071e-05 ***
L       1 0.00429 0.00429   0.0027   0.95879
B       1 1099.69 1099.69 684.8179 < 2.2e-16 ***
V:L     1    1.18    1.18   0.7356   0.39138
V:B     1    9.86    9.86   6.1373   0.01348 *
L:B     1    4.56    4.56   2.8370   0.09258 .
V:L:B   1    0.01    0.01   0.0086   0.92626
Resid 668 1072.69    1.61
```

```
#######################################################
```

Centre of Gravity (F2-F1)

```
#######################################################
ANOVA for CoG (F2-F1) at point 0
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  1.280   1.280  9.6222  0.002003 **
L       1  8.551   8.551 64.2908 4.774e-15 ***
B       1  0.173   0.173  1.3024  0.254187
V:L     1  0.621   0.621  4.6673  0.031096 *
V:B     1  0.134   0.134  1.0102  0.315209
L:B     1  0.129   0.129  0.9729  0.324317
V:L:B   1  0.046   0.046  0.3434  0.558084
Resid 668 88.851   0.133
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 1
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  0.127   0.127  0.9892   0.32029
L       1  8.526   8.526 66.3264 1.887e-15 ***
B       1  0.064   0.064  0.5013   0.47919
V:L     1  5.079   5.079 39.5127 5.884e-10 ***
V:B     1  0.535   0.535  4.1650   0.04166 *
L:B     1  0.242   0.242  1.8798   0.17082
V:L:B   1  0.251   0.251  1.9537   0.16265
Resid 668 85.872   0.129
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 2
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.154   0.154   0.9564    0.3285
L       1   9.493   9.493  59.1284 5.307e-14 ***
B       1   0.318   0.318   1.9780    0.1601
V:L     1  16.591  16.591 103.3377 < 2.2e-16 ***
V:B     1   0.372   0.372   2.3151    0.1286
L:B     1   0.085   0.085   0.5296    0.4670
V:L:B   1   0.312   0.312   1.9417    0.1640
Resid 668 107.251   0.161
```

```
########################################################
ANOVA for CoG (F2-F1) at point 3
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.023   0.023   0.1251   0.72364
L       1   8.919   8.919  48.9644 6.352e-12 ***
B       1   0.361   0.361   1.9831   0.15952
V:L     1  39.272  39.272 215.5904 < 2.2e-16 ***
V:B     1   0.809   0.809   4.4400   0.03548 *
L:B     1   0.058   0.058   0.3174   0.57337
V:L:B   1   0.178   0.178   0.9754   0.32368
Resid 668 121.683   0.182
```

```
########################################################
ANOVA for CoG (F2-F1) at point 4
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.367   0.367   1.8565   0.17349
L       1   5.421   5.421  27.4402 2.174e-07 ***
B       1   0.521   0.521   2.6392   0.10473
V:L     1  60.528  60.528 306.3686 < 2.2e-16 ***
V:B     1   0.949   0.949   4.8039   0.02874 *
L:B     1   0.106   0.106   0.5364   0.46418
V:L:B   1   0.330   0.330   1.6689   0.19686
Resid 668 131.974   0.198
```

```
########################################################
ANOVA for CoG (F2-F1) at point 5
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   2.321   2.321  11.0619 0.0009294 ***
L       1   2.590   2.590  12.3434 0.0004724 ***
B       1   0.420   0.420   2.0004 0.1577231
V:L     1  85.389  85.389 407.0201 < 2.2e-16 ***
V:B     1   1.847   1.847   8.8026 0.0031155 **
L:B     1   0.003   0.003   0.0130 0.9092906
V:L:B   1   0.121   0.121   0.5753 0.4484101
Resid 668 140.141   0.210
```

```
########################################################
ANOVA for CoG (F2-F1) at point 6
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1    3.280    3.280  14.3485 0.0001656 ***
L       1    0.057    0.057   0.2502 0.6171332
B       1    0.664    0.664   2.9045 0.0887960 .
V:L     1  102.227  102.227 447.1836 < 2.2e-16 ***
V:B     1    0.740    0.740   3.2363 0.0724761 .
L:B     1    0.022    0.022   0.0972 0.7553249
V:L:B   1 0.000326 0.000326   0.0014 0.9698868
Resid 668  152.706    0.229
```

```
########################################################
ANOVA for CoG (F2-F1) at point 7
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   4.572   4.572  19.9179 9.487e-06 ***
L       1   5.259   5.259  22.9094 2.092e-06 ***
B       1   0.588   0.588   2.5608   0.11002
V:L     1 129.154 129.154 562.5990 < 2.2e-16 ***
V:B     1   1.439   1.439   6.2678   0.01253 *
L:B     1   0.027   0.027   0.1178   0.73158
V:L:B   1   0.093   0.093   0.4036   0.52545
Resid 668 153.351   0.230
```

```
########################################################
ANOVA for CoG (F2-F1) at point 8
       Df    Sum Sq   Mean Sq   F value    Pr(>F)
V       1     2.946     2.946   13.4865 0.0002595 ***
L       1    15.073    15.073   69.0093 5.551e-16 ***
B       1     1.609     1.609    7.3651 0.0068219 **
V:L     1   149.081   149.081  682.5273 < 2.2e-16 ***
V:B     1     0.911     0.911    4.1696 0.0415470 *
L:B     1 2.204e-04 2.204e-04    0.0010 0.9746680
V:L:B   1 9.339e-06 9.339e-06 4.275e-05 0.9947849
Resid 668   145.908     0.218
```

```
########################################################
ANOVA for CoG (F2-F1) at point 9
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   0.423   0.423   1.9546 0.1625610
L       1  29.422  29.422 136.0311 < 2.2e-16 ***
B       1   2.888   2.888  13.3543 0.0002781 ***
V:L     1 167.369 167.369 773.8178 < 2.2e-16 ***
V:B     1   0.135   0.135   0.6258 0.4291978
L:B     1   0.043   0.043   0.1979 0.6565848
V:L:B   1   0.006   0.006   0.0286 0.8657719
Resid 668 144.482   0.216
```

```
########################################################
ANOVA for CoG (F2-F1) at point 10
       Df    Sum Sq   Mean Sq  F value    Pr(>F)
V       1 0.0001549 0.0001549   0.0008  0.977842
L       1    44.600    44.600 222.2923 < 2.2e-16 ***
B       1     1.901     1.901   9.4771  0.002166 **
V:L     1   186.921   186.921 931.6315 < 2.2e-16 ***
V:B     1     0.236     0.236   1.1752  0.278730
L:B     1     0.007     0.007   0.0330  0.855827
V:L:B   1 0.0003334 0.0003334   0.0017  0.967499
Resid 668   134.026     0.201
```

```
########################################################
ANOVA for CoG (F2-F1) at point 11
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   2.668   2.668   14.5717 0.0001475 ***
L       1  46.286  46.286  252.8409 < 2.2e-16 ***
B       1   3.094   3.094   16.9023 4.426e-05 ***
V:L     1 191.930 191.930 1048.4429 < 2.2e-16 ***
V:B     1   0.120   0.120    0.6548 0.4187015
L:B     1   0.014   0.014    0.0791 0.7786289
V:L:B   1   0.010   0.010    0.0523 0.8192610
Resid 668 122.285   0.183
```

```
########################################################
ANOVA for CoG (F2-F1) at point 12
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   4.296   4.296   24.1122 1.144e-06 ***
L       1  51.011  51.011  286.3373 < 2.2e-16 ***
B       1   2.678   2.678   15.0297 0.0001163 ***
V:L     1 205.816 205.816 1155.2992 < 2.2e-16 ***
V:B     1   0.356   0.356    1.9980 0.1579744
L:B     1   0.026   0.026    0.1465 0.7020248
V:L:B   1   0.137   0.137    0.7670 0.3814520
Resid 668 119.004   0.178
```

```
########################################################
ANOVA for CoG (F2-F1) at point 13
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   4.665   4.665   27.5202 2.090e-07 ***
L       1  61.869  61.869  364.9681 < 2.2e-16 ***
B       1   1.379   1.379    8.1350  0.004476 **
V:L     1 212.251 212.251 1252.0778 < 2.2e-16 ***
V:B     1   0.792   0.792    4.6722  0.031009 *
L:B     1   0.094   0.094    0.5552  0.456480
V:L:B   1   0.268   0.268    1.5800  0.209198
Resid 668 113.239   0.170
```

```
########################################################
ANOVA for CoG (F2-F1) at point 14
       Df  Sum Sq Mean Sq   F value    Pr(>F)
V       1   3.881   3.881   22.7317 2.288e-06 ***
L       1  55.279  55.279  323.7845 < 2.2e-16 ***
B       1   2.078   2.078   12.1734 0.0005166 ***
V:L     1 198.068 198.068 1160.1525 < 2.2e-16 ***
V:B     1   0.256   0.256    1.5000 0.2211093
L:B     1   0.535   0.535    3.1317 0.0772400 .
V:L:B   1   0.867   0.867    5.0784 0.0245491 *
Resid 668 114.045   0.171
```

```
########################################################
ANOVA for CoG (F2-F1) at point 15
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   5.093   5.093  26.7882 3.007e-07 ***
L       1  50.399  50.399 265.1105 < 2.2e-16 ***
B       1   2.575   2.575  13.5453 0.0002517 ***
V:L     1 181.867 181.867 956.6565 < 2.2e-16 ***
V:B     1   0.024   0.024   0.1288 0.7197481
L:B     1   0.299   0.299   1.5734 0.2101487
V:L:B   1   0.996   0.996   5.2409 0.0223735 *
Resid 668 126.991   0.190
```

```
########################################################
ANOVA for CoG (F2-F1) at point 16
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   4.573   4.573  24.1730 1.109e-06 ***
L       1  43.817  43.817 231.6307 < 2.2e-16 ***
B       1   2.084   2.084  11.0182 0.0009512 ***
V:L     1 161.428 161.428 853.3646 < 2.2e-16 ***
V:B     1   0.133   0.133   0.7012 0.4026791
L:B     1   0.945   0.945   4.9957 0.0257405 *
V:L:B   1   1.739   1.739   9.1949 0.0025208 **
Resid 668 126.363   0.189
```

```
########################################################
ANOVA for CoG (F2-F1) at point 17
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   6.728   6.728  35.7759 3.607e-09 ***
L       1  38.938  38.938 207.0625 < 2.2e-16 ***
B       1   0.553   0.553   2.9396  0.086894 .
V:L     1 143.143 143.143 761.1976 < 2.2e-16 ***
V:B     1   0.007   0.007   0.0393  0.842932
L:B     1   0.749   0.749   3.9822  0.046388 *
V:L:B   1   1.693   1.693   9.0021  0.002797 **
Resid 668 125.617   0.188
```

```
########################################################
ANOVA for CoG (F2-F1) at point 18
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1   4.845   4.845  24.8630 7.854e-07 ***
L       1  47.059  47.059 241.4723 < 2.2e-16 ***
B       1   0.686   0.686   3.5188 0.0611110 .
V:L     1 136.820 136.820 702.0519 < 2.2e-16 ***
V:B     1   0.128   0.128   0.6545 0.4188023
L:B     1   0.538   0.538   2.7607 0.0970768 .
V:L:B   1   2.536   2.536  13.0110 0.0003328 ***
Resid 668 130.183   0.195
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 19
        Df  Sum Sq Mean Sq  F value  Pr(>F)
V        1   0.839   0.839   3.5102 0.06143 .
L        1  55.528  55.528 232.3407 < 2e-16 ***
B        1   0.014   0.014   0.0576 0.81038
V:L      1 128.630 128.630 538.2117 < 2e-16 ***
V:B      1   0.004   0.004   0.0167 0.89726
L:B      1   0.222   0.222   0.9269 0.33602
V:L:B    1   1.432   1.432   5.9916 0.01463 *
Resid 668 159.648   0.239
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 20
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   4.805   4.805  15.7540 7.995e-05 ***
L        1  80.688  80.688 264.5432 < 2.2e-16 ***
B        1   1.170   1.170   3.8365  0.050563 .
V:L      1 141.762 141.762 464.7823 < 2.2e-16 ***
V:B      1   1.039   1.039   3.4075  0.065343 .
L:B      1   2.018   2.018   6.6159  0.010322 *
V:L:B    1   3.142   3.142  10.3005  0.001394 **
Resid 668 203.745   0.305
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 21
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   2.350   2.350   7.9968  0.004826 **
L        1  86.704  86.704 295.0184 < 2.2e-16 ***
B        1   9.519   9.519  32.3892 1.890e-08 ***
V:L      1 136.124 136.124 463.1751 < 2.2e-16 ***
V:B      1   0.489   0.489   1.6653  0.197330
L:B      1   2.067   2.067   7.0330  0.008192 **
V:L:B    1   3.001   3.001  10.2109  0.001462 **
Resid 668 196.321   0.294
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 22
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   0.356   0.356   1.1482 0.2843062
L        1  98.764  98.764 318.3753 < 2.2e-16 ***
B        1  20.126  20.126  64.8794 3.664e-15 ***
V:L      1 109.656 109.656 353.4867 < 2.2e-16 ***
V:B      1   0.064   0.064   0.2067 0.6494842
L:B      1   3.590   3.590  11.5713 0.0007097 ***
V:L:B    1   0.988   0.988   3.1860 0.0747262 .
Resid 668 207.222   0.310
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 23
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   0.009   0.009   0.0291  0.864712
L        1 103.194 103.194 338.4310 < 2.2e-16 ***
B        1  44.001  44.001 144.3043 < 2.2e-16 ***
V:L      1  87.738  87.738 287.7423 < 2.2e-16 ***
V:B      1   0.002   0.002   0.0075  0.931236
L:B      1   2.857   2.857   9.3682  0.002296 **
V:L:B    1   0.276   0.276   0.9039  0.342074
Resid 668 203.685   0.305
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 24
        Df  Sum Sq Mean Sq  F value  Pr(>F)
V        1   0.007   0.007   0.0200 0.88770
L        1  86.998  86.998 260.4326 < 2e-16 ***
B        1  76.784  76.784 229.8554 < 2e-16 ***
V:L      1  63.161  63.161 189.0757 < 2e-16 ***
V:B      1   0.243   0.243   0.7279 0.39388
L:B      1   1.480   1.480   4.4296 0.03569 *
V:L:B    1   0.024   0.024   0.0710 0.78997
Resid 668 223.147   0.334
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 25
        Df  Sum Sq Mean Sq  F value  Pr(>F)
V        1   0.020   0.020   0.0594 0.80756
L        1  70.068  70.068 206.4787 < 2e-16 ***
B        1 112.393 112.393 331.2022 < 2e-16 ***
V:L      1  47.904  47.904 141.1655 < 2e-16 ***
V:B      1   0.696   0.696   2.0502 0.15265
L:B      1   0.982   0.982   2.8924 0.08946 .
V:L:B    1   0.077   0.077   0.2260 0.63465
Resid 668 226.685   0.339
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 26
        Df  Sum Sq Mean Sq  F value  Pr(>F)
V        1   0.275   0.275   0.7877 0.37511
L        1  49.537  49.537 142.0333 < 2e-16 ***
B        1 151.187 151.187 433.4833 < 2e-16 ***
V:L      1  32.691  32.691  93.7310 < 2e-16 ***
V:B      1   0.982   0.982   2.8151 0.09385 .
L:B      1   0.035   0.035   0.0990 0.75309
V:L:B    1   0.401   0.401   1.1512 0.28369
Resid 668 232.980   0.349
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 27
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   0.191   0.191   0.5122   0.47442
L        1  45.247  45.247 121.2063 < 2.2e-16 ***
B        1 192.927 192.927 516.8067 < 2.2e-16 ***
V:L      1  20.940  20.940  56.0926 2.195e-13 ***
V:B      1   0.724   0.724   1.9382   0.16432
L:B      1   0.021   0.021   0.0557   0.81344
V:L:B    1   1.134   1.134   3.0376   0.08181 .
Resid 668 249.368   0.373
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 28
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   0.061   0.061   0.1552   0.69377
L        1  38.030  38.030  97.3829 < 2.2e-16 ***
B        1 228.302 228.302 584.6022 < 2.2e-16 ***
V:L      1  13.131  13.131  33.6227 1.032e-08 ***
V:B      1   0.417   0.417   1.0683   0.30171
L:B      1   0.036   0.036   0.0929   0.76061
V:L:B    1   1.731   1.731   4.4337   0.03561 *
Resid 668 260.871   0.391
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 29
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   0.155   0.155   0.3899   0.53256
L        1  34.978  34.978  88.1313 < 2.2e-16 ***
B        1 251.675 251.675 634.1178 < 2.2e-16 ***
V:L      1   8.175   8.175  20.5980 6.719e-06 ***
V:B      1   0.121   0.121   0.3060   0.58030
L:B      1   0.270   0.270   0.6791   0.41019
V:L:B    1   2.210   2.210   5.5673   0.01859 *
Resid 668 265.123   0.397
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 30
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   0.669   0.669   1.6688 0.1968655
L        1  27.210  27.210  67.8287 8.882e-16 ***
B        1 275.617 275.617 687.0590 < 2.2e-16 ***
V:L      1   5.187   5.187  12.9303 0.0003471 ***
V:B      1   0.273   0.273   0.6795 0.4100480
L:B      1   0.166   0.166   0.4128 0.5207964
V:L:B    1   1.945   1.945   4.8478 0.0280225 *
Resid 668 267.971   0.401
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 31
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1   4.798   4.798  14.7708 0.0001330 ***
L        1  16.165  16.165  49.7605 4.353e-12 ***
B        1 299.516 299.516 922.0088 < 2.2e-16 ***
V:L      1   3.379   3.379  10.4004 0.0013213 **
V:B      1   0.203   0.203   0.6236 0.4299846
L:B      1   0.116   0.116   0.3585 0.5495589
V:L:B    1   1.035   1.035   3.1853 0.0747591 .
Resid 668 217.001   0.325
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 32
        Df Sum Sq Mean Sq   F value    Pr(>F)
V        1   5.09    5.09   17.1102 3.977e-05 ***
L        1   7.73    7.73   26.0033 4.445e-07 ***
B        1 331.90  331.90 1116.4512 < 2.2e-16 ***
V:L      1   3.75    3.75   12.6043 0.0004119 ***
V:B      1   0.76    0.76    2.5703 0.1093578
L:B      1   0.03    0.03    0.1028 0.7486112
V:L:B    1   0.18    0.18    0.6053 0.4368559
Resid 668 198.58    0.30
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 33
        Df    Sum Sq  Mean Sq   F value    Pr(>F)
V        1      5.98     5.98   19.2715 1.318e-05 ***
L        1      3.85     3.85   12.4238 0.0004528 ***
B        1    380.28   380.28 1226.1190 < 2.2e-16 ***
V:L      1      4.39     4.39   14.1415 0.0001844 ***
V:B      1      1.72     1.72    5.5510 0.0187585 *
L:B      1 0.002362 0.002362    0.0076 0.9304842
V:L:B    1      0.21     0.21    0.6887 0.4069088
Resid 668    207.18     0.31
```

```
#########################################################
ANOVA for CoG (F2-F1) at point 34
        Df Sum Sq Mean Sq   F value    Pr(>F)
V        1   7.46    7.46   22.9705 2.029e-06 ***
L        1   3.00    3.00    9.2570 0.0024380 **
B        1 455.72  455.72 1403.9459 < 2.2e-16 ***
V:L      1   4.33    4.33   13.3386 0.0002804 ***
V:B      1   1.81    1.81    5.5847 0.0184031 *
L:B      1   0.04    0.04    0.1287 0.7198884
V:L:B    1   0.14    0.14    0.4444 0.5052535
Resid 668 216.83    0.32
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 35
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   6.43    6.43   17.9703  2.56e-05 ***
L       1   3.08    3.08    8.6103  0.003457 **
B       1 538.47  538.47 1505.3120 < 2.2e-16 ***
V:L     1   4.35    4.35   12.1610  0.000520 ***
V:B     1   2.17    2.17    6.0686  0.014012 *
L:B     1   0.12    0.12    0.3336  0.563718
V:L:B   1   0.07    0.07    0.1855  0.666838
Resid 668 238.95    0.36
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 36
       Df     Sum Sq   Mean Sq   F value    Pr(>F)
V       1       5.09      5.09   12.2127  0.000506 ***
L       1       2.70      2.70    6.4679  0.011208 *
B       1     606.30    606.30 1454.8473 < 2.2e-16 ***
V:L     1       3.33      3.33    7.9979  0.004824 **
V:B     1       1.05      1.05    2.5083  0.113722
L:B     1 2.079e-06 2.079e-06 4.988e-06  0.998219
V:L:B   1       0.02      0.02    0.0361  0.849362
Resid 668     278.39      0.42
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 37
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1   7.90    7.90   17.8639 2.703e-05 ***
L       1   2.40    2.40    5.4230   0.02017 *
B       1 673.44  673.44 1522.8921 < 2.2e-16 ***
V:L     1   1.67    1.67    3.7699   0.05260 .
V:B     1   0.78    0.78    1.7656   0.18439
L:B     1   0.24    0.24    0.5394   0.46293
V:L:B   1   0.07    0.07    0.1471   0.70141
Resid 668 295.40    0.44
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 38
       Df   Sum Sq  Mean Sq   F value    Pr(>F)
V       1     4.37     4.37    8.2896  0.004115 **
L       1     3.78     3.78    7.1615  0.007631 **
B       1   657.58   657.58 1246.2609 < 2.2e-16 ***
V:L     1     2.56     2.56    4.8507  0.027975 *
V:B     1     0.62     0.62    1.1823  0.277281
L:B     1 0.001882 0.001882    0.0036  0.952393
V:L:B   1     0.02     0.02    0.0467  0.829056
Resid 668   352.46     0.53
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 39
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1   5.40    5.40   8.6921  0.003307 **
L       1   3.07    3.07   4.9522  0.026390 *
B       1 618.07  618.07 995.4555 < 2.2e-16 ***
V:L     1   3.18    3.18   5.1186  0.023991 *
V:B     1   2.40    2.40   3.8576  0.049936 *
L:B     1   0.11    0.11   0.1784  0.672876
V:L:B   1   0.02    0.02   0.0310  0.860356
Resid 668 414.76    0.62
```

```
#######################################################
ANOVA for CoG (F2-F1) at point 40
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1   5.92    5.92   6.5179  0.010901 *
L       1   5.38    5.38   5.9176  0.015252 *
B       1 564.26  564.26 620.9186 < 2.2e-16 ***
V:L     1   0.48    0.48   0.5260  0.468543
V:B     1   6.38    6.38   7.0176  0.008262 **
L:B     1   1.31    1.31   1.4402  0.230526
V:L:B   1   0.05    0.05   0.0578  0.810061
Resid 668 607.05    0.91
```

```
#######################################################
```

Variance (F2-F1)

```
#######################################################
ANOVA for Variance (F2-F1) at point 0
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  0.6401  0.6401 20.9253 5.693e-06 ***
L       1  1.2809  1.2809 41.8724 1.885e-10 ***
B       1  0.1363  0.1363  4.4564   0.03514 *
V:L     1  0.9950  0.9950 32.5265 1.766e-08 ***
V:B     1  0.0026  0.0026  0.0866   0.76866
L:B     1  0.0054  0.0054  0.1779   0.67333
V:L:B   1  0.0031  0.0031  0.1012   0.75048
Resid 668 20.4349  0.0306
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 1
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  0.5575  0.5575 15.9384 7.269e-05 ***
L       1  2.3341  2.3341 66.7303 1.554e-15 ***
B       1  0.2725  0.2725  7.7906  0.005402 **
V:L     1  3.0768  3.0768 87.9628 < 2.2e-16 ***
V:B     1  0.0083  0.0083  0.2379  0.625887
L:B     1  0.0017  0.0017  0.0496  0.823872
V:L:B   1  0.0009  0.0009  0.0252  0.873930
Resid 668 23.3658  0.0350
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 2
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  0.3271  0.3271   8.8925  0.002968 **
L       1  2.9801  2.9801  81.0208 < 2.2e-16 ***
B       1  0.0484  0.0484   1.3164  0.251649
V:L     1  8.1433  8.1433 221.3942 < 2.2e-16 ***
V:B     1  0.0265  0.0265   0.7200  0.396436
L:B     1  0.0027  0.0027   0.0740  0.785752
V:L:B   1  0.0237  0.0237   0.6431  0.422865
Resid 668 24.5703  0.0368
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 3
       Df  Sum Sq Mean Sq  F value Pr(>F)
V       1  0.0206  0.0206   0.5565 0.4559
L       1  2.6833  2.6833  72.3996 <2e-16 ***
B       1  0.0004  0.0004   0.0111 0.9160
V:L     1 13.6918 13.6918 369.4222 <2e-16 ***
V:B     1  0.0199  0.0199   0.5363 0.4642
L:B     1  0.0343  0.0343   0.9246 0.3366
V:L:B   1  0.0034  0.0034   0.0931 0.7604
Resid 668 24.7579  0.0371
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 4
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  0.0892  0.0892   2.0763    0.1501
L       1  1.3001  1.3001  30.2773  5.34e-08 ***
B       1  0.0267  0.0267   0.6221    0.4305
V:L     1 18.4618 18.4618 429.9308 < 2.2e-16 ***
V:B     1  0.0274  0.0274   0.6374    0.4249
L:B     1  0.0826  0.0826   1.9226    0.1660
V:L:B   1  0.0083  0.0083   0.1934    0.6603
Resid 668 28.6848  0.0429
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 5
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  0.587   0.587  12.0841 0.0005415 ***
L       1  0.649   0.649  13.3641 0.0002766 ***
B       1  0.078   0.078   1.5954 0.2069923
V:L     1 23.515  23.515 483.9734 < 2.2e-16 ***
V:B     1  0.029   0.029   0.5915 0.4420945
L:B     1  0.099   0.099   2.0359 0.1540894
V:L:B   1  0.040   0.040   0.8237 0.3644234
Resid 668 32.456   0.049
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 6
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  2.526   2.526  45.6283 3.113e-11 ***
L       1  0.562   0.562  10.1514  0.001509 **
B       1  0.007   0.007   0.1238  0.725089
V:L     1 32.597  32.597 588.8622 < 2.2e-16 ***
V:B     1  0.241   0.241   4.3553  0.037274 *
L:B     1  0.035   0.035   0.6381  0.424699
V:L:B   1  0.012   0.012   0.2228  0.637047
Resid 668 36.977   0.055
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 7
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1  6.589   6.589 100.3652 < 2.2e-16 ***
L       1  0.642   0.642   9.7719  0.001849 **
B       1  0.033   0.033   0.5080  0.476258
V:L     1 48.306  48.306 735.8280 < 2.2e-16 ***
V:B     1  0.122   0.122   1.8590  0.173199
L:B     1  0.058   0.058   0.8821  0.347979
V:L:B   1  0.006   0.006   0.0885  0.766157
Resid 668 43.853   0.066
```

```
#######################################################
ANOVA for Variance (F2-F1) at point 8
       Df    Sum Sq   Mean Sq  F value  Pr(>F)
V       1    10.651    10.651 153.2369 < 2e-16 ***
L       1     0.576     0.576   8.2873 0.00412 **
B       1     0.010     0.010   0.1445 0.70396
V:L     1    59.911    59.911 861.9737 < 2e-16 ***
V:B     1     0.058     0.058   0.8335 0.36159
L:B     1     0.060     0.060   0.8670 0.35212
V:L:B   1 0.0001548 0.0001548   0.0022 0.96238
Resid 668    46.429     0.070
```

```
############################################################
ANOVA for Variance (F2-F1) at point 9
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1 13.119  13.119 191.9548 < 2e-16 ***
L       1  0.572   0.572   8.3649 0.00395 **
B       1  0.022   0.022   0.3262 0.56808
V:L     1 67.596  67.596 989.0175 < 2e-16 ***
V:B     1  0.043   0.043   0.6358 0.42552
L:B     1  0.010   0.010   0.1457 0.70283
V:L:B   1  0.001   0.001   0.0154 0.90137
Resid 668 45.655   0.068
```

```
############################################################
ANOVA for Variance (F2-F1) at point 10
       Df Sum Sq Mean Sq   F value Pr(>F)
V       1 15.012  15.012  212.8775 <2e-16 ***
L       1  0.136   0.136    1.9272 0.1655
B       1  0.178   0.178    2.5237 0.1126
V:L     1 76.640  76.640 1086.7775 <2e-16 ***
V:B     1  0.062   0.062    0.8794 0.3487
L:B     1  0.008   0.008    0.1105 0.7397
V:L:B   1  0.014   0.014    0.1933 0.6603
Resid 668 47.108   0.071
```

```
############################################################
ANOVA for Variance (F2-F1) at point 11
       Df Sum Sq Mean Sq   F value Pr(>F)
V       1 13.279  13.279  170.8726 <2e-16 ***
L       1  0.062   0.062    0.8014 0.3710
B       1  0.086   0.086    1.1091 0.2927
V:L     1 87.137  87.137 1121.3058 <2e-16 ***
V:B     1  0.020   0.020    0.2538 0.6146
L:B     1  0.036   0.036    0.4621 0.4969
V:L:B   1  0.014   0.014    0.1768 0.6742
Resid 668 51.911   0.078
```

```
############################################################
ANOVA for Variance (F2-F1) at point 12
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1 13.980  13.980  183.4604 < 2e-16 ***
L       1  0.322   0.322    4.2242 0.04024 *
B       1  0.059   0.059    0.7724 0.37980
V:L     1 87.357  87.357 1146.3537 < 2e-16 ***
V:B     1  0.099   0.099    1.3029 0.25409
L:B     1  0.066   0.066    0.8610 0.35381
V:L:B   1  0.001   0.001    0.0084 0.92705
Resid 668 50.905   0.076
```

```
############################################################
ANOVA for Variance (F2-F1) at point 13
       Df Sum Sq Mean Sq   F value  Pr(>F)
V       1 15.649  15.649  195.3847 < 2e-16 ***
L       1  0.352   0.352    4.3931 0.03646 *
B       1  0.100   0.100    1.2470 0.26453
V:L     1 89.769  89.769 1120.8033 < 2e-16 ***
V:B     1  0.209   0.209    2.6084 0.10677
L:B     1  0.011   0.011    0.1369 0.71153
V:L:B   1  0.043   0.043    0.5319 0.46608
Resid 668 53.503   0.080
```

```
############################################################
ANOVA for Variance (F2-F1) at point 14
       Df Sum Sq Mean Sq   F value    Pr(>F)
V       1 18.845  18.845  214.0112 < 2.2e-16 ***
L       1  0.783   0.783    8.8886  0.002974 **
B       1  0.071   0.071    0.8060  0.369643
V:L     1 88.533  88.533 1005.4451 < 2.2e-16 ***
V:B     1  0.206   0.206    2.3408  0.126495
L:B     1  0.142   0.142    1.6121  0.204635
V:L:B   1  0.070   0.070    0.7993  0.371619
Resid 668 58.820   0.088
```

```
############################################################
ANOVA for Variance (F2-F1) at point 15
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 21.565  21.565 220.5293 < 2.2e-16 ***
L       1  0.987   0.987  10.0925  0.001557 **
B       1  0.102   0.102   1.0467  0.306648
V:L     1 87.691  87.691 896.7506 < 2.2e-16 ***
V:B     1  0.189   0.189   1.9312  0.165093
L:B     1  0.288   0.288   2.9464  0.086532 .
V:L:B   1  0.106   0.106   1.0829  0.298427
Resid 668 65.322   0.098
```

```
############################################################
ANOVA for Variance (F2-F1) at point 16
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 23.755  23.755 231.4401 < 2.2e-16 ***
L       1  2.287   2.287  22.2792 2.873e-06 ***
B       1  0.019   0.019   0.1829    0.6691
V:L     1 80.227  80.227 781.6345 < 2.2e-16 ***
V:B     1  0.090   0.090   0.8781    0.3491
L:B     1  0.076   0.076   0.7449    0.3884
V:L:B   1  0.032   0.032   0.3090    0.5785
Resid 668 68.563   0.103
```

```
############################################################
ANOVA for Variance (F2-F1) at point 17
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 26.122  26.122 246.1588 < 2.2e-16 ***
L       1  3.200   3.200  30.1502 5.686e-08 ***
B       1  0.059   0.059   0.5557   0.45624
V:L     1 76.179  76.179 717.8531 < 2.2e-16 ***
V:B     1  0.048   0.048   0.4508   0.50218
L:B     1  0.362   0.362   3.4076   0.06534 .
V:L:B   1  0.041   0.041   0.3876   0.53376
Resid 668 70.888   0.106
```

```
############################################################
ANOVA for Variance (F2-F1) at point 18
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 26.385  26.385 229.9384 < 2.2e-16 ***
L       1  4.839   4.839  42.1671 1.636e-10 ***
B       1  0.006   0.006   0.0482   0.82633
V:L     1 67.536  67.536 588.5653 < 2.2e-16 ***
V:B     1  0.020   0.020   0.1785   0.67281
L:B     1  0.512   0.512   4.4650   0.03497 *
V:L:B   1  0.098   0.098   0.8575   0.35476
Resid 668 76.651   0.115
```

```
############################################################
ANOVA for Variance (F2-F1) at point 19
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 25.805  25.805 189.2685 < 2.2e-16 ***
L       1  6.813   6.813  49.9697 3.942e-12 ***
B       1  0.082   0.082   0.5997   0.43897
V:L     1 56.917  56.917 417.4603 < 2.2e-16 ***
V:B     1  0.009   0.009   0.0624   0.80284
L:B     1  0.858   0.858   6.2895   0.01238 *
V:L:B   1  0.298   0.298   2.1825   0.14006
Resid 668 91.076   0.136
```

```
############################################################
ANOVA for Variance (F2-F1) at point 20
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  29.024  29.024 160.8194 < 2.2e-16 ***
L       1   8.587   8.587  47.5782 1.228e-11 ***
B       1   0.735   0.735   4.0703  0.044042 *
V:L     1  49.800  49.800 275.9404 < 2.2e-16 ***
V:B     1   0.160   0.160   0.8864  0.346786
L:B     1   1.212   1.212   6.7164  0.009762 **
V:L:B   1   0.497   0.497   2.7535  0.097513 .
Resid 668 120.557   0.180
```

```
############################################################
ANOVA for Variance (F2-F1) at point 21
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  30.478  30.478 152.0313 < 2.2e-16 ***
L       1   9.161   9.161  45.6956 3.014e-11 ***
B       1   1.644   1.644   8.2005  0.004319 **
V:L     1  43.822  43.822 218.5978 < 2.2e-16 ***
V:B     1   0.079   0.079   0.3950  0.529883
L:B     1   0.996   0.996   4.9688  0.026140 *
V:L:B   1   0.436   0.436   2.1736  0.140870
Resid 668 133.914   0.200
```

```
############################################################
ANOVA for Variance (F2-F1) at point 22
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  28.889  28.889 133.7351 < 2.2e-16 ***
L       1  10.605  10.605  49.0952  5.97e-12 ***
B       1   2.734   2.734  12.6588 0.0004003 ***
V:L     1  37.021  37.021 171.3808 < 2.2e-16 ***
V:B     1   0.015   0.015   0.0689 0.7930782
L:B     1   0.598   0.598   2.7665 0.0967265 .
V:L:B   1   0.287   0.287   1.3265 0.2498411
Resid 668 144.297   0.216
```

```
############################################################
ANOVA for Variance (F2-F1) at point 23
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  29.970  29.970 124.8751 < 2.2e-16 ***
L       1  11.706  11.706  48.7756 6.948e-12 ***
B       1   5.191   5.191  21.6278 3.991e-06 ***
V:L     1  29.195  29.195 121.6453 < 2.2e-16 ***
V:B     1   0.008   0.008   0.0316    0.8590
L:B     1   0.371   0.371   1.5448    0.2143
V:L:B   1   0.147   0.147   0.6108    0.4348
Resid 668 160.318   0.240
```

```
############################################################
ANOVA for Variance (F2-F1) at point 24
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  30.469  30.469 110.5027 < 2.2e-16 ***
L       1  12.564  12.564  45.5648 3.209e-11 ***
B       1   9.218   9.218  33.4319 1.133e-08 ***
V:L     1  20.428  20.428  74.0861 < 2.2e-16 ***
V:B     1   0.001   0.001   0.0019    0.9655
L:B     1   0.080   0.080   0.2916    0.5894
V:L:B   1   0.070   0.070   0.2527    0.6153
Resid 668 184.187   0.276
```

```
########################################################
ANOVA for Variance (F2-F1) at point 25
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  29.650  29.650 94.5843 < 2.2e-16 ***
L       1  11.699  11.699 37.3191 1.703e-09 ***
B       1  15.054  15.054 48.0243 9.931e-12 ***
V:L     1  14.790  14.790 47.1821 1.483e-11 ***
V:B     1   0.001   0.001  0.0019    0.9652
L:B     1   0.014   0.014  0.0440    0.8340
V:L:B   1   0.021   0.021  0.0685    0.7937
Resid 668 209.401   0.313
```

```
########################################################
ANOVA for Variance (F2-F1) at point 26
       Df    Sum Sq   Mean Sq F value    Pr(>F)
V       1    27.506    27.506 74.3926 < 2.2e-16 ***
L       1    10.281    10.281 27.8071 1.812e-07 ***
B       1    22.386    22.386 60.5453 2.742e-14 ***
V:L     1     7.409     7.409 20.0386 8.923e-06 ***
V:B     1     0.050     0.050  0.1361    0.7124
L:B     1 0.0003974 0.0003974  0.0011    0.9739
V:L:B   1     0.043     0.043  0.1175    0.7319
Resid 668   246.986     0.370
```

```
########################################################
ANOVA for Variance (F2-F1) at point 27
       Df   Sum Sq  Mean Sq F value    Pr(>F)
V       1   22.547   22.547 52.3387 1.285e-12 ***
L       1    8.135    8.135 18.8833 1.606e-05 ***
B       1   30.970   30.970 71.8916 < 2.2e-16 ***
V:L     1    3.146    3.146  7.3020  0.007063 **
V:B     1    0.297    0.297  0.6894  0.406658
L:B     1 0.000135 0.000135  0.0003  0.985881
V:L:B   1    0.252    0.252  0.5858  0.444302
Resid 668  287.765    0.431
```

```
########################################################
ANOVA for Variance (F2-F1) at point 28
       Df   Sum Sq  Mean Sq F value    Pr(>F)
V       1    17.74    17.74 36.4068 2.653e-09 ***
L       1     5.65     5.65 11.5992 0.0006993 ***
B       1    37.32    37.32 76.5869 < 2.2e-16 ***
V:L     1     1.22     1.22  2.4958 0.1146206
V:B     1     0.63     0.63  1.2975 0.2550742
L:B     1 0.000368 0.000368  0.0008 0.9780845
V:L:B   1     0.43     0.43  0.8886 0.3462039
Resid 668   325.49     0.49
```

```
########################################################
ANOVA for Variance (F2-F1) at point 29
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  14.81   14.81 27.2238 2.421e-07 ***
L       1   4.03    4.03  7.4050  0.006674 **
B       1  45.83   45.83 84.2744 < 2.2e-16 ***
V:L     1   0.19    0.19  0.3558  0.551054
V:B     1   1.09    1.09  2.0129  0.156434
L:B     1   0.02    0.02  0.0428  0.836143
V:L:B   1   0.74    0.74  1.3655  0.243000
Resid 668 363.30    0.54
```

```
########################################################
ANOVA for Variance (F2-F1) at point 30
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  12.73   12.73 21.4598 4.344e-06 ***
L       1   2.08    2.08  3.5029    0.0617 .
B       1  52.10   52.10 87.8430 < 2.2e-16 ***
V:L     1   0.01    0.01  0.0099    0.9209
V:B     1   1.60    1.60  2.6974    0.1010
L:B     1   0.06    0.06  0.1052    0.7458
V:L:B   1   0.86    0.86  1.4454    0.2297
Resid 668 396.22    0.59
```

```
########################################################
ANOVA for Variance (F2-F1) at point 31
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1   9.27    9.27 13.5789 0.0002473 ***
L       1   0.50    0.50  0.7350 0.3915746
B       1  56.57   56.57 82.8688 < 2.2e-16 ***
V:L     1   0.29    0.29  0.4307 0.5118880
V:B     1   1.37    1.37  2.0128 0.1564410
L:B     1   0.21    0.21  0.3021 0.5827656
V:L:B   1   0.62    0.62  0.9113 0.3401282
Resid 668 456.03    0.68
```

```
########################################################
ANOVA for Variance (F2-F1) at point 32
       Df Sum Sq Mean Sq F value  Pr(>F)
V       1   6.54    6.54  8.4557 0.00376 **
L       1   0.07    0.07  0.0912 0.76280
B       1  63.41   63.41 81.9231 < 2e-16 ***
V:L     1   0.43    0.43  0.5570 0.45573
V:B     1   1.46    1.46  1.8875 0.16994
L:B     1   0.42    0.42  0.5477 0.45951
V:L:B   1   0.87    0.87  1.1274 0.28872
Resid 668 517.03    0.77
```

```
########################################################
ANOVA for Variance (F2-F1) at point 33
       Df Sum Sq Mean Sq F value  Pr(>F)
V       1   4.45    4.45  5.4398 0.01998 *
L       1   0.86    0.86  1.0533 0.30513
B       1  71.72   71.72 87.5845 < 2e-16 ***
V:L     1   0.30    0.30  0.3698 0.54331
V:B     1   1.70    1.70  2.0745 0.15025
L:B     1   0.37    0.37  0.4572 0.49915
V:L:B   1   0.48    0.48  0.5869 0.44389
Resid 668 547.02    0.82
```

```
########################################################
ANOVA for Variance (F2-F1) at point 34
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1   2.76    2.76   3.3823 0.06634 .
L       1   1.46    1.46   1.7818 0.18239
B       1  85.77   85.77 104.9803 < 2e-16 ***
V:L     1   0.27    0.27   0.3318 0.56477
V:B     1   1.83    1.83   2.2342 0.13546
L:B     1   0.24    0.24   0.2949 0.58730
V:L:B   1   0.39    0.39   0.4832 0.48724
Resid 668 545.79    0.82
```

```
########################################################
ANOVA for Variance (F2-F1) at point 35
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1   2.57    2.57   3.3261 0.06863 .
L       1   1.31    1.31   1.6934 0.19360
B       1 102.49  102.49 132.5719 < 2e-16 ***
V:L     1   0.12    0.12   0.1556 0.69340
V:B     1   1.52    1.52   1.9722 0.16068
L:B     1   0.10    0.10   0.1318 0.71668
V:L:B   1   0.17    0.17   0.2189 0.64002
Resid 668 516.43    0.77
```

```
########################################################
ANOVA for Variance (F2-F1) at point 36
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1   3.52    3.52   4.9626 0.02623 *
L       1   1.67    1.67   2.3563 0.12525
B       1 127.43  127.43 179.7308 < 2e-16 ***
V:L     1   0.02    0.02   0.0309 0.86053
V:B     1   0.93    0.93   1.3092 0.25294
L:B     1   0.09    0.09   0.1259 0.72278
V:L:B   1   0.05    0.05   0.0721 0.78846
Resid 668 473.60    0.71
```

```
########################################################
ANOVA for Variance (F2-F1) at point 37
       Df   Sum Sq  Mean Sq  F value  Pr(>F)
V       1     4.01     4.01   6.1690 0.01324 *
L       1     1.37     1.37   2.1079 0.14701
B       1   151.11   151.11 232.2715 < 2e-16 ***
V:L     1     0.04     0.04   0.0556 0.81362
V:B     1     0.40     0.40   0.6075 0.43602
L:B     1 0.003914 0.003914   0.0060 0.93820
V:L:B   1     0.07     0.07   0.1095 0.74085
Resid 668   434.58     0.65
```

```
########################################################
ANOVA for Variance (F2-F1) at point 38
       Df   Sum Sq  Mean Sq  F value    Pr(>F)
V       1     5.05     5.05   8.5182  0.003634 **
L       1     0.98     0.98   1.6623  0.197739
B       1   164.79   164.79 278.1985 < 2.2e-16 ***
V:L     1 0.003888 0.003888   0.0066  0.935456
V:B     1     0.18     0.18   0.3108  0.577353
L:B     1     0.04     0.04   0.0669  0.795920
V:L:B   1     0.07     0.07   0.1148  0.734802
Resid 668   395.70     0.59
```

```
########################################################
ANOVA for Variance (F2-F1) at point 39
       Df    Sum Sq   Mean Sq  F value    Pr(>F)
V       1      4.12      4.12   7.6682  0.005776 **
L       1      0.60      0.60   1.1202  0.290249
B       1    155.69    155.69 289.5478 < 2.2e-16 ***
V:L     1 0.0002030 0.0002030   0.0004  0.984505
V:B     1      0.43      0.43   0.8019  0.370850
L:B     1 0.0009908 0.0009908   0.0018  0.965774
V:L:B   1      0.10      0.10   0.1920  0.661371
Resid 668    359.19      0.54
```

```
########################################################
ANOVA for Variance (F2-F1) at point 40
       Df Sum Sq Mean Sq  F value  Pr(>F)
V       1   4.71    4.71   9.0337 0.00275 **
L       1   0.03    0.03   0.0513 0.82096
B       1 133.16  133.16 255.3097 < 2e-16 ***
V:L     1   0.08    0.08   0.1560 0.69295
V:B     1   0.55    0.55   1.0491 0.30609
L:B     1   0.07    0.07   0.1377 0.71066
V:L:B   1   0.39    0.39   0.7415 0.38950
Resid 668 348.41    0.52
```

```
########################################################
```

Skew (F2-F1)

```
########################################################
ANOVA for Skew (F2-F1) at point 0
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.3438  0.3438  25.6375 5.334e-07 ***
L       1 1.6800  1.6800 125.2806 < 2.2e-16 ***
B       1 0.0024  0.0024   0.1814    0.6703
V:L     1 0.0047  0.0047   0.3483    0.5553
V:B     1 0.0024  0.0024   0.1800    0.6716
L:B     1 0.0029  0.0029   0.2159    0.6423
V:L:B   1 0.0005  0.0005   0.0375    0.8465
Resid 668 8.9580  0.0134

########################################################
ANOVA for Skew (F2-F1) at point 1
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.2069  0.2069  16.2099  6.32e-05 ***
L       1 1.8390  1.8390 144.1018 < 2.2e-16 ***
B       1 0.0051  0.0051   0.4005   0.52706
V:L     1 0.0611  0.0611   4.7840   0.02907 *
V:B     1 0.0032  0.0032   0.2505   0.61686
L:B     1 0.0042  0.0042   0.3268   0.56776
V:L:B   1 0.0234  0.0234   1.8305   0.17653
Resid 668 8.5247  0.0128

########################################################
ANOVA for Skew (F2-F1) at point 2
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.3694  0.3694  25.3506 6.156e-07 ***
L       1 2.6615  2.6615 182.6290 < 2.2e-16 ***
B       1 0.0019  0.0019   0.1331  0.715335
V:L     1 0.1273  0.1273   8.7331  0.003235 **
V:B     1 0.0007  0.0007   0.0452  0.831622
L:B     1 0.0007  0.0007   0.0489  0.825001
V:L:B   1 0.0374  0.0374   2.5656  0.109683
Resid 668 9.7351  0.0146

########################################################
ANOVA for Skew (F2-F1) at point 3
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.4810  0.4810  34.1196 8.096e-09 ***
L       1 3.2886  3.2886 233.2826 < 2.2e-16 ***
B       1 0.0008  0.0008   0.0587    0.8086
V:L     1 0.4061  0.4061  28.8091 1.103e-07 ***
V:B     1 0.0023  0.0023   0.1607    0.6887
L:B     1 0.0099  0.0099   0.6998    0.4032
V:L:B   1 0.0012  0.0012   0.0820    0.7747
Resid 668 9.4167  0.0141

########################################################
ANOVA for Skew (F2-F1) at point 4
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.5685  0.5685  41.4450 2.316e-10 ***
L       1 3.2905  3.2905 239.8856 < 2.2e-16 ***
B       1 0.0001  0.0001   0.0042    0.9482
V:L     1 0.6750  0.6750  49.2051 5.666e-12 ***
V:B     1 0.0195  0.0195   1.4226    0.2334
L:B     1 0.0154  0.0154   1.1212    0.2900
V:L:B   1 0.0061  0.0061   0.4483    0.5034
Resid 668 9.1630  0.0137

########################################################
ANOVA for Skew (F2-F1) at point 5
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.5268  0.5268  39.1519 7.005e-10 ***
L       1 2.8434  2.8434 211.3268 < 2.2e-16 ***
B       1 0.0021  0.0021   0.1562   0.69281
V:L     1 0.8379  0.8379  62.2781 1.221e-14 ***
V:B     1 0.0064  0.0064   0.4793   0.48898
L:B     1 0.0547  0.0547   4.0676   0.04411 *
V:L:B   1 0.0152  0.0152   1.1290   0.28837
Resid 668 8.9879  0.0135

########################################################
ANOVA for Skew (F2-F1) at point 6
       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  0.7230  0.7230 47.1238 1.525e-11 ***
L       1  1.3413  1.3413 87.4221 < 2.2e-16 ***
B       1  0.0027  0.0027  0.1751    0.6758
V:L     1  0.7432  0.7432 48.4361 8.165e-12 ***
V:B     1  0.0024  0.0024  0.1546    0.6943
L:B     1  0.0225  0.0225  1.4690    0.2259
V:L:B   1  0.0085  0.0085  0.5564    0.4560
Resid 668 10.2493  0.0153
```

```
########################################################
ANOVA for Skew (F2-F1) at point 7
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.6172  0.6172  41.9828 1.788e-10 ***
L       1 0.3116  0.3116  21.1985 4.958e-06 ***
B       1 0.0056  0.0056   0.3830   0.53624
V:L     1 1.4850  1.4850 101.0178 < 2.2e-16 ***
V:B     1 0.0127  0.0127   0.8644   0.35286
L:B     1 0.0669  0.0669   4.5497   0.03329 *
V:L:B   1 0.0305  0.0305   2.0745   0.15025
Resid 668 9.8198  0.0147

########################################################
ANOVA for Skew (F2-F1) at point 8
       Df     Sum Sq   Mean Sq  F value Pr(>F)
V       1     1.1544    1.1544  76.1680 <2e-16 ***
L       1 1.426e-05 1.426e-05   0.0009 0.9755
B       1 1.318e-06 1.318e-06   0.0001 0.9926
V:L     1     1.9654    1.9654 129.6733 <2e-16 ***
V:B     1     0.0029    0.0029   0.1916 0.6617
L:B     1     0.0173    0.0173   1.1435 0.2853
V:L:B   1     0.0081    0.0081   0.5351 0.4647
Resid 668    10.1246    0.0152

########################################################
ANOVA for Skew (F2-F1) at point 9
       Df  Sum Sq Mean Sq  F value  Pr(>F)
V       1  1.8558  1.8558 113.8773 < 2e-16 ***
L       1  0.1059  0.1059   6.4984 0.01102 *
B       1  0.0112  0.0112   0.6897 0.40655
V:L     1  2.4016  2.4016 147.3679 < 2e-16 ***
V:B     1  0.0006  0.0006   0.0360 0.84953
L:B     1  0.0034  0.0034   0.2115 0.64573
V:L:B   1  0.0036  0.0036   0.2188 0.64011
Resid 668 10.8863  0.0163

########################################################
ANOVA for Skew (F2-F1) at point 10
       Df     Sum Sq   Mean Sq  F value    Pr(>F)
V       1     1.8828    1.8828 109.7418 < 2.2e-16 ***
L       1     0.3195    0.3195  18.6226 1.834e-05 ***
B       1     0.0044    0.0044   0.2573    0.6121
V:L     1     3.3187    3.3187 193.4419 < 2.2e-16 ***
V:B     1 2.863e-06 2.863e-06   0.0002    0.9897
L:B     1     0.0006    0.0006   0.0369    0.8478
V:L:B   1     0.0104    0.0104   0.6084    0.4357
Resid 668    11.4604    0.0172

########################################################
ANOVA for Skew (F2-F1) at point 11
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  2.3478  2.3478 128.4656 < 2.2e-16 ***
L       1  0.4045  0.4045  22.1353 3.089e-06 ***
B       1  0.0049  0.0049   0.2659    0.6063
V:L     1  3.4054  3.4054 186.3381 < 2.2e-16 ***
V:B     1  0.0003  0.0003   0.0144    0.9045
L:B     1  0.0013  0.0013   0.0727    0.7876
V:L:B   1  0.0017  0.0017   0.0911    0.7628
Resid 668 12.2081  0.0183

########################################################
ANOVA for Skew (F2-F1) at point 12
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  2.2774  2.2774 124.6227 < 2.2e-16 ***
L       1  0.4409  0.4409  24.1258 1.136e-06 ***
B       1  0.0038  0.0038   0.2071    0.6492
V:L     1  3.9280  3.9280 214.9480 < 2.2e-16 ***
V:B     1  0.0090  0.0090   0.4902    0.4841
L:B     1  0.0066  0.0066   0.3600    0.5487
V:L:B   1  0.0110  0.0110   0.5995    0.4390
Resid 668 12.2071  0.0183

########################################################
ANOVA for Skew (F2-F1) at point 13
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  1.8387  1.8387  96.1209 < 2.2e-16 ***
L       1  0.8347  0.8347  43.6345 8.085e-11 ***
B       1  0.0146  0.0146   0.7630   0.38272
V:L     1  4.6760  4.6760 244.4445 < 2.2e-16 ***
V:B     1  0.0733  0.0733   3.8293   0.05078 .
L:B     1  0.0016  0.0016   0.0819   0.77479
V:L:B   1  0.0158  0.0158   0.8252   0.36398
Resid 668 12.7782  0.0191

########################################################
ANOVA for Skew (F2-F1) at point 14
       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  1.4502  1.4502  75.5055 < 2.2e-16 ***
L       1  0.5602  0.5602  29.1662 9.244e-08 ***
B       1  0.0103  0.0103   0.5379   0.46357
V:L     1  4.2872  4.2872 223.2177 < 2.2e-16 ***
V:B     1  0.0078  0.0078   0.4076   0.52339
L:B     1  0.0042  0.0042   0.2196   0.63949
V:L:B   1  0.0747  0.0747   3.8870   0.04907 *
Resid 668 12.8300  0.0192
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 15
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  1.5957  1.5957  80.3508 < 2.2e-16 ***
L       1  0.4452  0.4452  22.4190 2.678e-06 ***
B       1  0.0018  0.0018   0.0930    0.7605    
V:L     1  2.9884  2.9884 150.4775 < 2.2e-16 ***
V:B     1  0.0036  0.0036   0.1797    0.6718    
L:B     1  0.0192  0.0192   0.9655    0.3262    
V:L:B   1  0.0416  0.0416   2.0927    0.1485    
Resid 668 13.2663  0.0199
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 16
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  1.6828  1.6828  78.2322 < 2.2e-16 ***
L       1  0.4291  0.4291  19.9494 9.336e-06 ***
B       1  0.0668  0.0668   3.1038   0.07857 .  
V:L     1  2.5398  2.5398 118.0732 < 2.2e-16 ***
V:B     1  0.0170  0.0170   0.7918   0.37389    
L:B     1  0.0406  0.0406   1.8852   0.17021    
V:L:B   1  0.0755  0.0755   3.5115   0.06138 .  
Resid 668 14.3687  0.0215
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 17
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  2.1230  2.1230 102.1247 < 2.2e-16 ***
L       1  0.2965  0.2965  14.2629 0.0001731 ***
B       1  0.2941  0.2941  14.1473 0.0001839 ***
V:L     1  1.6829  1.6829  80.9548 < 2.2e-16 ***
V:B     1  0.0055  0.0055   0.2627 0.6084562    
L:B     1  0.0353  0.0353   1.6983 0.1929543    
V:L:B   1  0.0567  0.0567   2.7259 0.0992005 .  
Resid 668 13.8867  0.0208
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 18
       Df  Sum Sq Mean Sq F value    Pr(>F)    
V       1  1.7990  1.7990 82.4972 < 2.2e-16 ***
L       1  1.0294  1.0294 47.2059 1.466e-11 ***
B       1  0.2636  0.2636 12.0874 0.0005405 ***
V:L     1  1.8756  1.8756 86.0131 < 2.2e-16 ***
V:B     1  0.0027  0.0027  0.1236 0.7252785    
L:B     1  0.0247  0.0247  1.1312 0.2879067    
V:L:B   1  0.0929  0.0929  4.2615 0.0393703 *  
Resid 668 14.5666  0.0218
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 19
       Df  Sum Sq Mean Sq F value    Pr(>F)    
V       1  1.1541  1.1541 47.5564 1.241e-11 ***
L       1  1.8561  1.8561 76.4811 < 2.2e-16 ***
B       1  0.8793  0.8793 36.2328 2.888e-09 ***
V:L     1  1.9540  1.9540 80.5142 < 2.2e-16 ***
V:B     1  0.0453  0.0453  1.8659    0.1724    
L:B     1  0.0124  0.0124  0.5111    0.4749    
V:L:B   1  0.0530  0.0530  2.1825    0.1401    
Resid 668 16.2116  0.0243
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 20
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  0.0585  0.0585   2.4820   0.11563    
L       1  2.8697  2.8697 121.7979 < 2.2e-16 ***
B       1  0.9264  0.9264  39.3185 6.463e-10 ***
V:L     1  1.9782  1.9782  83.9625 < 2.2e-16 ***
V:B     1  0.0019  0.0019   0.0804   0.77686    
L:B     1  0.1034  0.1034   4.3868   0.03659 *  
V:L:B   1  0.0262  0.0262   1.1104   0.29238    
Resid 668 15.7387  0.0236
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 21
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  0.0932  0.0932   4.7538   0.02958 *  
L       1  2.3490  2.3490 119.7904 < 2.2e-16 ***
B       1  0.3457  0.3457  17.6285 3.049e-05 ***
V:L     1  2.4517  2.4517 125.0312 < 2.2e-16 ***
V:B     1  0.0151  0.0151   0.7678   0.38120    
L:B     1  0.0097  0.0097   0.4968   0.48117    
V:L:B   1  0.0240  0.0240   1.2223   0.26932    
Resid 668 13.0987  0.0196
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 22
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  0.1030  0.1030   5.2612   0.02212 *  
L       1  2.3553  2.3553 120.2470 < 2.2e-16 ***
B       1  0.4284  0.4284  21.8734 3.526e-06 ***
V:L     1  2.5917  2.5917 132.3184 < 2.2e-16 ***
V:B     1  0.0303  0.0303   1.5461   0.21414    
L:B     1  0.0524  0.0524   2.6729   0.10254    
V:L:B   1  0.0137  0.0137   0.6974   0.40395    
Resid 668 13.0840  0.0196
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 23
       Df  Sum Sq Mean Sq  F value    Pr(>F)    
V       1  0.0757  0.0757   4.6217  0.031928 *  
L       1  2.1622  2.1622 132.0600 < 2.2e-16 ***
B       1  0.1600  0.1600   9.7704  0.001850 ** 
V:L     1  2.2870  2.2870 139.6860 < 2.2e-16 ***
V:B     1  0.0539  0.0539   3.2901  0.070149 .  
L:B     1  0.0011  0.0011   0.0685  0.793675    
V:L:B   1  0.0028  0.0028   0.1738  0.676883    
Resid 668 10.9369  0.0164
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 24
       Df  Sum Sq Mean Sq  F value Pr(>F)    
V       1  0.0345  0.0345   2.1308 0.1448    
L       1  1.4929  1.4929  92.0733 <2e-16 ***
B       1  0.0216  0.0216   1.3343 0.2485    
V:L     1  1.8444  1.8444 113.7502 <2e-16 ***
V:B     1  0.0036  0.0036   0.2203 0.6389    
L:B     1  0.0226  0.0226   1.3966 0.2377    
V:L:B   1  0.0205  0.0205   1.2615 0.2618    
Resid 668 10.8313  0.0162
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 25
       Df    Sum Sq   Mean Sq  F value    Pr(>F)    
V       1    0.0247    0.0247   1.5756    0.2098    
L       1    1.0310    1.0310  65.8742 2.331e-15 ***
B       1 1.883e-05 1.883e-05   0.0012    0.9723    
V:L     1    1.5719    1.5719 100.4341 < 2.2e-16 ***
V:B     1    0.0046    0.0046   0.2919    0.5892    
L:B     1    0.0217    0.0217   1.3885    0.2391    
V:L:B   1    0.0183    0.0183   1.1688    0.2800    
Resid 668   10.4546    0.0157
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 26
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1 0.0013  0.0013  0.0997   0.75227    
L       1 0.4765  0.4765 35.6407 3.853e-09 ***
B       1 0.0478  0.0478  3.5720   0.05920 .  
V:L     1 1.0450  1.0450 78.1658 < 2.2e-16 ***
V:B     1 0.0139  0.0139  1.0368   0.30894    
L:B     1 0.0932  0.0932  6.9725   0.00847 ** 
V:L:B   1 0.0416  0.0416  3.1098   0.07828 .  
Resid 668 8.9303  0.0134
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 27
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1 0.0208  0.0208  1.5236  0.217510    
L       1 0.5100  0.5100 37.3840 1.650e-09 ***
B       1 0.1440  0.1440 10.5584  0.001215 ** 
V:L     1 0.6820  0.6820 49.9966 3.892e-12 ***
V:B     1 0.0292  0.0292  2.1425  0.143741    
L:B     1 0.0774  0.0774  5.6755  0.017483 *  
V:L:B   1 0.0641  0.0641  4.6960  0.030585 *  
Resid 668 9.1127  0.0136
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 28
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1 0.0135  0.0135  0.9440  0.331609    
L       1 0.3839  0.3839 26.8315 2.943e-07 ***
B       1 0.2762  0.2762 19.3065 1.295e-05 ***
V:L     1 0.3613  0.3613 25.2490 6.476e-07 ***
V:B     1 0.0162  0.0162  1.1336  0.287384    
L:B     1 0.1249  0.1249  8.7280  0.003244 ** 
V:L:B   1 0.0973  0.0973  6.8035  0.009301 ** 
Resid 668 9.5577  0.0143
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 29
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1 0.0017  0.0017  0.1290 0.7195740    
L       1 0.4845  0.4845 35.7329 3.684e-09 ***
B       1 0.2823  0.2823 20.8240 5.992e-06 ***
V:L     1 0.1940  0.1940 14.3074 0.0001692 ***
V:B     1 0.0009  0.0009  0.0700 0.7913596    
L:B     1 0.1595  0.1595 11.7632 0.0006413 ***
V:L:B   1 0.0795  0.0795  5.8638 0.0157209 *  
Resid 668 9.0572  0.0136
```

```
#####################################################
ANOVA for Skew (F2-F1) at point 30
       Df Sum Sq Mean Sq F value    Pr(>F)    
V       1 0.0176  0.0176  1.2215  0.269462    
L       1 0.2472  0.2472 17.1974 3.803e-05 ***
B       1 0.5035  0.5035 35.0220 5.210e-09 ***
V:L     1 0.1001  0.1001  6.9655  0.008503 ** 
V:B     1 0.0014  0.0014  0.0960  0.756731    
L:B     1 0.1112  0.1112  7.7321  0.005578 ** 
V:L:B   1 0.0701  0.0701  4.8798  0.027511 *  
Resid 668 9.6028  0.0144
```

```
########################################################
ANOVA for Skew (F2-F1) at point 31
          Df    Sum Sq   Mean Sq F value    Pr(>F)
V          1    0.1956    0.1956 15.6650 8.371e-05 ***
L          1    0.0698    0.0698  5.5933  0.018314 *
B          1    0.3714    0.3714 29.7379 6.969e-08 ***
V:L        1 3.376e-05 3.376e-05  0.0027  0.958551
V:B        1    0.0354    0.0354  2.8337  0.092775 .
L:B        1    0.1316    0.1316 10.5394  0.001227 **
V:L:B      1    0.0419    0.0419  3.3515  0.067587 .
Resid 668    8.3417    0.0125
```

```
########################################################
ANOVA for Skew (F2-F1) at point 32
          Df Sum Sq Mean Sq F value    Pr(>F)
V          1 0.0979  0.0979  6.6733  0.009998 **
L          1 0.0008  0.0008  0.0538  0.816646
B          1 0.2905  0.2905 19.7960 1.009e-05 ***
V:L        1 0.0111  0.0111  0.7555  0.385051
V:B        1 0.0357  0.0357  2.4357  0.119076
L:B        1 0.0539  0.0539  3.6725  0.055743 .
V:L:B      1 0.0074  0.0074  0.5032  0.478332
Resid 668 9.8025  0.0147
```

```
########################################################
ANOVA for Skew (F2-F1) at point 33
          Df    Sum Sq   Mean Sq F value   Pr(>F)
V          1    0.0678    0.0678  3.9304  0.04783 *
L          1    0.0004    0.0004  0.0236  0.87789
B          1    0.3645    0.3645 21.1349 5.12e-06 ***
V:L        1    0.0443    0.0443  2.5668  0.10960
V:B        1    0.0763    0.0763  4.4214  0.03586 *
L:B        1 1.109e-05 1.109e-05  0.0006  0.97977
V:L:B      1    0.0047    0.0047  0.2701  0.60344
Resid 668   11.5203    0.0172
```

```
########################################################
ANOVA for Skew (F2-F1) at point 34
          Df  Sum Sq Mean Sq F value    Pr(>F)
V          1  0.0378  0.0378  1.9269   0.16557
L          1  0.0155  0.0155  0.7930   0.37353
B          1  0.5387  0.5387 27.4716 2.141e-07 ***
V:L        1  0.0576  0.0576  2.9394   0.08691 .
V:B        1  0.1105  0.1105  5.6367   0.01787 *
L:B        1  0.0244  0.0244  1.2419   0.26551
V:L:B      1  0.0001  0.0001  0.0045   0.94658
Resid 668 13.0980  0.0196
```

```
########################################################
ANOVA for Skew (F2-F1) at point 35
          Df  Sum Sq Mean Sq F value    Pr(>F)
V          1  0.0001  0.0001  0.0060   0.93826
L          1  0.0044  0.0044  0.2062   0.64991
B          1  0.9692  0.9692 45.7996 2.868e-11 ***
V:L        1  0.0807  0.0807  3.8157   0.05119 .
V:B        1  0.0903  0.0903  4.2664   0.03926 *
L:B        1  0.0313  0.0313  1.4791   0.22434
V:L:B      1  0.0200  0.0200  0.9433   0.33179
Resid 668 14.1363  0.0212
```

```
########################################################
ANOVA for Skew (F2-F1) at point 36
          Df  Sum Sq Mean Sq F value    Pr(>F)
V          1  0.0295  0.0295  1.0084    0.3156
L          1  0.0030  0.0030  0.1036    0.7477
B          1  1.8043  1.8043 61.7509 1.565e-14 ***
V:L        1  0.0627  0.0627  2.1461    0.1434
V:B        1  0.0269  0.0269  0.9215    0.3374
L:B        1  0.0277  0.0277  0.9479    0.3306
V:L:B      1  0.0090  0.0090  0.3092    0.5784
Resid 668 19.5182  0.0292
```

```
########################################################
ANOVA for Skew (F2-F1) at point 37
          Df    Sum Sq   Mean Sq F value  Pr(>F)
V          1    0.0133    0.0133  0.4385 0.50810
L          1 3.145e-05 3.145e-05  0.0010 0.97430
B          1    2.6318    2.6318 86.9471 < 2e-16 ***
V:L        1    0.1012    0.1012  3.3427 0.06795 .
V:B        1    0.0919    0.0919  3.0372 0.08184 .
L:B        1    0.0135    0.0135  0.4475 0.50374
V:L:B      1 3.182e-05 3.182e-05  0.0011 0.97415
Resid 668   20.2197    0.0303
```

```
########################################################
ANOVA for Skew (F2-F1) at point 38
          Df    Sum Sq   Mean Sq   F value Pr(>F)
V          1    0.0049    0.0049    0.1288 0.7198
L          1    0.0199    0.0199    0.5216 0.4704
B          1    3.0570    3.0570   79.9576 <2e-16 ***
V:L        1    0.0847    0.0847    2.2145 0.1372
V:B        1    0.0329    0.0329    0.8597 0.3542
L:B        1 4.022e-08 4.022e-08 1.052e-06 0.9992
V:L:B      1    0.0003    0.0003    0.0089 0.9247
Resid 668   25.5394    0.0382
```

```
########################################################
ANOVA for Skew (F2-F1) at point 39
          Df  Sum Sq Mean Sq F value Pr(>F)
V          1  0.0410  0.0410  0.8901 0.3458
L          1  0.0044  0.0044  0.0960 0.7568
B          1  3.5898  3.5898 77.9186 <2e-16 ***
V:L        1  0.1224  0.1224  2.6558 0.1036
V:B        1  0.0152  0.0152  0.3294 0.5662
L:B        1  0.0244  0.0244  0.5298 0.4670
V:L:B      1  0.0207  0.0207  0.4482 0.5034
Resid 668 30.7758  0.0461
```

```
########################################################
ANOVA for Skew (F2-F1) at point 40
          Df Sum Sq Mean Sq F value Pr(>F)
V          1  0.003   0.003  0.0615 0.8043
L          1  0.034   0.034  0.6988 0.4035
B          1  3.510   3.510 72.7431 <2e-16 ***
V:L        1  0.001   0.001  0.0183 0.8923
V:B        1  0.004   0.004  0.0799 0.7776
L:B        1  0.049   0.049  1.0114 0.3149
V:L:B      1  0.018   0.018  0.3726 0.5418
Resid 668 32.237   0.048
```

```
########################################################
```

Kurtosis (F2-F1)

```
########################################################
ANOVA for Kurtosis (F2-F1) at point 0
          Df    Sum Sq   Mean Sq F value    Pr(>F)
V          1    0.0022    0.0022  0.3709  0.542746
L          1    0.1923    0.1923 33.1474 1.303e-08 ***
B          1    0.0032    0.0032  0.5535  0.457133
V:L        1    0.0403    0.0403  6.9467  0.008592 **
V:B        1    0.0011    0.0011  0.1873  0.665272
L:B        1 2.919e-05 2.919e-05  0.0050  0.943462
V:L:B      1    0.0040    0.0040  0.6865  0.407658
Resid 668    3.8745    0.0058
```

```
########################################################
ANOVA for Kurtosis (F2-F1) at point 1
          Df Sum Sq Mean Sq F value    Pr(>F)
V          1 0.0306  0.0306  5.6665  0.017571 *
L          1 0.1057  0.1057 19.5645 1.135e-05 ***
B          1 0.0431  0.0431  7.9753  0.004883 **
V:L        1 0.0386  0.0386  7.1451  0.007701 **
V:B        1 0.0024  0.0024  0.4534  0.500935
L:B        1 0.0001  0.0001  0.0129  0.909568
V:L:B      1 0.0147  0.0147  2.7159  0.099823 .
Resid 668 3.6089  0.0054
```

```
########################################################
ANOVA for Kurtosis (F2-F1) at point 2
          Df    Sum Sq   Mean Sq F value   Pr(>F)
V          1    0.0344    0.0344  5.0009 0.025664 *
L          1    0.0532    0.0532  7.7328 0.005575 **
B          1    0.0009    0.0009  0.1353 0.713127
V:L        1    0.0436    0.0436  6.3285 0.012115 *
V:B        1    0.0191    0.0191  2.7704 0.096488 .
L:B        1 9.387e-06 9.387e-06  0.0014 0.970554
V:L:B      1    0.0143    0.0143  2.0785 0.149853
Resid 668    4.5985    0.0069
```

```
########################################################
ANOVA for Kurtosis (F2-F1) at point 3
          Df Sum Sq Mean Sq F value Pr(>F)
V          1 0.0027  0.0027  0.3078 0.5792
L          1 0.0026  0.0026  0.2924 0.5888
B          1 0.0021  0.0021  0.2351 0.6279
V:L        1 0.0022  0.0022  0.2522 0.6157
V:B        1 0.0227  0.0227  2.5796 0.1087
L:B        1 0.0003  0.0003  0.0389 0.8438
V:L:B      1 0.0003  0.0003  0.0312 0.8598
Resid 668 5.8786  0.0088
```

```
########################################################
ANOVA for Kurtosis (F2-F1) at point 4
          Df Sum Sq Mean Sq F value  Pr(>F)
V          1 0.0371  0.0371  5.7067 0.01718 *
L          1 0.0215  0.0215  3.3020 0.06964 .
B          1 0.0134  0.0134  2.0651 0.15117
V:L        1 0.0127  0.0127  1.9620 0.16177
V:B        1 0.0078  0.0078  1.1994 0.27384
L:B        1 0.0087  0.0087  1.3411 0.24725
V:L:B      1 0.0045  0.0045  0.6913 0.40603
Resid 668 4.3399  0.0065
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 5
        Df    Sum Sq   Mean Sq   F value    Pr(>F)
V        1    0.0526    0.0526    8.9230  0.002919 **
L        1    0.1306    0.1306   22.1504 3.066e-06 ***
B        1    0.0028    0.0028    0.4675  0.494400
V:L      1    0.0318    0.0318    5.3878  0.020578 *
V:B      1    0.0060    0.0060    1.0140  0.314314
L:B      1    0.0211    0.0211    3.5859  0.058705 .
V:L:B    1 5.151e-08 5.151e-08 8.734e-06  0.997643
Resid  668    3.9398    0.0059
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 6
        Df Sum Sq Mean Sq F value    Pr(>F)
V        1 0.0312  0.0312  4.6732   0.03099 *
L        1 0.3887  0.3887 58.2309 8.060e-14 ***
B        1 0.0077  0.0077  1.1497   0.28400
V:L      1 0.1214  0.1214 18.1890 2.289e-05 ***
V:B      1 0.0006  0.0006  0.0918   0.76199
L:B      1 0.0333  0.0333  4.9838   0.02592 *
V:L:B    1 0.0013  0.0013  0.1964   0.65778
Resid  668 4.4592  0.0067
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 7
        Df Sum Sq Mean Sq F value    Pr(>F)
V        1 0.0001  0.0001  0.0154    0.9013
L        1 0.4484  0.4484 69.0106 5.551e-16 ***
B        1 0.0164  0.0164  2.5266    0.1124
V:L      1 0.3586  0.3586 55.1906 3.353e-13 ***
V:B      1 0.0078  0.0078  1.2056    0.2726
L:B      1 0.1085  0.1085 16.6997 4.911e-05 ***
V:L:B    1 0.0083  0.0083  1.2782    0.2586
Resid  668 4.3408  0.0065
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 8
        Df    Sum Sq   Mean Sq  F value    Pr(>F)
V        1    0.0512    0.0512   8.0872  0.004594 **
L        1    0.2822    0.2822  44.5736 5.155e-11 ***
B        1 1.870e-06 1.870e-06   0.0003  0.986293
V:L      1    0.7403    0.7403 116.9138 < 2.2e-16 ***
V:B      1    0.0229    0.0229   3.6212  0.057476 .
L:B      1    0.0486    0.0486   7.6706  0.005768 **
V:L:B    1    0.0066    0.0066   1.0441  0.307248
Resid  668    4.2297    0.0063
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 9
        Df Sum Sq Mean Sq  F value    Pr(>F)
V        1 0.2514  0.2514  27.8570 1.768e-07 ***
L        1 0.0122  0.0122   1.3553   0.24477
B        1 0.0010  0.0010   0.1084   0.74211
V:L      1 1.3470  1.3470 149.2577 < 2.2e-16 ***
V:B      1 0.0118  0.0118   1.3032   0.25404
L:B      1 0.0374  0.0374   4.1459   0.04213 *
V:L:B    1 0.0066  0.0066   0.7342   0.39183
Resid  668 6.0283  0.0090
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 10
        Df Sum Sq Mean Sq  F value    Pr(>F)
V        1 0.5556  0.5556  43.1633 1.014e-10 ***
L        1 0.0444  0.0444   3.4524   0.06360 .
B        1 0.0199  0.0199   1.5496   0.21363
V:L      1 2.6875  2.6875 208.7680 < 2.2e-16 ***
V:B      1 0.0092  0.0092   0.7167   0.39753
L:B      1 0.0498  0.0498   3.8674   0.04964 *
V:L:B    1 0.0327  0.0327   2.5441   0.11118
Resid  668 8.5991  0.0129
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 11
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.9181  0.9181  59.9502 3.619e-14 ***
L        1  0.1679  0.1679  10.9662 0.0009778 ***
B        1  0.0238  0.0238   1.5542 0.2129595
V:L      1  3.4565  3.4565 225.6969 < 2.2e-16 ***
V:B      1  0.0030  0.0030   0.1936 0.6600543
L:B      1  0.0425  0.0425   2.7720 0.0963963 .
V:L:B    1  0.0197  0.0197   1.2862 0.2571576
Resid  668 10.2302  0.0153
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 12
        Df Sum Sq Mean Sq  F value    Pr(>F)
V        1 0.6952  0.6952  50.4633  3.12e-12 ***
L        1 0.1299  0.1299   9.4282  0.002223 **
B        1 0.0179  0.0179   1.3016  0.254329
V:L      1 4.0618  4.0618 294.8303 < 2.2e-16 ***
V:B      1 0.0038  0.0038   0.2726  0.601774
L:B      1 0.0127  0.0127   0.9244  0.336670
V:L:B    1 0.0135  0.0135   0.9773  0.323222
Resid  668 9.2028  0.0138
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 13
        Df    Sum Sq   Mean Sq  F value    Pr(>F)
V        1    0.5422    0.5422  37.0038 1.985e-09 ***
L        1    0.0928    0.0928   6.3333   0.01208 *
B        1    0.0528    0.0528   3.6061   0.05800 .
V:L      1    5.1596    5.1596 352.1316 < 2.2e-16 ***
V:B      1    0.0116    0.0116   0.7930   0.37350
L:B      1    0.0009    0.0009   0.0608   0.80530
V:L:B    1 1.032e-05 1.032e-05   0.0007   0.97884
Resid  668    9.7879    0.0147
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 14
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.3310  0.3310  21.3982 4.482e-06 ***
L        1  0.0275  0.0275   1.7771   0.18296
B        1  0.0474  0.0474   3.0648   0.08047 .
V:L      1  5.6699  5.6699 366.5558 < 2.2e-16 ***
V:B      1  0.0348  0.0348   2.2486   0.13421
L:B      1  0.0007  0.0007   0.0447   0.83259
V:L:B    1  0.0021  0.0021   0.1361   0.71226
Resid  668 10.3326  0.0155
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 15
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.2290  0.2290  14.3301 0.0001672 ***
L        1  0.0029  0.0029   0.1826 0.6692908
B        1  0.0523  0.0523   3.2752 0.0707850 .
V:L      1  5.6278  5.6278 352.1049 < 2.2e-16 ***
V:B      1  0.0027  0.0027   0.1672 0.6827095
L:B      1  0.0010  0.0010   0.0603 0.8060860
V:L:B    1  0.0162  0.0162   1.0147 0.3141393
Resid  668 10.6768  0.0160
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 16
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.2641  0.2641  14.0853 0.0001899 ***
L        1  0.1061  0.1061   5.6596 0.0176405 *
B        1  0.1816  0.1816   9.6856 0.0019365 **
V:L      1  5.1336  5.1336 273.8049 < 2.2e-16 ***
V:B      1  0.0205  0.0205   1.0921 0.2963904
L:B      1  0.0016  0.0016   0.0845 0.7713641
V:L:B    1  0.0005  0.0005   0.0256 0.8728188
Resid  668 12.5243  0.0187
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 17
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.2689  0.2689  17.1713 3.855e-05 ***
L        1  0.3768  0.3768  24.0606 1.174e-06 ***
B        1  0.4729  0.4729  30.1997 5.549e-08 ***
V:L      1  3.9922  3.9922 254.9182 < 2.2e-16 ***
V:B      1  0.0996  0.0996   6.3586   0.01191 *
L:B      1  0.0082  0.0082   0.5225   0.47002
V:L:B    1  0.0429  0.0429   2.7378   0.09847 .
Resid  668 10.4613  0.0157
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 18
        Df    Sum Sq   Mean Sq  F value    Pr(>F)
V        1    0.2611    0.2611  14.4961 0.0001534 ***
L        1    0.3627    0.3627  20.1340 8.501e-06 ***
B        1    0.8643    0.8643  47.9762 1.016e-11 ***
V:L      1    4.1272    4.1272 229.1099 < 2.2e-16 ***
V:B      1    0.0887    0.0887   4.9256 0.0267974 *
L:B      1 3.799e-05 3.799e-05   0.0021 0.9633853
V:L:B    1    0.0702    0.0702   3.8984 0.0487448 *
Resid  668   12.0335    0.0180
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 19
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.2462  0.2462  13.9179 0.0002072 ***
L        1  0.3688  0.3688  20.8432 5.934e-06 ***
B        1  1.2514  1.2514  70.7292 2.220e-16 ***
V:L      1  3.2406  3.2406 183.1607 < 2.2e-16 ***
V:B      1  0.1261  0.1261   7.1257 0.0077834 **
L:B      1  0.0008  0.0008   0.0444 0.8331519
V:L:B    1  0.1287  0.1287   7.2749 0.0071688 **
Resid  668 11.8188  0.0177
```

```
##################################################
ANOVA for Kurtosis (F2-F1) at point 20
        Df  Sum Sq Mean Sq  F value    Pr(>F)
V        1  0.0102  0.0102   0.6309  0.427314
L        1  0.3997  0.3997  24.8213  8.02e-07 ***
B        1  1.1869  1.1869  73.7092 < 2.2e-16 ***
V:L      1  2.4659  2.4659 153.1439 < 2.2e-16 ***
V:B      1  0.0595  0.0595   3.6930  0.055067 .
L:B      1  0.0033  0.0033   0.2070  0.649276
V:L:B    1  0.1273  0.1273   7.9072  0.005068 **
Resid  668 10.7562  0.0161
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 21
       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 0.0001  0.0001   0.0046   0.94618
L       1 0.3583  0.3583  29.1725 9.215e-08 ***
B       1 0.8089  0.8089  65.8674 2.331e-15 ***
V:L     1 1.8047  1.8047 146.9593 < 2.2e-16 ***
V:B     1 0.0371  0.0371   3.0239   0.08251 .
L:B     1 0.0029  0.0029   0.2377   0.62600
V:L:B   1 0.0713  0.0713   5.8022   0.01628 *
Resid 668 8.2033  0.0123
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 22
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0431  0.0431  3.5975  0.058298 .
L       1 0.1388  0.1388 11.5731  0.000709 ***
B       1 0.7493  0.7493 62.4764 1.110e-14 ***
V:L     1 1.1035  1.1035 92.0092 < 2.2e-16 ***
V:B     1 0.1352  0.1352 11.2709  0.000832 ***
L:B     1 0.0212  0.0212  1.7691  0.183947
V:L:B   1 0.0852  0.0852  7.1017  0.007887 **
Resid 668 8.0118  0.0120
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 23
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0080  0.0080  0.8374  0.360486
L       1 0.1039  0.1039 10.8561  0.001037 **
B       1 0.4323  0.4323 45.1720 3.872e-11 ***
V:L     1 0.4343  0.4343 45.3817 3.502e-11 ***
V:B     1 0.0749  0.0749  7.8251  0.005301 **
L:B     1 0.0157  0.0157  1.6385  0.200972
V:L:B   1 0.0469  0.0469  4.8979  0.027226 *
Resid 668 6.3922  0.0096
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 24
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0008  0.0008  0.0946 0.7584702
L       1 0.1062  0.1062 12.0076 0.0005637 ***
B       1 0.3075  0.3075 34.7505 5.948e-09 ***
V:L     1 0.1952  0.1952 22.0647 3.201e-06 ***
V:B     1 0.0546  0.0546  6.1668 0.0132614 *
L:B     1 0.0069  0.0069  0.7822 0.3767729
V:L:B   1 0.0267  0.0267  3.0166 0.0828787 .
Resid 668 5.9102  0.0088
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 25
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0001  0.0001  0.0058 0.9395641
L       1 0.1536  0.1536 16.3946 5.746e-05 ***
B       1 0.3455  0.3455 36.8912 2.097e-09 ***
V:L     1 0.1399  0.1399 14.9392 0.0001219 ***
V:B     1 0.0433  0.0433  4.6236 0.0318935 *
L:B     1 0.0097  0.0097  1.0349 0.3093886
V:L:B   1 0.0239  0.0239  2.5518 0.1106430
Resid 668 6.2568  0.0094
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 26
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0244  0.0244  2.7243   0.09930 .
L       1 0.1896  0.1896 21.1623 5.049e-06 ***
B       1 0.2309  0.2309 25.7677 4.999e-07 ***
V:L     1 0.0361  0.0361  4.0265   0.04519 *
V:B     1 0.0353  0.0353  3.9388   0.04759 *
L:B     1 0.0040  0.0040  0.4438   0.50554
V:L:B   1 0.0146  0.0146  1.6290   0.20229
Resid 668 5.9861  0.0090
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 27
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0490  0.0490  5.9402  0.015059 *
L       1 0.2792  0.2792 33.8675 9.158e-09 ***
B       1 0.1738  0.1738 21.0771 5.272e-06 ***
V:L     1 0.0003  0.0003  0.0310  0.860281
V:B     1 0.0846  0.0846 10.2673  0.001418 **
L:B     1 0.0012  0.0012  0.1448  0.703718
V:L:B   1 0.0061  0.0061  0.7428  0.389088
Resid 668 5.5068  0.0082
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 28
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0469  0.0469  4.8378  0.028184 *
L       1 0.2547  0.2547 26.2625 3.906e-07 ***
B       1 0.2652  0.2652 27.3486 2.276e-07 ***
V:L     1 0.0014  0.0014  0.1473  0.701210
V:B     1 0.1022  0.1022 10.5378  0.001228 **
L:B     1 0.0058  0.0058  0.6008  0.438536
V:L:B   1 0.0051  0.0051  0.5213  0.470536
Resid 668 6.4775  0.0097
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 29
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0631  0.0631  6.6520 0.0101174 *
L       1 0.2430  0.2430 25.6307 5.352e-07 ***
B       1 0.1380  0.1380 14.5529 0.0001489 ***
V:L     1 0.0011  0.0011  0.1156 0.7339688
V:B     1 0.1075  0.1075 11.3362 0.0008037 ***
L:B     1 0.0253  0.0253  2.6664 0.1029613
V:L:B   1 0.0052  0.0052  0.5472 0.4597285
Resid 668 6.3337  0.0095
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 30
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.0706  0.0706  6.6334 0.0102223 *
L       1 0.1288  0.1288 12.0951 0.0005383 ***
B       1 0.2235  0.2235 20.9910 5.506e-06 ***
V:L     1 0.0004  0.0004  0.0417 0.8383236
V:B     1 0.1874  0.1874 17.6038 3.088e-05 ***
L:B     1 0.0249  0.0249  2.3424 0.1263694
V:L:B   1 0.0007  0.0007  0.0666 0.7964961
Resid 668 7.1112  0.0106
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 31
       Df    Sum Sq   Mean Sq F value    Pr(>F)
V       1    0.0479    0.0479  4.2125 0.0405162 *
L       1    0.0611    0.0611  5.3788 0.0206831 *
B       1    0.2282    0.2282 20.0806 8.735e-06 ***
V:L     1 6.104e-06 6.104e-06  0.0005 0.9815191
V:B     1    0.1369    0.1369 12.0429 0.0005533 ***
L:B     1    0.1034    0.1034  9.1004 0.0026526 **
V:L:B   1    0.0292    0.0292  2.5683 0.1095006
Resid 668    7.5928    0.0114
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 32
       Df Sum Sq Mean Sq F value   Pr(>F)
V       1 0.0630  0.0630  4.6661 0.031118 *
L       1 0.0123  0.0123  0.9097 0.340548
B       1 0.0908  0.0908  6.7328 0.009674 **
V:L     1 0.0044  0.0044  0.3245 0.569135
V:B     1 0.1161  0.1161  8.6070 0.003464 **
L:B     1 0.1015  0.1015  7.5189 0.006269 **
V:L:B   1 0.0007  0.0007  0.0486 0.825530
Resid 668 9.0137  0.0135
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 33
       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 0.1426  0.1426  9.9711 0.0016618 **
L       1 0.0123  0.0123  0.8631 0.3532194
B       1 0.0762  0.0762  5.3261 0.0213129 *
V:L     1 0.0139  0.0139  0.9735 0.3241722
V:B     1 0.1630  0.1630 11.3925 0.0007801 ***
L:B     1 0.0499  0.0499  3.4881 0.0622485 .
V:L:B   1 0.0002  0.0002  0.0133 0.9083222
Resid 668 9.5561  0.0143
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 34
       Df  Sum Sq Mean Sq F value   Pr(>F)
V       1  0.0682  0.0682  3.8096 0.051376 .
L       1  0.0023  0.0023  0.1294 0.719168
B       1  0.0108  0.0108  0.6027 0.437817
V:L     1  0.0779  0.0779  4.3494 0.037400 *
V:B     1  0.1912  0.1912 10.6826 0.001137 **
L:B     1  0.0117  0.0117  0.6523 0.419563
V:L:B   1  0.0012  0.0012  0.0666 0.796422
Resid 668 11.9569  0.0179
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 35
       Df  Sum Sq Mean Sq F value  Pr(>F)
V       1  0.0655  0.0655  3.9879 0.04623 *
L       1  0.0136  0.0136  0.8269 0.36351
B       1  0.0705  0.0705  4.2890 0.03874 *
V:L     1  0.0218  0.0218  1.3254 0.25004
V:B     1  0.0700  0.0700  4.2592 0.03942 *
L:B     1  0.0268  0.0268  1.6314 0.20195
V:L:B   1  0.0319  0.0319  1.9424 0.16387
Resid 668 10.9727  0.0164
```

```
##########################################################
ANOVA for Kurtosis (F2-F1) at point 36
       Df  Sum Sq Mean Sq F value  Pr(>F)
V       1  0.1237  0.1237  5.9948 0.01460 *
L       1  0.0234  0.0234  1.1352 0.28705
B       1  0.0603  0.0603  2.9252 0.08767 .
V:L     1  0.0294  0.0294  1.4264 0.23278
V:B     1  0.0480  0.0480  2.3247 0.12781
L:B     1  0.0423  0.0423  2.0519 0.15249
V:L:B   1  0.0337  0.0337  1.6320 0.20187
Resid 668 13.7791  0.0206
```

```
####################################################
ANOVA for Kurtosis (F2-F1) at point 37
       Df  Sum Sq Mean Sq F value   Pr(>F)
V       1  0.1943  0.1943  9.1009 0.002652 **
L       1  0.0192  0.0192  0.9006 0.342975
B       1  0.0412  0.0412  1.9303 0.165190
V:L     1  0.0299  0.0299  1.3980 0.237473
V:B     1  0.0537  0.0537  2.5163 0.113149
L:B     1  0.0027  0.0027  0.1244 0.724408
V:L:B   1  0.0018  0.0018  0.0844 0.771479
Resid 668 14.2652  0.0214
```

```
####################################################
ANOVA for Kurtosis (F2-F1) at point 38
       Df  Sum Sq Mean Sq F value   Pr(>F)
V       1  0.1617  0.1617  7.2861 0.007125 **
L       1  0.0384  0.0384  1.7319 0.188623
B       1  0.0230  0.0230  1.0382 0.308615
V:L     1  0.0216  0.0216  0.9728 0.324331
V:B     1  0.0767  0.0767  3.4587 0.063359 .
L:B     1  0.0081  0.0081  0.3630 0.547063
V:L:B   1  0.0061  0.0061  0.2764 0.599230
Resid 668 14.8222  0.0222
```

```
####################################################
ANOVA for Kurtosis (F2-F1) at point 39
       Df     Sum Sq    Mean Sq F value  Pr(>F)
V       1     0.0326     0.0326  1.2727 0.25966
L       1     0.1348     0.1348  5.2597 0.02213 *
B       1     0.0037     0.0037  0.1431 0.70538
V:L     1     0.0120     0.0120  0.4688 0.49380
V:B     1     0.1428     0.1428  5.5735 0.01852 *
L:B     1     0.1238     0.1238  4.8326 0.02827 *
V:L:B   1 6.327e-06 6.327e-06  0.0002 0.98747
Resid 668    17.1178     0.0256
```

```
####################################################
ANOVA for Kurtosis (F2-F1) at point 40
       Df     Sum Sq    Mean Sq   F value   Pr(>F)
V       1     0.0069     0.0069    0.2519 0.615876
L       1     0.1865     0.1865    6.8422 0.009104 **
B       1     0.0053     0.0053    0.1963 0.657861
V:L     1 5.724e-07 5.724e-07 2.100e-05 0.996345
V:B     1     0.0881     0.0881    3.2320 0.072666 .
L:B     1     0.0215     0.0215    0.7893 0.374641
V:L:B   1     0.0409     0.0409    1.5013 0.220906
Resid 668    18.2045     0.0273
```

ANOVAs for temporal information (Experiment 2).

```
####################################################
ANOVA for duration of F1 transition into liquid

       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  2.155   2.155 36.9332 2.048e-09 ***
L       1  1.605   1.605 27.5051 2.102e-07 ***
V:L     1  0.252   0.252  4.3226   0.03799 *
Resid 672 39.208   0.058
```

```
####################################################
ANOVA for duration of F1 steady state

       Df  Sum Sq Mean Sq  F value Pr(>F)
V       1  3.9351  3.9351 175.9614 <2e-16 ***
L       1  1.8141  1.8141  81.1183 <2e-16 ***
V:L     1  0.0445  0.0445   1.9884 0.1590
Resid 671 15.0060  0.0224
```

```
####################################################
ANOVA for duration of F1 transition out of liquid

       Df Sum Sq Mean Sq  F value Pr(>F)
V       1 16.186  16.186 301.1139 <2e-16 ***
L       1 18.187  18.187 338.3402 <2e-16 ***
V:L     1  0.258   0.258   4.8002 0.0288 *
Resid 672 36.123   0.054
```

```
####################################################
ANOVA for duration of F2 transition into liquid

       Df  Sum Sq Mean Sq  F value Pr(>F)
V       1  3.8740  3.8740 239.5736 <2e-16 ***
L       1  0.0349  0.0349   2.1566 0.1424
V:L     1  2.3539  2.3539 145.5707 <2e-16 ***
Resid 672 10.8664  0.0162
```

```
####################################################
ANOVA for duration of F2 steady state

       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1  9.3948  9.3948 275.617 < 2.2e-16 ***
L       1  1.6288  1.6288  47.785 1.107e-11 ***
V:L     1  1.5685  1.5685  46.016 2.575e-11 ***
Resid 672 22.9061  0.0341
```

```
####################################################
ANOVA for duration of F2 transition out of liquid

       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 11.477  11.477 139.414 < 2.2e-16 ***
L       1  0.701   0.701   8.517 0.0036360 **
V:L     1  0.923   0.923  11.210 0.0008589 ***
Resid 672 55.322   0.082
```

```
####################################################
ANOVA for duration of F3 transition into liquid

       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1 11.9753 11.9753 307.470 < 2.2e-16 ***
L       1  7.9122  7.9122 203.150 < 2.2e-16 ***
V:L     1  0.9675  0.9675  24.841 7.931e-07 ***
Resid 672 26.1729  0.0389
```

```
####################################################
ANOVA for duration of F3 steady state

       Df  Sum Sq Mean Sq  F value    Pr(>F)
V       1  5.5193  5.5193 240.2517 < 2.2e-16 ***
L       1  0.6953  0.6953  30.2650 5.362e-08 ***
V:L     1  0.0045  0.0045   0.1975    0.6569
Resid 672 15.4379  0.0230
```

```
####################################################
ANOVA for duration of F3 transition out of liquid

       Df Sum Sq Mean Sq  F value    Pr(>F)
V       1 11.217  11.217 204.2590 < 2.2e-16 ***
L       1 10.816  10.816 196.9479 < 2.2e-16 ***
V:L     1  0.488   0.488   8.8941  0.002964 **
Resid 672 36.905   0.055
```

```
####################################################
ANOVA for duration of liquid steady state

       Df  Sum Sq Mean Sq F value    Pr(>F)
V       1 11.3498 11.3498 303.576 < 2.2e-16 ***
L       1  0.4430  0.4430  11.849  0.000613 ***
V:L     1  0.7056  0.7056  18.873 1.615e-05 ***
Resid 666 24.8997  0.0374
```

```
####################################################
ANOVA for duration of total transitional portion

       Df Sum Sq Mean Sq F value    Pr(>F)
V       1 3.8029  3.8029 518.113 < 2.2e-16 ***
L       1 1.1032  1.1032 150.309 < 2.2e-16 ***
V:L     1 0.2328  0.2328  31.721 2.617e-08 ***
Resid 672 4.9324  0.0073
```

```
####################################################
ANOVA: relative timing, start of trans. into liquid

       Df Sum Sq Mean Sq F value    Pr(>F)
V       1   1223    1223  4.0490   0.04460 *
L       1    226     226  0.7471   0.38771
V:L     1  15895   15895 52.6054 1.126e-12 ***
Resid 672 203052     302

####################################################
ANOVA: relative timing, end of trans. into liquid

       Df Sum Sq Mean Sq F value    Pr(>F)
V       1  36030   36030 110.986 < 2.2e-16 ***
L       1   8442    8442  26.005 4.434e-07 ***
V:L     1   5544    5544  17.077 4.043e-05 ***
Resid 672 218156     325

####################################################
ANOVA: relative timing, start of trans. out of liquid

       Df Sum Sq Mean Sq F value    Pr(>F)
V       1   9005    9005 37.0436 1.941e-09 ***
L       1   4137    4137 17.0194 4.164e-05 ***
V:L     1   1768    1768  7.2741  0.007171 **
Resid 672 163350     243

####################################################
ANOVA: relative timing, end of trans. out of liquid

        Df Sum Sq Mean Sq F value    Pr(>F)
V       1  29852   29852  29.617 7.383e-08 ***
L       1 114940  114940 114.036 < 2.2e-16 ***
V:L     1  23515   23515  23.330 1.692e-06 ***
Resid 672 677328    1008
```

Appendix 6: Additional formant data

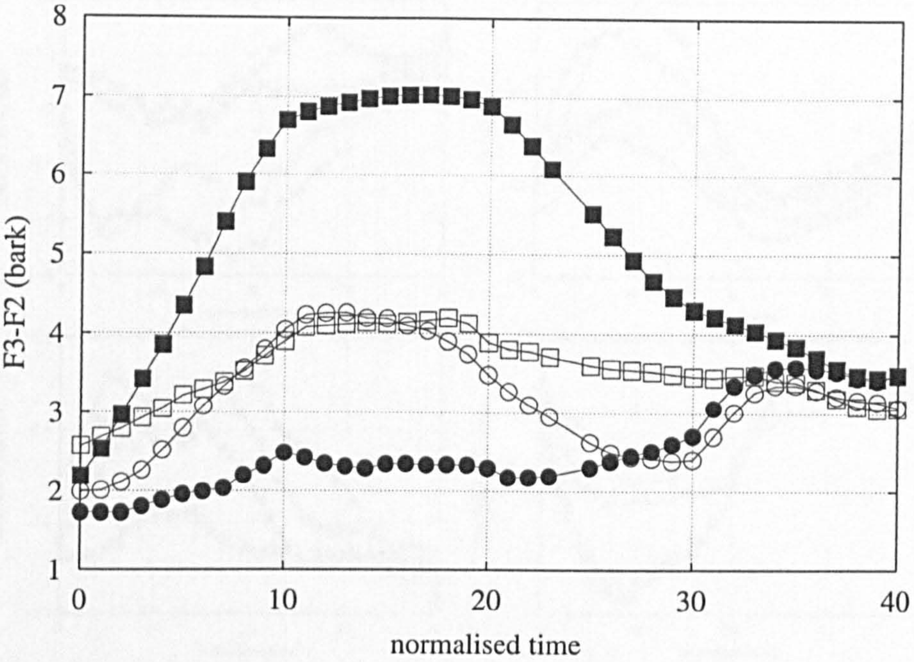


Figure 90. Mean F3-F2 frequencies (bark) for onset liquids. Open shapes: Sunderland; filled shapes: Manchester. Squares: [l]; circles: [r].

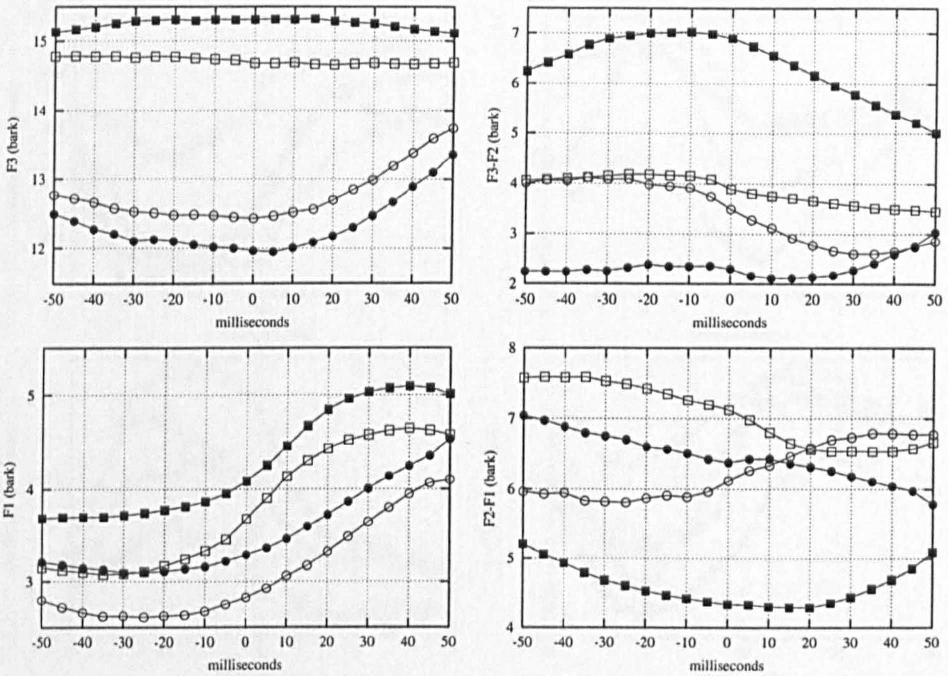


Figure 91. Onset liquids sampled in 5 ms steps aligned at the start of the F2 transition out of the liquid. Upper left: mean F3 (bark). Lower left: mean F1 (bark). Upper right: mean F3-F2 (bark). Lower right: mean F2-F1 (bark). Open shapes: Sunderland; filled shapes: Manchester. Squares: [l]; circles: [r].

Appendix 7: Further results of spectral moments analysis

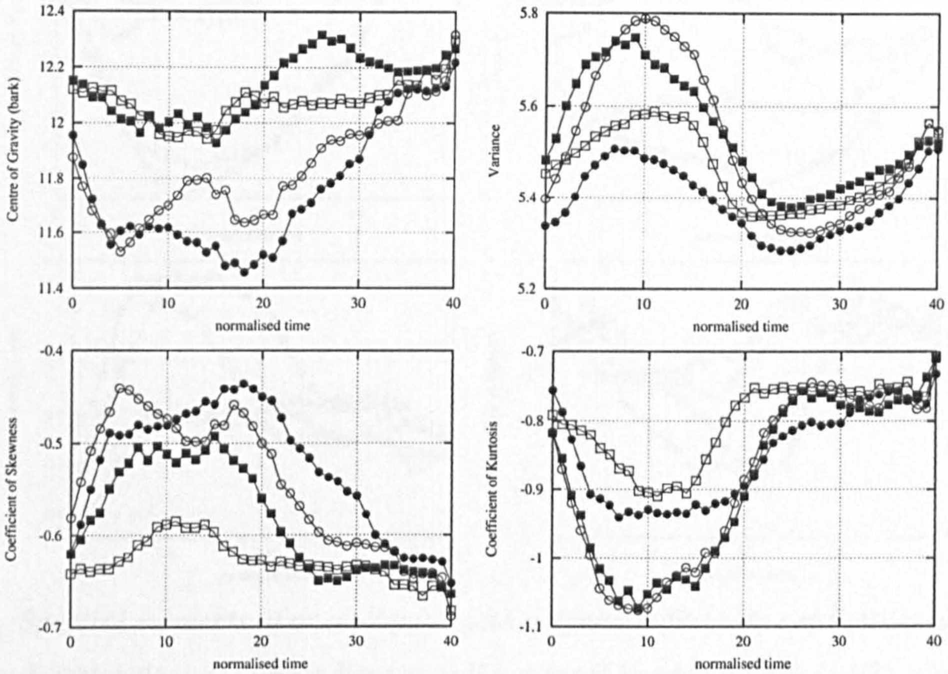


Figure 92. Spectral moments of onset liquids with a low pass filter set at the Nyquist frequency (5512.5 Hz). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

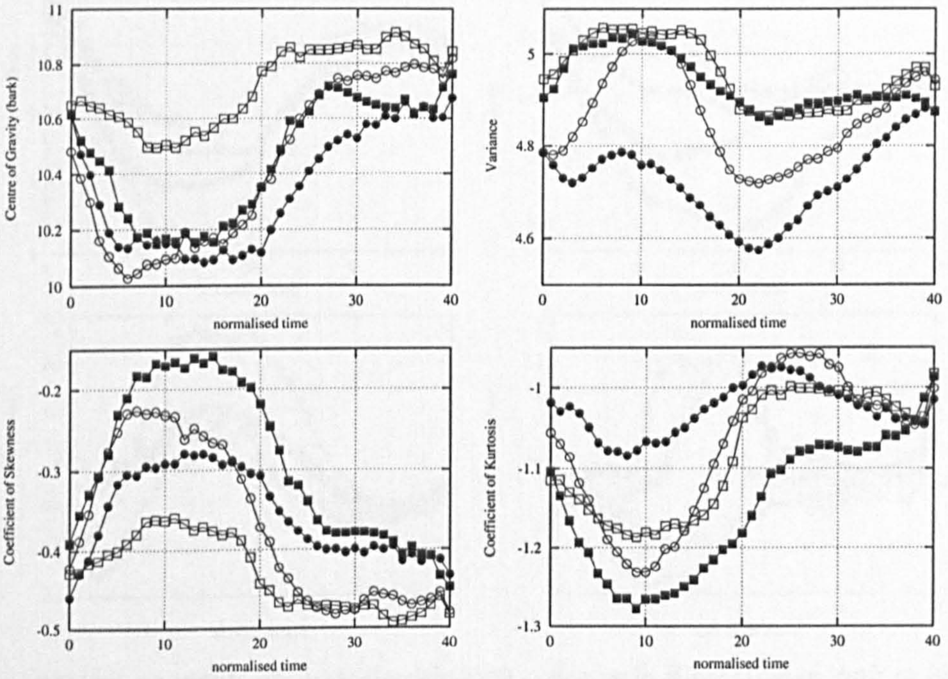


Figure 93. Spectral moments of onset liquids with a filter set with the lower limit at 100 Hz and the upper limit at half a critical bandwidth above the highest F3 frequency in the dataset (i.e. 17.463 bark/4000 Hz). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

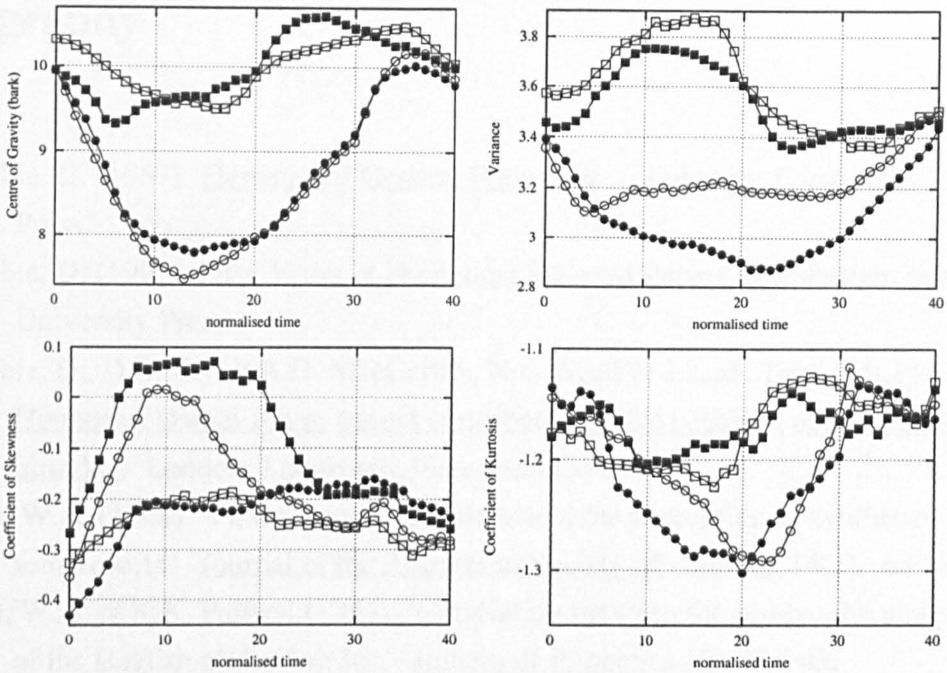


Figure 94. Spectral moments of onset liquids with a dynamic filter (lower limit at half a critical bandwidth below F1; upper limit at half a critical bandwidth above F3). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

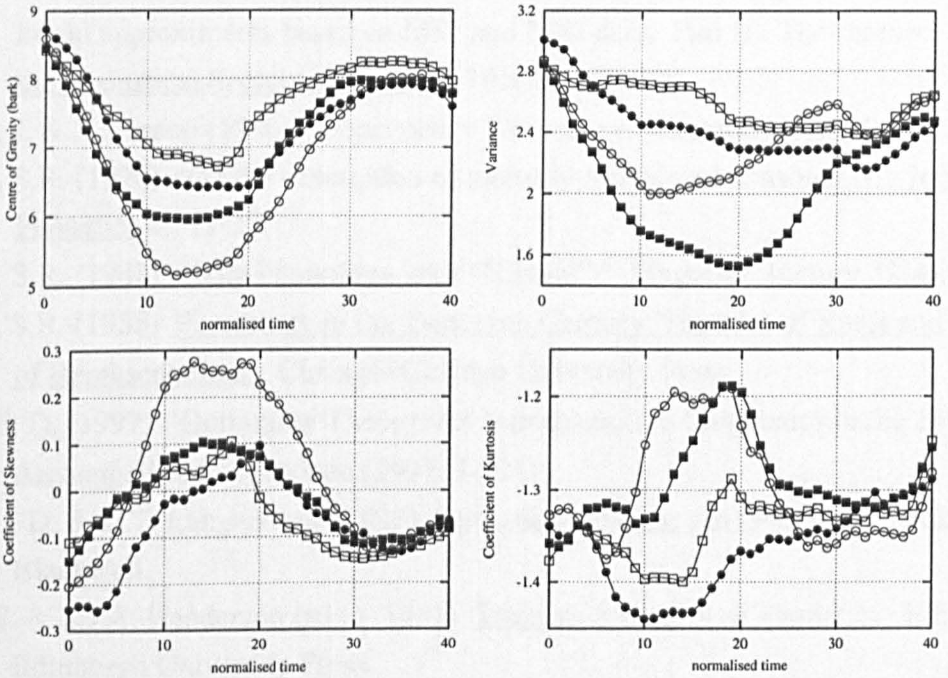


Figure 95. Spectral moments of onset liquids with a dynamic filter (lower limit at half a critical bandwidth below F1; upper limit at half a critical bandwidth above F2). Open shapes represent the Sunderland speaker; filled shapes represent the Manchester speaker. Squares represent [l]; circles represent [r].

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