MUSIC-COLOUR SYNAESTHESIA: A CONCEPTUAL CORRESPONDENCE GROUNDED IN ACTION

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A thesis by publication submitted in
partial fulfilment of the requirements for the degree of
Doctor of Philosophy

The University of Sheffield
Faculty of Arts and Humanity
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March 2022

Abstract

This thesis describes a radically different account of music-colour synaesthesia in four journal-style papers that develop and test the hypothesis that some forms of music-colour synaesthesia are mediated by concept and context, but grounded in sensorimotor action. Paper One illustrates the breadth of the phenomenology surrounding music-colour synaesthesia, reviews eight neuroimaging studies examining coloured hearing, and discusses the role of conceptual and semantic inducers. Paper Two presents an empirical investigation that demonstrates synaesthesia elicited by written musical key signatures is a genuine form of synaesthesia elicited from the concept, or the idea, of the key. The results also suggest an active role for the body and Paper Three sets out a theoretical framework for a sensorimotor explanation for music-colour synaesthesia. This stems from embodied and enactive accounts of typical music cognition and it is argued that the attributes of "bodiliness" and "grabbiness" might be found in a sonic environment, and that music listening might be perceived as an "act of doing". Finally, Paper Four presents the results of an empirical investigation that examines the relationships between emotion, action, and synaesthesia and continuations with non-synaesthetic perception. Overall, the results of the project reinforce an existing argument that a single mechanism is not sufficient to explain synaesthetic experiences that arise on hearing music, and highlight the role of multimodal/sensorimotor features in music-colour synaesthesia with a particular focus on its embodied and enactive nature. Future researchers are encouraged to place synaesthesia in response to music on a continuum from "synaesthesia" to "typical music cognition" including consideration of the implications that this may have for theories of synaesthesia, rather than assuming it to be special, separate and unconnected.

Keywords: synaesthesia; concept; ideaesthesia; music-colour; qualia; music perception; sensorimotor; cognition; embodiment; emotion; music performance

Acknowledgements

I would like to thank my supervisors, Professor Renee Timmers and Doctor Andrea Schiavio, for their expert advice and guidance. I am especially grateful to Renee for her enthusiasm and interest in my research, her honest and timely critique, her assistance in refining methodology and research design, and her consistently positive support and mentoring throughout the entire doctoral process. Renee encouraged me to publish and present from an early stage, which proved to be a key motivator both in formulating and articulating my research and in managing the merits and challenges of receiving constructive criticism. The smaller achievable targets were also a valuable means of measuring progress.

I owe particular thanks to my second supervisor Doctor Andrea Schiavio for his expertise in embodied musical cognition. Andrea's own research interests include the role of action and interaction in musical experience, and his encouragement of my enactive and embodied approach to music-colour synaesthesia research has been invaluable.

I extend thanks to the members of the Music Mind Machine reading group at the University of Sheffield for their valuable feedback on my early ideas and proposals, and to all the participants who took part in the studies, both for your time and for your interest. This thesis could not have been written without your willingness.

Finally, special thanks must go to Kate Wareham and Doctor Jacob Kingsbury Downs for whom I have much love and appreciation. Our unique online reading group (named to challenge prevarication and lambast pomposity) was an immense support to me throughout lockdown and a wonderful release from academic and work pressures. I also thank Jake for his excellent language editing and proofreading skills.

Funding

Completion of this doctoral research was supported by the Gladys Hall Postgraduate Continuation Scholarship in Music.

Dedication

I would like to dedicate this thesis to my husband, Doctor Raj Curwen, and my children, Georgia, Alex and Sam. My research has ignited some fabulous discussions. Computer science and the psychology of music have more in common than anyone could have imagined. My love and thanks also go to my parents, David and Margaret. Thank you all for your constant love and support.

List of Publications by Candidate

Published Journal Papers

For the published article in **Chapter Two** please see:

> Curwen, C. (2018). Music-colour synaesthesia: Concept, context and qualia. *Consciousness and Cognition*, *61*, 94–106. https://doi.org/10.1016/j.concog.2018.04.005

For the published article in **Chapter Three** please see:

> Curwen, C. (2022a). The role of synaesthesia in reading written musical key signatures. *Journal of Experimental Psychology: General.* Advance online publication. http://dx.doi.org/10.1037/xge0001193

For the published article in **Chapter Four** please see:

> Curwen, C. (2020a). Music-colour synaesthesia: A sensorimotor account. *Musicae Scientiae*. https://doi.org/10.1177/1029864920956295

Forthcoming

For the study in **Chapter Five** please see**:**

> Curwen, C., Timmers, R., & Schiavio, A., *Synaesthetic responses to music in non-synaesthetes: From multimodality to emotion and synaesthesia*. [Manuscript in preparation]. Department of Music, The University of Sheffield.

(Candidate contribution: established methodology and research design, writing and compilation of the manuscript, data collection and analysis, preparation of tables and figures.)

Underlying, openly accessible datasets

For the underlying, openly accessible, datasets for the study in **Chapter Three** please see:

> Curwen, C. (2020b). *The role of synaesthesia in reading written musical keys* (Version 4). [Dataset]. The University of Sheffield. https://doi.org/10.15131/shef.data.13140086.v4

For the underlying, openly accessible, datasets for the study in **Chapter Five** please see:

> Curwen, C. (2022b). *Synaesthetic responses to music in non-synaesthetes: From multimodality to emotion and synaesthesia* (Version 1). [Dataset]. The University of Sheffield. https://doi.org/10.15131/shef.data.16943941.v1

CONTENTS

CHAPTER ONE – INTRODUCTION

'The lights grow brighter as the earth lurches away from the sun, and now the orchestra is playing yellow cocktail music…'

— S.F. Fitzgerald (1925), *The Great Gatsby*

Background and Context

It was not until I began my postgraduate studies that I discovered that there was a term to describe the phenomenon of shapes, colours and textures that I experience on hearing music. Synaesthesia was such an integral part of my musical life that it had never occurred to me that other people might not experience the same. I also learned that music-colour synaesthesia was more commonly attributed to seeing colours as a response to individual tones, known as tone-colour synaesthesia. My experience was more complicated. I rarely experienced colours or shapes from a single tone, but needed the context of a whole section of music to elicit a response. A musical concept, such as "style" or "key", was as important as the perception of sound itself. I could not explain my experience as purely perceptual, yet neither was it simply metaphorical. I have a conscious and automatic response to music that has a fundamental role in my musical sense making.

In this thesis I argue that certain forms of music-colour synaesthesia are mediated by concept and context, and challenge the traditional (and most frequently examined) view that synaesthesia arising from music is fundamentally a perceptual phenomenon elicited on hearing individual tones. Music-colour synaesthesia has a broad scope encompassing not only tone-colour synaesthesia, but a complex and idiosyncratic mixture of experiences often mediated by timbre, tempo, emotion and differing musical style. Research in general music cognition has recently embraced embodied and enactive accounts that include an active role for the body and its situated power of action. Stemming from an ecological approach I propose that the role of perception in general music cognition – as suggested by embodied and enactive accounts – may be extended to some forms of music-colour synaesthesia, and that music-colour synaesthesia might be better understood as a sensorimotor phenomenon.

Developments in research in general music cognition have described human engagement with music from a sensorimotor perspective i.e., as an "act of doing", and I extend this to higher, concept-driven, forms of music-colour synaesthesia. Fundamentally the phenomenon of music-colour synaesthesia represents something about the real-world environment for the synaesthete, and is integral to their musical perception, knowledge, and understanding. Yet I do not dismiss the unique phenomenal experience, and the automaticity, general consistency, and specificity of inducer and congruent pairings that set synaesthesia apart from typical cross-modal associations, and neither do I propose a single underlying mechanism to explain all forms of synaesthesia. The inefficiency of such "one-for-all" explanations is well documented (Auvray & Deroy, 2015; Simner, 2012) and discussed in detail in this thesis. Instead, I argue that music-colour synaesthesia might be better examined not as a separate and distinct condition, but as a continuation of typical perception and cognition, offering an opportunity to gain a better understanding of the processes of general cognition and consciousness from person to person.

Research Questions

My research focussed on three key questions that were investigated through a series of papers: i) is music-colour synaesthesia purely based on sound, or can it also be induced from a musical concept; ii) do certain forms of music-colour synaesthesia have a grounding in sensorimotor action; iii) can music-colour synaesthesia be explained as a continuation of typical perception and cognition and, in particular, of general music cognition?

Linkage of Papers

Paper One – Music-Colour Synaesthesia: Concept, Context and Qualia

Paper One (Chapter Two) presents a commentary on coloured hearing that arises from hearing music. It serves both as a literature review and as a challenge to the traditional explanations of the mechanisms that underlie music-colour synaesthesia. The breadth of the phenomenology surrounding music-colour synaesthesia is described illustrating how it can extend beyond an experience of colour to include shapes, textures and moving landscapes. It is a complex and highly idiosyncratic response elicited from musical stimuli that is not limited to the sensory perception of sound itself. This is further evidenced by the inability to satisfactorily explain the phenomenon through neurological studies alone. Commonalities between synaesthetic experience and typical cross-modal perceptions in non-synaesthetes suggest that non-synaesthetic people appear to use comparable mental processes to make associations between colours and music, and to make similar pairings at a conceptual level. From this I argue that certain types of synaesthesia may simply be developed as a useful method for a child to process its first encounter with abstract concepts more easily, such as music unfolding over time afforded by the "extra qualia" (Wager, 1999) of their synaesthetic experience. The different types of experience in music-colour synaesthesia and the individual differences between synaesthetes, together with the implications this has for the current methods used to verify the condition, reinforce an existing argument that a single mechanism is not sufficient to explain the experiences that arise on hearing music, neither from a sensory musical stimulus, nor from a non-sensory musical concept (Auvray & Deroy, 2015).

Paper Two – The Role of Synaesthesia in Reading Written Musical Key Signatures

Chapter Three presents the results of Paper Two, an empirical study that seeks to demonstrate that music-colour synaesthesia may be elicited by concept and that a perceptual "sounding out" of the musical stimulus is not always necessary. The study provides the first empirical demonstration of synaesthesia for reading written musical keys in five experiments that test two hypotheses: i) longer reaction times will be observed when naming synaesthetic colours if presented with incongruent pairings between colour and musical key, indicating the presence of synaesthesia for written musical keys; and ii) synaesthetic association persists irrespective of presentation modality and form, and that a change in the form of the stimuli from a key signature written in words to that of a key signature written on the stave (either in the treble or the bass clef) should not result in a change of synaesthetic colour. The results of the study indicate that to gain a full understanding of music-colour synaesthesia it is important to extend investigations beyond the more commonly examined tone-colour synaesthesia. The findings of this study also suggest that synaesthesia associated with music may be mediated by concept but grounded in sensorimotor action. For example, notation on the stave may provide more sensorimotor information about the concept of key rather than the written word, i.e., thoughts about production or hand shape (Curwen, 2020a).

Paper Three – Music-Colour Synaesthesia: A Sensorimotor Account

Paper Three is a theoretical paper and its arguments are presented in Chapter Four. This chapter aims to describe how the role of accounts of perception inspired by embodied and enactive views in general music cognition may be extended to some forms of music-colour synaesthesia, and how music-colour synaesthesia might be better understood as a sensorimotor phenomenon. Developments in research in general music cognition are outlined describing engagement with music from a sensorimotor perspective i.e., as an "act of doing". It is argued that this may be extended to higher, concept-driven, forms of music-colour synaesthesia, and that the experience represents something about the real-world environment for the synaesthete and is integral to their musical perception, knowledge, and understanding. The conclusion of the chapter points to future empirical research starting from the hypothesis that synaesthesia associated with music is mediated by concept and context but – as also suggested in Chapter

Three – grounded in sensorimotor action. The results of such an investigation are discussed in detail in Chapter Five.

Paper Four – Synaesthetic Responses to Music in Non-synaesthetes: From Multimodality to Emotion and Synaesthesia

Building on the findings from the previous studies, Chapter Five presents an empirical investigation of the role of sensorimotor features in music-colour synaesthesia with the objective of demonstrating that certain forms of music-colour synaesthesia may be mediated by concept and context, but grounded in action. The chapter is presented in a form suitable for submission to a journal. The aim of this experiment was to investigate the relationships between emotion, action, and synaesthesia and continuations with non-synaesthetic perception, and to test the following hypotheses:

Changes to action-related qualities of a musical stimulus will affect the resulting synaesthetic experience: H1) a change of instrument from their own instrument to one with which they have no expertise; H2) whether or not the music is performed by a human.

A relationship exists between multimodal and emotional responses to music in the general population: H3) there will not be a significant difference between synaesthetes and non-synaesthetes when rating emotional and multimodal factors across different listening conditions; H4) emotional responses will feed into synaesthetic responses; H5) a supposed continuity between multimodal and synaesthetic responses predicts a stronger relationship between these two factors irrespective of emotion.

Two groups (synaesthetes/non-synaesthetes) were asked to report their experience while listening to three sets of four musical excerpts presented in random order: on an instrument they were very familiar with; on an instrument they had never played before; or on an electronic instrument played with no expression. Participants selected and rated the applicability and intensity of the terms that best describe their emotional, sensorimotor/multimodal and synaesthetic experience, and the strength of their motivation to move and vocalise to the music. The results suggest that multimodal ratings have a significantly stronger influence on the strength of synaesthetic response than emotional ratings and provide evidence that music-colour synaesthesia may have a grounding in action.

Research Aim and Objective

Together the four papers aim to develop and test the hypothesis that higher forms of music-colour synaesthesia are mediated by concept and context, but grounded in sensorimotor action.

CHAPTER TWO – MUSIC-COLOUR SYNAESTHESIA: CONCEPT, CONTEXT AND QUALIA

'What was she seeking through millions of pages, in her old plush dress, and her wig of claret-coloured hair, with her gems and her chilblains? Sometimes one thing, sometimes another, to confirm her philosophy that colour is sound — or, perhaps, it has something to do with music.

— V. Woolf & K. Flint (1922), *Jacob's Room*

Published as: Curwen, C. (2018). Music-colour synaesthesia: Concept, context and qualia. *Consciousness and Cognition*, *61*, 94–106. https://doi.org/10.1016/j.concog.2018.04.005

This chapter is produced in a slightly different format to that of the published journal paper referred to above, but is otherwise identical.

Linkage of Paper to Research Methodology and Development

The purpose of this paper is to provide both a literature review and a challenge to the traditional explanations of the mechanisms that underlie music-colour synaesthesia. Although music-colour synaesthesia is often assumed to be a purely perceptual phenomenon arising from the sound of a single tone (tone-colour synaesthesia), recent research supports a role for concept and meaning in the understanding of the cause of synaesthetic experiences. A review of eight neurological studies, together with a discussion of the challenges presented to established philosophies of mind, show that there is a need to extend research to concept driven forms of music-colour synaesthesia other than the more commonly examined tone-colour synaesthesia.

Abstract

This review provides a commentary on coloured hearing arising on hearing music: music-colour synaesthesia. Although traditionally explained by the hyperconnectivity theory (Ramachandran & Hubbard, 2001a) and the disinhibited feedback theory (Grossenbacher & Lovelace, 2001) as a purely perceptual phenomenon, the review of eight coloured hearing neuroimaging studies shows that it may not be assumed that these explanations are directly translatable to music-colour synaesthesia. The concept of "ideaesthesia" (Nikolić, 2009) and the role of conceptual and semantic inducers challenge the likelihood of a single mechanism underlying the cause of synaesthesia and argue for a move away from a purely sensory to sensory explanation. Finally, music-colour synaesthesia forms a challenge for established philosophical theories and the position of synaesthesia is considered within the larger context of musical qualia.

Keywords: synaesthesia/synesthesia; ideaesthesia; concept; music-colour/color, chromesthesia; qualia

Synaesthesia is a relatively rare condition that manifests itself in approximately four percent of the population. It is a phenomenon that occurs automatically, and generally with considerable consistency over time. It has been described as a "union of the senses" (Cytowic, 1989, 2002; Marks, 1975; Motluk, 1994; Vernon, 1930) and typically arises as result of stimulation in one sense (an inducer) triggering a reaction in an unstimulated second sense (a concurrent). The most commonly examined form is grapheme-colour synaesthesia in which colours are experienced in response to digits or letters (Hubbard, 2007) although many other combinations exist: a sensation of colour may be elicited on hearing certain sounds, or in association with certain tastes, or by touch. Furthermore, although often described as a purely sensory to sensory phenomenon, it is also possible for inducers to be non-sensory in nature. For example, some common forms result in an experience of colours and spatial layouts in association with days of the week or calendar months; neither months, nor days of the week, can be described as delivering any sensory input, per se. This review provides a commentary in three parts on the existing literature that explores a form of synaesthesia also known as chromesthesia, or coloured hearing, that arises on hearing music. The first part of the review begins by considering the characteristics of music-colour synaesthesia and the commonalities between the synaesthetic experience and normal cross-modal perceptions in non-synaesthetes (Ward, Huckstep, & Tsakanikos, 2006; Isbilen & Krumhansl, 2016). The second part of the review discusses the two main neurological hypotheses pertaining to the cause of synaesthesia: the hyperconnectivity theory (Ramachandran & Hubbard, 2001a) and the disinhibited feedback theory (Grossenbacher & Lovelace, 2001) followed by a discussion of the results of eight neuroimaging studies with a sound-colour focus. The final section explores how some types of music-colour synaesthesia provide further evidence in support of the importance of the role of conceptual and semantic inducers in synaesthesia, and the alternative theory of "ideaesthesia" (Nikolić, 2009; Mroczko-Wąsowicz & Nikolić, 2014). The review concludes with a consideration of the challenge presented by synaesthesia to established philosophical theories and the position music-colour synaesthesia might occupy within the larger context of musical qualia.

Characteristics and Commonalities

The Characteristics of Music-Colour Synaesthesia

The umbrella term "music-colour synaesthesia" or simply "coloured hearing" has been applied to the experience of colour elicited on hearing sounds. There are several different types of music-colour synaesthesia which manifest in quite different ways and might include not just the experience of colours, but also of textures, shapes and spatial landscapes (Eagleman & Goodale, 2009). Peacock (1985) broadly classified four groups of "inducers" related to compositional style, timbre, tonality, and pitch (or tone). These may be further differentiated to include relationships between colour per individual composer, colour and certain keys, and colour occurring from differing harmonic progressions (Vernon, 1930). It is not uncommon for synaesthetes to experience combinations of these different types, and the idiosyncratic nature of the condition frequently results in individual synaesthetes disagreeing about the colours and imagery associated with musical inducers: one synaesthete may consider B minor to be the colour of sunlight on a window pane, yet for another B minor is sea green. Examples of the different types of music-colour synaesthesia experienced are given by GS, the subject of Mills, et al.'s (2003) study. Her experiences encompass shapes, texture, and movement, in addition to colours. GS reports big blocks of dark colours in response to heavy metal music, and displeasing combinations of colours to music that she does not like. GS does not possess absolute pitch but found that higher pitches would be accompanied by lighter colours and lower pitches by darker colours. GS also explained that different instruments, or combinations of instruments, would produce different colours and patterns, and that the same note played at the same pitch but on a different instrument would result in a different colour. Musical intervals, tonality and themes created landscapes that she referred to as maps, and the tempo of the music would dictate the speed at which the maps moved. GS commented that she often found the maps easier to follow than standard musical notation.

Normal Cross-Modal Associations

Although there is a uniqueness to the visual and/or spatial phenomenon synaesthetes experience on hearing music, some commonalities with cross-modal associations in non-synaesthetes have been identified (Ward, 2013). For example, in the general population the visualised size and location of pitches has been shown to be associated with certain auditory characteristics: higher pitches tend to be associated with an elevated spatial position and a smaller size, and lower pitches with a lower space and a larger size (Marks, 1987, 2004; Gallace

& Spence, 2006; Walker et al., 2010; Ward, Huckstead & Tsakanikos, 2006). Ward, Huckstead and Tsakanikos (2006) posit that although there are differences between synaesthetes and non-synaesthetes in respect of automaticity, consistency and specificity of colour selections, both groups do appear to employ similar pitch mapping with regard to pitch-lightness. Tsiounta, et al. (2013) also found that non-synaesthetic people appeared to use comparable mental processes to make associations between colours and music, and to make similar pairings at a conceptual level. The study examined the correlations that people from different cultures and backgrounds made between colour and music. Twenty different music genres were presented to participants and then twenty different themes from movies and television soundtracks. In each case participants were required to select a colour from a palette that they thought was best associated with the track they were hearing. The results demonstrated a level of common association in some genres between colour and music in non-synaesthetic people.

Role of Emotion

Similarly, a level of common association has been demonstrated between emotion and music, and emotion and colour (Palmer, et al., 2013; 2016). Palmer's studies were carried out with non-synaesthetes and demonstrated an association between major keys and more saturated, yellow, and brighter colours, and an association between minor keys and darker, bluer, less saturated colours. In addition, emotional ratings of the colours and the musical excerpts showed a correlation between the emotional state and the musical excerpts, and emotional state to the colours, suggesting that music to colour associations might be mediated by emotion in the general population.

Isbilen & Krumhansl (2016) carried out further studies to test this hypothesis including in their study musicians, non-musicians, absolute pitch possessors, and music-colour synaesthetes. Using the preludes from Bach's Well Tempered Clavier, musical excerpts were presented in each of the major and minor keys and in a diverse range of styles. The study comprised three experiments. Experiment 1 required participants to choose from a palette of eight colours and to match them to excerpts heard from 24 preludes. From the colour choices made, it was found that the preludes could be grouped together in terms of tempo, key, pitch height and attack rate. In Experiment 2, participants were asked to rate the colours on an emotional scale, and in Experiment 3, they were asked to rate the preludes they heard on the same emotional scale. The results of Experiments 2 and 3 were then combined and it was found that the music-colour associations observed in Experiment 1 could be predicted by the colour-emotion rating given in Experiment 2, and the music-emotion rating given in Experiment 3. The possession of synaesthesia or absolute pitch was shown to have very little effect on the actual colours chosen for each of the musical excerpts, but it might be reasonable to expect that music that elicits a strong emotional response may be more likely to induce synaesthesia than music that does not (Marks, 2004). Such results suggest that there may be similarities on a general level in the way that people conceptualise emotions associated with music and those associated with colours. The conceptual meaning of music may vary with its emotional (Cutsforth, 1925; Marks, 2004) which in some forms of music-colour synaesthesia may also be represented by a corresponding change in colour.

Although the studies above lend support to the hypotheses that synaesthesia may rely on normal cross-modal associations (Marks, 2013; Simner, 2013) and that chromesthesia is a general mental mechanism that helps us process aural information (Marks, 1975), this apparent common association should not be used to dismiss synaesthesia as a distinct phenomenon per se. Both synaesthetes and non-synaesthetes are exposed to the same learned cultural and environmental associations: large objects do tend to make louder noises on impact than smaller ones, and higher pitches are generally associated with the sounds made by smaller objects (Spence, 2011). Indeed, Parise and Spence (2009) posit that the connection between pitch and elevation might be the brain's employment of coupling priors to enable it to interpret the natural environment. However, it has been pointed out that it is the automaticity, general consistency, and specificity of inducer and congruent pairings that set synaesthesia apart from normal cross-modal associations (Ward, Huckstead & Tsakanikos 2006).

Notwithstanding the similarities to the cross-modal associations made between music excerpts, emotion, and colour by non-synaesthetes, studies exploring coloured hearing or auditory-colour synaesthesia frequently focus on those synaesthetes who report sensations of colour arising from the sound of pure tones (Ward, Huckstead & Tsakanikos, 2006). From these stems comparisons to the hypothesised mechanisms of absolute pitch and the ability to assign a label to individual notes (Gregersen et al., 2013; Loui et al., 2013; Profita et al., 1988; Takeuchi & Hulse, 1993). However, music-colour synaesthesia is not simply about the ability to label an isolated pitch or a chord and is not always accompanied by the possession of absolute pitch (Mills et al., 1999). As previously discussed, music-colour synaesthesia is often dependent on timbre, context, and key, and accompanied by shapes, spatial layouts and textures (Eagleman & Goodale, 2009). Self-report is often the only means of discovery and although questionnaires and interviews are useful means of gathering data these do not provide a method of verification of its existence and properties.

Methods of Verification

The development of the test of genuineness (TOG) for word-colour synaesthesia established consistency over time as the primary measure to distinguish real cases of synaesthesia from non-genuine cases (Baron-Cohen et al., 1987). From this principle, the Synaesthesia Battery ("the Battery") was developed by Eagleman et al. (2007) to provide a quantifiable battery of online tests for several different types of synaesthesia. The Battery comprises a questionnaire to identify the type of synaesthesia that might be present, which is then tested by appropriately designed software programs. A palette of 16.7 million colours is offered from which a corresponding concurrent may be chosen. Each inducer is presented three times during the trial and any variation in the colours chosen is analysed for consistency by measuring the geometric distance in RGB (red, green, blue) colour space. A total colour variation score per participant is then calculated from this. Those who score less than 1 are verified as having synaesthesia, with controls generally scoring over 2 (Eagleman et al., 2007). The Battery has been used successfully in verifying grapheme-colour synaesthesia (Rothen et al., 2013) and also offers tests for tone-colour synaesthesia, single chords to colour, and instruments to colour (Zamm et al., 2013). However, the sheer number of colour choices available may make it difficult to find the exact same colour the second time around, and not all synaesthetes just experience a single colour. Synaesthetes who experience textures, shapes, and movement in addition to colour, may find the colour palette too limited. Music-colour synaesthetes are frequently reported to experience combinations of different colours, hues and shapes (Mills et al., 2003; Marks, 2011) and so the Battery may be less useful in identifying this form of synaesthesia. Indeed, the exclusive use of the Battery might result in certain types of music-colour synaesthesia being ruled out altogether. Synaesthesia elicited from music is mediated by more than just sound. Changes in timbre, pitch height, tempo, emotional content and style, either individually or in combination, might significantly affect the synaesthetic texture, hue, saturation and movement of a musical excerpt, possibly making the perceived colour inconsistent across presentation (Mills et al., 2003). Consequently, those that require the context of an entire piece of music to elicit colours may find that the presentation of isolated chords, tones or instrumental timbres simply insufficient to bring about a synaesthetic response.

The requirement of consistency as the primary measure in the TOG for the existence of synaesthesia has been placed under scrutiny by both Simner (2012) and Cohen Kadosh and Terhune (2012). Simner points out that with the existence of so many different types of synaesthesia it may be incorrect to assume that each type operates through the same mechanism. The danger of the reliance on measures that solely use the consistency test for verification might result in some forms of synaesthesia being overlooked, such as the types of music-colour synaesthesia mentioned earlier that require more than an isolated tone to elicit a synaesthetic response. Furthermore, it has been demonstrated that in reality there can be some inconsistency in synaesthesia and that some variation over time has been observed, particularly in children (Cytowic, 2002; Eagleman et al., 2007; Rogers, 1987). The subject of Mills' case study, GS, reported inconsistencies in her experiences: "Sometimes the same note would be played, but will be a different color. I don't know why, even on the same instrument it'll be a different color" (Mills et al., 2003, p.1364). Ward and Mattingley (2006) also question the prescriptive nature of the consistency requirement in the TOG asking, "Would we not consider a person to be a synaesthete if the colours he or she experienced for particular musical notes changed over time?" and suggest that it should be regarded as an "associated characteristic" rather than as an all defining one (p. 130). Simner (2012) presents the challenge of finding a better measure than consistency. Cohen Kadosh and Terhune (2012) agree and remark that failure of a consistency test should not result in the exclusion of those that nonetheless report synaesthetic experiences equally well demonstrated through behavioural tests such as Stroop interference (Stroop, 1935). For example, a synaesthete who sees a "7" as green and a "6" as red may find it more difficult to identify a "7" in red ink or a "6" in green ink, should this be incongruous with their synaesthetic colour (Mills et al., 1999; Dixon et al., 2000; Mattingley et al., 2001). Yet it should be noted, as demonstrated by Elias et al. (2003), that Stroop interference alone is not sufficient to confirm the existence of synaesthesia, as it may demonstrate the presence of learned associations. In this study one control had been using cross stitch patterns for eight years during which time learned associations had formed between certain colours and numbers. Significant Stroop interference was noted for both the grapheme-colour synaesthete and the control, but it was not possible to categorically distinguish between the two. However, although the consistency test might be best used in association with other measures rather than alone, it does show us that a difference exists between synaesthetes and non synaesthetes (Hubbard et al., 2005) and suggests that the experience is vivid and specific enough to be able to select very precisely.

Individual Differences between Synaesthetes

A further complication in finding a suitable method of verification for synaesthesia is a noted difference in phenomenological experience between categories of synaesthetes themselves: “associators” and “projectors”, and “higher” and “lower” synaesthetes. Associators often describe their experience of colour as being in “the mind’s eye” (Dixon et al., 2004; Dixon & Smilek, 2005) or as “knowing” the colour (Ward et al., 2007) suggesting the application of higher cognitive processes (Meier & Rothen, 2007). In contrast projectors describe being able to “see” colours which are often projected outside the body and into external space (Smilek et al., 2001). A behavioural study carried out by Dixon et al. (2004) demonstrated that the distinction is not just confined to the self-reporting phenomenal experience but that it also points to different cognitive mechanisms. The study carried out a Stroop test on grapheme-colour synaesthetes and demonstrated that projectors were slower in naming the actual colour of digits when the colour was incongruent with their synaesthetic colours, whilst the reverse pattern was demonstrated by associators. Overall, different patterns of Stroop interference were shown by projectors and associators. Van Leeuwen et al. (2011) also demonstrated differences in processing between associators and projectors using dynamic causal modelling (DCM) of fMRI data. Evidence was shown that associators demonstrated disinhibited feedback from the parietal cortex to the V4 colour area, whilst projectors favoured cross-activation from an area that processed letter shape, or form, directly to the V4 area. Compared to the literature on associators and projectors, there is less empirical evidence for the categorisation of higher and lower synaesthetes (Chiou & Rich, 2014). The distinction between higher and lower synaesthetes was first proposed by Ramachandran and Hubbard

(2001b) in the face of contradictory results, who posited that cross-activation mechanisms were occurring at a different time and place in the brain in each case. Lower synaesthetes were thought to be processing at an earlier stage in the fusiform areas that manage grapheme form and the perception of colour, whilst higher synaesthetes were thought to process at a later stage in the areas that dealt with conceptual aspects of colour. The distinction between higher and lower synaesthetes lies in the type of inducer and the level of processing. Synaesthesia in a lower synaesthete is thought to be triggered by bottom-up lower level features such as the shape or texture of an inducer, whilst in higher synaesthetes the conceptual characteristics of the inducer influence higher level later stage processing (van Leeuwen, 2013). The early stage in processing in lower synaesthetes can lead to early perceptual effects known as “pop out” (Ramachandran & Hubbard, 2001b). It was originally thought that all synaesthetes would demonstrate the ability to do this, as in Ramachandran and Hubbard’s (2001a) experiment asking participants to find a hidden shape of “2”s in a pattern of “5”s. However, a later study found that this was not the case. Lower synaesthetes might be able to identify a target amongst distractors very fast, but in higher synaesthetes this ability is not as strong (Hubbard et al., 2005). This is because it is not the shape of the digit that induces the concurrent for higher synaesthetes, but the concept or meaning of the letter (Cytowic & Eagleman, 2009). Although on the face of it, it may be reasonable to suppose that associators should be mapped to higher synaesthetes and projectors to lower synaesthetes, this has not been substantiated and in some studies proved to be orthogonal (Ward et al., 2007). The distinction between associators and projectors is in the experience of the concurrent, whilst that between higher and lower synaesthetes is the nature of the inducer. Consequently, in principle, it is not impossible to have a lower synaesthete that perceives colours in his “mind’s eye”, or a higher synaesthete that is a projector. Although much of the literature has focused on grapheme-colour synaesthesia (Dixon et al., 2004; Rouw & Scholte, 2007; Ward et al., 2007), the distinction between higher and lower synaesthetes has significant implications for music-colour synaesthesia. Experiences resulting from different musical styles, composers, harmonic progressions, association with keys, written notation (Ward, Tsakanikos & Bray, 2006) or emotion (Isbilen & Krumhansl, 2016; Ward, 2004) present a variety of types of inducers. The correct categorisation of synaesthetes as associators, projectors, and or lower or higher synaesthetes is pertinent to the true interpretation of experimental results. Only with consideration of the individual differences between synaesthetes can an understanding of the mechanisms at work in music-colour synaesthesia be achieved. If all the synaesthetes in a study are classed as higher synaesthetes, then results cannot be expected to support a hypothesis based on synaesthetic responses from early stage processing.

Neurological Theories

Disinhibited Feedback Theory and Hyperconnectivity Theory

Much of the literature in the last twenty years has focused on establishing the existence of synaesthesia as a true phenomenon and explaining its cause. Currently, the general agreement is "that synaesthesia is neither imagination nor is it metaphorical thinking, instead it has a neural basis" (Rothen et al., 2012, p. 1953). The two primary neurological theories for the causes of synaesthesia are the disinhibited feedback hypothesis (Grossenbacher & Lovelace, 2001) and the hyperconnectivity theory, or the revised hyperbinding theory (Ramachandran & Hubbard, 2001a; Hubbard et al., 2011). The disinhibited feedback theory has been developed from behavioural studies and suggests that synaesthesia may come about through a diminution of inhibition travelling through feedback pathways. Information travels in either direction between primary sensory areas to association areas such as the parietal lobe or limbic system. It could be possible that later stages of processing might influence earlier stages of processing if feedback signals were not sufficiently inhibited (Neufeld, Sinke, Zedler et al., 2012).

In contrast, the hyperconnectivity theory suggests that direct connections exist between the areas of the brain that process the inducer stimulus and those that process the concurrent experience. No higher-level processing is involved and the process is purely bottom-up without the parietal cortex playing a major role (van Leeuwen et al., 2015). However, it should be noted that the more recent hyperbinding model revises the hyperconnectivity theory by adding a role for the parietal cortex in binding together colour and grapheme (Hubbard, et al., 2011). Analysis of the timing of neural activations may indicate whether synaesthetic experiences are mainly governed by top-down (late conceptual) or bottom-up (early perceptual) processes (Jäncke, 2013).

Although not addressed by Grossenbacher and Lovelace (2001), Brang et al. (2010) identify that because of later top-down processing in disinhibited feedback, there should be an observable time lag between the processing of the inducer and the concurrent. In the case of the hyperconnectivity/hyperbinding theory, the direct connections between the inducing and concurrent areas of the brain should occur without delay, as processing in both areas should occur almost simultaneously. Yet neither theory has been categorically proven to be better than the other, nor that they cannot exist side by side (Cytowic & Eagleman, 2009). Although some support for the neurological basis of synaesthesia has been observed in the activation of the V4 colour area in grapheme-colour synaesthesia (Nunn et al., 2002), a limitation of most neuroimaging studies is that they focus on grapheme-colour synaesthesia alone. Nunn et al. (2002) considered the activation of the V4 area as proof for the existence of synaesthesia and the presence of hyperconnectivity, but it cannot necessarily be assumed that it is directly translatable to other forms (Zamm et al., 2013). For example, Neufeld, Sinke, Dillo et al.'s (2012) study found that there was no activation in the V4 areas for music-colour synaesthetes. The next section compares the results of eight neuroimaging studies (Table 1) conducted on synaesthetes with forms of coloured hearing to examine the evidence for the presence of disinhibited feedback or hyperconnectivity. The studies comprise three functional studies (Goller et al., 2009; Jäncke et al., 2012; Neufeld, Sinke, Dillo et al., 2012) and five structural studies (Banissy et al., 2012; Hänggi et al., 2008; Zamm et al., 2013; Jäncke & Langer, 2011; Neufeld, Sinke, Zedler et al., 2012).

Table 1

Summary of the Results of Eight Coloured Hearing Neuroimaging Studies

Study	Participants	Synaesthesia Type	Modality	Results
		Functional		
Goller 2009	10 Synaesthetes 10 Controls	Coloured hearing 5 Projectors 3 Associators 2 Mixed	EEG	Differences in auditory ERPs but no visual potential.
Jäncke 2012	11 Synaesthetes 11 Controls	Coloured hearing	EEG	MMNs larger for two largest deviant tones suggesting early pre-attentive processing.
Neufeld 2012a	14 Synaesthetes 14 Controls	Tone-colour 14 Associators	fMRI	BOLD differences in left inferior parietal cortex only. None at V4 or other visual regions.
		Structural		
Hänggi 2008	1 Synaesthete 17 Musicians 20 Controls	Tone-colour Interval-taste Absolute pitch	DTI	DTI and T1 weighted difference in FA and WM in auditory areas.
Jäncke 2011	12 Synaesthetes 13 Controls	Coloured hearing	EEG	No increased connectivity in fusiform gyrus, and no general difference in connectivity.
Banissy 2012	9 Synaesthetes 42 Controls	Tone-colour and Grapheme-colour	VBM – GM	GM larger in left posterior and less in left anterior of fusiform gyrus. No difference in whole brain analysis.
Neufeld 2012b	14 Synaesthetes 14 Controls	Tone-colour 14 Associators	fMRI	No increased connectivity between visual and auditory cortex. Connectivity between right auditory cortex and left and right motor cortex, and left inferior parietal cortex and both left primary auditory cortex and right primary visual cortex.
Zamm 2013	10 Synaesthetes 10 Controls	Tone-colour and Music-colour	DTI	WM greater in right IFOF

Note: Neufeld 2012a = Neufeld, Sinke, Dillo et al. (2012), Neufeld 2012b = Neufeld, Sinke, Zedler et al. (2012)

Neurological Studies

Functional

Goller et al. (2009) carried out a study of 10 coloured hearing synaesthetes and 10 controls to see if there was a stronger activation in the visual cortex for synaesthetes compared to controls. Of the synaesthetes, five were identified as projectors: two seeing colours in front of them and three from where the sound originated. Of the remainder, three were classed as associators, seeing colours in the mind's eye, and two were a combination of associator and projector. An Electroencephalograph (EEG) study was carried out during which all participants heard five pure tones. The purpose of the study was to investigate whether early differences in auditory event-related potentials (ERPs) existed in the synaesthetes, which might indicate that sound processing differences in coloured hearing synaesthesia involves the auditory cortex and superior temporal regions. Although there were differences in auditory ERPs in the synaesthetes suggesting the involvement of auditory cortex and superior temporal regions, the results did not support a visual potential. The authors consider the results to be complementary to the disinhibited feedback theory, rather than to a suggestion of special direct connections between visual and auditory pathways in the brain. It should also be noted that a difference was found between two particular synaesthetes: SL, who was identified as an associator, and, JL, a projector. The authors suggest that earlier processing in projectors (Dixon et al., 2004; Ward et al., 2007) might be an explanation for JL's greater size of visual P1 (an early visual related ERP component) of 80–120 msec, compared to SL's negative later deflection of 230–270 msec. Later Jäncke et al. (2012) tested 11 coloured hearing synaesthetes and 11 controls with a more intricate test, again to see if there was an involvement of the visual area in the synaesthetes. EEG signals were measured whilst participants watched a silent movie and attempted to ignore presented tones: 440Hz 60% of the time, and four deviants (438Hz, 422Hz, 416Hz and 264Hz) each presented 10% of the time. Mismatch negativity (MMN) was observed for both groups but the MMNs were larger in synaesthetes for the two largest deviant tones (416Hz and 264Hz) suggesting that the larger deviance was due to the synaesthetic colour being processed early and pre-attentively. A LORETA source reconstruction suggested the possible involvement of visual areas in this group. However, Hupé and Dojat (2015) comment that a limitation with this study is the absence of MMN readings for tones that did not produce a synaesthetic response. It cannot be certain whether this group, particularly, just had a better MMN for stronger deviants irrespective of the presence of their synaesthesia.

No further clarity was produced from Neufeld, Sinke, Dillo et al.'s (2012) fMRI study that compared the blood oxygenation level deviation (BOLD) responses in 14 tone-colour synaesthetes and 14 controls to different sounds played by different instruments. The authors found that the only difference was a stronger activation in the synaesthetes in the left inferior parietal cortex and no difference was found in the ROI (regions of interest) analysis at the V4 colour area nor any other visual area. The increased activity observed in the parietal cortex of the synaesthetes lends support to the hypothesis of its role in "hyperbinding" in synaesthesia (Hubbard et al., 2011) as a sensory hub between auditory (inducer) and visual (concurrent) information. The results do not support direct connections between auditory or visual areas in the brain as predicted by the hyperconnectivity theory.

Structural

Hänggi et al. (2008) carried out a single case study on a professional flute player, ES, who had tone-colour, interval-taste synaesthesia and absolute pitch, compared to 17 musicians and 20 controls. Both groups were tested for diffusion tensor imaging (DTI) and T1 weighted differences in both fractional anisotropy (FA) and white matter (WM) in the auditory area of ES. As in Goller et al.'s (2009) study, Hänggi found differences in the auditory areas. Banissy et al. (2012) examined nine synaesthetes and 42 controls. The synaesthetes all reported grapheme-colour synaesthesia and eight also had tone-colour synaesthesia. Voxel-based morphometry (VBM) was used to observe whether there was an increased volume of grey matter (GM) in the synaesthetes compared to controls. ROI analysis revealed a larger GM in the left posterior and less GM in the left anterior part of the fusiform gyrus of the synaesthete group. However, no difference between the two groups was observed on whole brain analysis. Furthermore, how much the overall results may have been influenced by the presence of grapheme-colour synaesthesia as well as tone-colour is not clear. It is noted by Zamm et al. (2013) that whilst certain functional MRI, EEG and MEG studies have found activation in the V4 area in synaesthetes (van Leeuwen et al., 2010; Weiss et al., 2005; Brang et al., 2008; Sagiv & Ward, 2006; Beeli et al., 2008), most of these studies have concentrated on grapheme-colour synaesthesia. Because the areas of inducer and concurrent in grapheme synaesthesia may be adjacent to one another, Zamm et al. (2013) remark that the results may not be translatable to other forms of synaesthesia. Encouraged by the studies of Goller et al. (2009), Jäncke et al. (2012) and Hänggi et al. (2008), Zamm tested the hypothesis that there might be increased connectivity in WM pathways passing through the temporal and occipital regions in music-colour synaesthesia. In a study that compared 10 controls to 10 synaesthetes with tone-colour, chord-colour and instrument-colour (as defined by the subsets in the Eagleman Battery, 2007), Zamm used DTI to trace WM tracts in these areas and found that WM integrity within the right inferior fronto-occipital fasciculus (IFOF) was significantly greater in synaesthetes than controls. Zamm considers these results to suggest a likelihood of an increased connectivity in visual and auditory areas in music-colour synaesthesia. In contrast, instead of using structural or functional measures, Jäncke & Langer (2011) focused on resting state electroencephalography (EEG) to test the role and connectivity between the parietal cortex, auditory cortex and fusiform gyrus in coloured hearing synaesthesia. 12 coloured hearing synaesthetes and 13 non-synaesthetes were tested. The results showed that there was no increased connectivity in the fusiform gyrus and that there was no difference in general connectivity between the two groups. Although still lacking in direct evidence, higher values for synaesthetes in the parietal cortex led to the suggestion that more highly interconnected hubs might exist in the parietal regions in coloured hearing synaesthesia thereby lending support to the hyperbinding theory (Hubbard et al., 2011). Finally, Neufeld, Sinke, Zedler et al. (2012) performed a functional connectivity analysis on fMRI data collected from 14 tone-colour synaesthetes and 14 controls. The study found no increased connectivity in synaesthetes between the visual and the auditory cortex, but they did detect increased connectivity between the right auditory cortex and the left and right motor cortex, as well as between the left inferior parietal cortex and both the left primary auditory cortex and the right primary visual cortex. The authors consider these findings to be further support for the disinhibited feedback theory. A point of note is that all 14 of the synaesthetes were classed as associators, which van Leeuwen (2013) suggests might strengthen the theory that associators tend to rely more on top-down processing.

Summary of Neurological Studies

In summary, the results of the eight studies were largely inconclusive. Only Goller et al. (2009) and Neufeld, Sinke, Zedler et al. (2012) considered that their results supported the operation of disinhibited feedback, whilst Neufeld, Sinke, Dillo et al. (2012), and Jäncke and Langer (2011), favoured hyperbinding. Zamm et al. (2013) identified structural differences in increased white matter tracts between visual and auditory areas in synaesthetes that could suggest hyperconnectivity, which was also largely supported by Hänggi et al. (2008) Banissy et al. (2012) and Jäncke et al.'s (2012) studies. However, there are some limitations. It cannot be certain how Banissy et al.'s (2012) results might have been influenced by grapheme-colour synaesthesia, as all but one of the synaesthete group possessed both grapheme and tone-colour synaesthesias. Hänggi et al.'s (2008) subject, ES, also possessed absolute pitch. Consequently, it is not possible to be sure that the differences found were because of synaesthesia alone, as the comparisons made with musicians with absolute pitch were not conclusive (Hupé & Dojat, 2015). Furthermore, it should be noted that although both Banissy et al. (2012) and Zamm et al. (2013) found structural differences in synaesthetes, it is difficult to categorically say whether there are differences in the brain anatomy of synaesthetes, per se, or if the differences have developed because of years of synaesthetic activity (van Leeuwen et al., 2015). Lastly, as acknowledged by Jäncke et al. (2012) the small size of the synaesthete group in this study meant that it was not possible to distinguish between individual differences in synaesthetes, particularly with regard to whether synaesthetes might be associators or projectors. The detection of differences in the very early stages of processing may have been affected by a large proportion of lower synaesthetes in the group. One important finding is the identification of the role of the parietal cortex (Neufeld, Sinke, Dillo et al., 2012; Neufeld, Sinke, Zedler et al., 2012; Jäncke and Langer, 2011) as a potential hub in both the disinhibited feedback and hyperconnectivity/hyperbinding theories.

Concept, Meaning and Qualia

The Role of Concept and Meaning in Music-Colour Synaesthesia

Although research over the last twenty years has predominantly concentrated on attempting to explain the cause of synaesthesia in perceptual terms, there is evidence to show that in some forms of synaesthesia a concept alone may be enough to induce the condition (van Leeuwen et al., 2015). Of the dominant theories positing a neurophysiological basis of synaesthesia the disinhibited feedback theory offers the more compatible mechanism for the role of conceptual-level information promoting top down processing, but direct evidence is lacking. Several behavioural studies have suggested that synaesthesia is influenced by the conceptual representation of the inducer rather than its low-level characteristics (Chiou & Rich, 2014). It has been shown that the same physical shape can be interpreted as a “5” or an “S” depending on context and will result in a different concurrent experience in each case (Dixon et al., 2006; Myles et al., 2003). Also, Dixon et al. (2000) demonstrated with grapheme-colour synaesthesia how a synaesthetic experience can be triggered without a sensory stimulus. Synaesthetes were presented with written numerical additions, such as 5 + 2, followed by a colour patch. The colour patch was either congruent or incongruent with the synaesthete's colour for the correct answer. Results showed that reaction times were faster when the colour was congruent with the synaesthete's colour for the correct number, demonstrating that synaesthesia could be activated conceptually and that the physical presence of the inducer was not necessary: the semantic knowledge of the system was sufficient (Meier, 2014). Synaesthesia associated with days of the week or months, one of the most commonly studied forms of synaesthesia, has also been shown to be conceptual in nature (Simner, 2009). Colours and spatial layouts are associated with the position of the day in the sequence of a week, or its meaning, rather than because of the letter the name of the day begins with. Indeed, the synaesthete Smilack's photograph entitled, "Weekends are taller than Weekdays" illustrates Saturdays and Sundays as being taller than other days of the week. The meaning of "the weekend" is represented in the way both days occupy a graphically larger, or elevated, position in space (Smilack, 2012).

Ideaesthesia

These findings have led to an alternative theory of "ideaesthesia" (Nikolić, 2009; Mroczko-Wąsowicz & Nikolić, 2014) and a replacement definition: "Synaesthesia is a phenomenon in which a mental activation of a certain concept or idea is associated consistently with a certain perception-like experience" (Nikolić, 2009, p. 28). Ideaesthesia has its foundation in the theory of "practopoiesis" that states that concepts are applied and learned as nerve cells quickly adapt to external stimuli (Nikolić, 2015). Although at first glance ideaesthesia would appear to be similar to the earlier described associative synaesthesia, what sets it apart is the way semantic associations may be translated from a physical synaesthesia-inducing stimulus (van Leeuwen et al., 2015). The assigned meaning to the stimulus then serves to mediate the perception-like concurrent synaesthetic experience. In theory, ideaesthesia would not preclude perceptual stimuli from inducing conceptually mediated concurrents (Mroczko-Wąsowicz & Nikolić, 2014; van Leeuwen et al., 2015). The speed at which some synaesthetic associations are able to be made also support ideaesthesia. In a study conducted by Mroczko-Wąsowicz et al. (2009) grapheme-colour synaesthetes were able to transfer their synaesthetic colours to an alphabet of Glagolitic graphemes (an ancient Slavic writing system) within as short a time as ten minutes. This would be far too fast for new low level connections between brain areas to form as suggested by the hyperconnectivity theory of Ramachandran & Hubbard (2001a, 2001b). The authors explain the speed of the transfer by the activation of mental processes that recognise the meaning of the letter, rather than its form or shape, in so far as a grapheme in either the Latin alphabet, or in its Glagolitic equivalent, might represent the abstract concept of the letter "A" (Mroczko-Wąsowicz et al. 2009).

Nikolić, et al. (2011) also demonstrate the importance of purely semantic representations in synaesthesia in a study examining different swimming styles. Two known grapheme-colour synaesthetes who were also semi-professional swimmers were found to associate four swimming strokes (breaststroke, crawl, butterfly and backstroke) with distinct synaesthetic colours. In a laboratory situation using a Stroop-like task, it was shown that it was not necessary for participants to be swimming in a pool to induce the corresponding colour experience. Both synaesthetes only had to think about practising the different strokes, or to think about the concept of each swimming style to induce synaesthesia. Each synaesthete reported that they had always had this experience with swimming styles and that the colours had remained consistent throughout their lives.

The role that semantic knowledge may play in some forms of music-colour synaesthesia is similarly suggested in an unpublished case study by De Thornley Head (1985) in which a tone-colour synaesthete, MH, without absolute pitch, self-triggered tones on a synthesiser and noted down each colour response. The synthesiser was then transposed, without MH's knowledge, and the task was re-performed. There was no change in the responses. The colours noted down were in reaction to the tones the synaesthete thought they were hearing rather than to the actual pitches. Ward, Tsakanikos and Bray (2006) also present a first empirical study supporting synaesthesia for musical notation which suggests that this type of music-colour synaesthesia may be linked to conceptual rather than perceptual processing. Case studies were carried out on three participants who had synaesthesia for written musical notation, graphemes and heard music. All three had a high level of musical ability and could read music. None of them had absolute pitch. The synaesthetes were shown to be slow at playing musical notes when they were notated in colours incongruent to their synaesthetic colour, and Stroop interference was observed when they were required to name the synaesthetic colour of the written musical note and ignore the veridical colour. This type of synaesthesia was not affected by the shape of the musical note in the way that the shape of a letter or number has been shown to affect grapheme-colour synaesthesia (Ward, Tsakanikos & Bray, 2006). The results of the study suggest that the synaesthetic experience in this case was elicited at a conceptual level: at the time the pitch of the note is required to be processed. As the name suggests "ideaesthesia" may mean that synaesthetes are not pre-disposed to synaesthesia as previously thought, but may learn to assign meanings to certain stimuli to strengthen their knowledge and understanding of abstract concepts (van Leeuwen et al., 2015). Stemming from this Jürgens and Nikolić (2012) posit that certain types of synaesthesia may simply be a useful method a child may develop to process its first encounter of abstract concepts more easily, such as music unfolding over time.

Such studies should not be taken to dismiss the existence of purely perceptual forms of synaesthesia. However, extending research to music affords the opportunity to study the causes of different types of synaesthesia in a form other than the more frequently examined grapheme-colour (Nikolić, 2009).

Music-Colour Synaesthesia and Musical Qualia

In a later study, Nikolić (2016) continues to explore ideaesthesia developing an "ideaesthesia balance theory" with a view to formulating a "theory of art". Nikolić states that at the heart of the theory lies a relationship between concept (or meaning) and sensation (or experience) as the two forces of ideaesthesia. Although the relationship between ideaesthesia and art is beyond the scope of this review, Nikolić identifies sensation and its relationship to phenomenal experiences in terms of our understanding of what is known as "qualia". Qualia is the term used to describe the qualities of subjective experience associated with certain sensory stimuli (e.g., Jackson, 1982) such as the difference between seeing a red rose and yellow rose or, in musical terms, the difference between a melody played on a piano and the same melody played on a French horn. Music offers a rich variety of experience and such properties form, often ineffable, differences between one person's experience and that of another's.

Synaesthesia has been described by Wager (1999) as an "extra qualia" that manifests itself differently from synaesthete to synaesthete. So, what do the different types of "concurrent qualia" (van Leeuwen et al., 2015) synaesthetes experience on hearing music illustrate about individual consciousness? Eagleman (2015) posits that synaesthesia is "… a reminder that from person to person – and from brain to brain – our internal experience of reality can be somewhat different" (p. 59). Indeed, there are different kinds of synaesthesia in music and, together with the different categories of synaesthete, the assumption that there is a unity between all types of synaesthesia and that each operates by means of similar mechanisms is questionable. Auvray and Deroy (2015) argue that it might be better to regard each form as a separate condition and that defining synaesthesia remains an area for further research. Indeed, synaesthetic experiences may best be described as suggested by Auvray and Deroy "…as richer unified experiences where additional sensory info (or qualia) get hosted in the content of perception" (p. 12). Yet the phenomenal experience of music-colour synaesthesia, indeed of synaesthesia as a whole, presents a challenge to established philosophical theories, three of which are discussed in the next part of this review: functionalism, physicalism and representationalism.

Functionalism

The debate about qualia began in the 1960s and 1970s surrounding discussions about functionalism. The theory of functionalism states that "the function of a mental state is its defining feature" (Kind, n.d.). There are different types of functionalism but their common thread is the understanding of a mental state from the position of its functional role instead of in terms of its physical set up (Block 1990; Chalmers, 1996). For example, the function of pain is not the firing of C fibres (as a physicalist view might uphold, as discussed below) but the avoidance of the cause of pain itself. In theory functionalism allows for creatures with quite different physical setups to experience the same mental state (Smart, 1959).

However, functionalism has been the target of opposition for its limitation in accounting for qualia (see Block, 1990; Chalmers, 1996; Shoemaker, 1984; Tye, 1996). Functionalism does not attempt to explain qualia per se, but as described by Gray and colleagues (2002) looks for an understanding of the mechanisms behind the behavioural responses an individual may display as a "function" of qualitative experience. Well known objections to functionalist theories have been presented in the form of the following thought experiments: the "inverted qualia argument" (Block, 1990) where two systems may be functionally identical but each experience very different qualia; the "absent qualia argument" (Block & Fodor, 1972) where two systems are functionally identical but one experiences no qualia at all. "Synesthetic experiences can be defined as richer, unified experiences, where an additional sensory attribute (or qualia) gets hosted in the content of perception" (Auvray & Deroy, 2015 p. 12). The difficulty presented to functionalism by synaesthesia arises when the same mental state produces green on hearing an "A" but also on seeing grass and trees (Auvray & Deroy, 2015). In this case the same kind of mental state "seeing green" emanates from two separate streams, both auditory and visual, not just from vision. In music-colour synaesthesia two quite different functions, that of hearing and vision, produce the same experience of colour and from this position Gray argues that synaesthesia provides a counter example to functionalism (Gray, 2005). However, Gray's argument only holds for strong versions of functionalism that add the condition that not only should any difference in function correspond to a difference in experience, but for any difference in experience there must also be a corresponding difference in function (Macpherson, 2007). Macpherson (2007) also notes that Gray's premise is based on the acceptance that the experience of synaesthesia is perceptual and works the same way as non-synaesthetic experience. For this to be true both the inducer and the concurrent would need to be normal experiences of sound and colour, and to be entirely independent of each other. However, evidence from neuroimaging studies is lacking in support of this assumption (van Leeuwen et al., 2010; Hupé et al., 2012) and Eagleman and Goodale (2009) have demonstrated that coloured synaesthetic experiences are very different to non-synaesthetic colours, often including other elements such as texture and movement. Furthermore, the behavioural studies discussed earlier in this review support the importance of the role of conceptual rather than purely perceptual processing in some forms of synaesthesia. Consequently, Macpherson's challenge to Gray's "dualist model" account of synaesthesia would appear to allow functionalism to hold its ground.

Physicalism

If it can be considered that two people might be in identical mental states in functionalism, so might it be that they could have physically similar brain structures but very different phenomenal experiences on hearing music (Kind, n.d.). Physicalism is the very general view that everything supervenes on the physical (Smart, 1959). In the philosophy of mind, this has been sometimes treated with the following claim: there is no difference between physical implementation and mental states (Gray et al., 2006; Block, 1997). Accordingly, physicalists are inclined to explain synaesthesia through a direct correlation between phenomenal experience and brain activity (Ramachandran & Hubbard, 2001a, 2001b). This is, however, not an easy task: as previously discussed, experimental results are still highly inconsistent. So, while some maintain that future advances in neuroscience will eventually allow us to explain all mental phenomena in neural terms (e.g., P. M. Churchland, 1994; P. S. Churchland, 1989) we currently lack epistemological and methodological tools to fully capture most of the properties of our mental life. And this is not the only problem. Some aspects of mind may be more easily explained than others. As we learn more and more about the brain, phenomena that might be explained in terms of computational or neural mechanisms, the "easy problems of consciousness" (Chalmers, 1995, 1996) are expected to be solved at some point in the future. The problem of how we account for qualia, instead, presents a far more difficult challenge. Although it may well be likely that a physical system is responsible for qualia, we do not know what kind of mechanism that might be, nor have we any idea about what kind of biological law is involved in transforming electrical signals in the brain into consciousness. Consequently, the "hard problem" of consciousness, that which accounts for qualia, remains.

Chalmers's "hard problem" also has a similarity to Levine's earlier identification of the "explanatory gap" (Levine, 1983). Levine states that an explanation of such phenomena as the transfer of heat may be given from our scientific understanding of the motion of molecules. Having discovered this, no further explanation is necessary. However, even when endowed with considerable knowledge about how a certain experience is due to a neural or functional state, something is still left unexplained. For example, understanding that pain is the function of the firing of "C" fibres does not supply us with an explanation of why pain feels the way it does (Kind, n.d.).

Representationalism

Wager's (1999) description of representationalism is that it is "the view that the phenomenal character of an experience supervenes on its representational content" and offers some clarification of this statement in "the way an experience seems to its subject is […] the way the experience represents the world as being" (Wager, 1999, p. 263). Arguably, the strongest version of representationalism is the view that phenomenal character is identical to its representational content (Tye, 1998) and in this way, representationalism attempts to explain qualia.

However, representationalism has been challenged by work on synaesthesia (Brogaard, 2016; Rosenberg, 2004; Wager, 1999). Musical qualia might be described as the experiential difference between hearing a piece played on a cello and the same piece played on a flute. However, it might also include the synaesthetic experience of seeing green on hearing an "A". The latter is not immediately explainable from a representationalist's standpoint as the phenomenal experience is at odds with reality: experiencing a note as green does not mean the note is actually green, or that the person is experiencing "green-ness" (Auvray & Deroy, 2015). Adapting Schiavio and van der Schyff's (2016) inverted qualia example (Block, 1990) as further illustration, a synaesthete might hear a glissando but also experience purple, whilst a non synaesthete would just hear the glissando. It might be argued that both experiences have the same representational content (the glissando), but have shared and very different phenomenal characters. From this standpoint Tye's theory cannot account for such synaesthetic experiences. Wager (1999) suggests an alternative and describes synaesthesia as "extra qualia" in which, "two states with the same representational content share some but not all of their phenomenal content" (p. 264). On the face of it this might seem reasonable. For example, the colours, shapes and textures experienced in music-colour synaesthesia contribute as much to the qualitative experience of music as the more common subjective qualities experienced by non-synaesthetes.

However, a representationalist might offer a straightforward argument in response. The challenge to representationalism only holds if it can be argued that the additional synaesthetic experience does not instantiate the inducer. The representationalist might argue that the synaesthetic experience does in fact represent something. In the case of a synaesthete experiencing “green-ness” on hearing an “A”, R. Gray argues that the concurrent does differ representationally in that it “misrepresents” green-ness (R. Gray, 2001). Instead of saying that the green-ness is attributed to an “A”, why not attribute it to the misrepresentation of green triggered by the auditory stimulus?

Yet Rosenberg (2004) argues against misrepresentation using an example from grapheme-colour synaesthesia. The fact grapheme-colour synaesthetes are still able to recognise the veridical colour of the printed letter as well as their synaesthetic colour would suggest that the association of a colour with a letter is not a misrepresentation of surface reflectance at all, but is in fact an accurate representation of the letter. Alter (2006, p. 6) does not agree and asks why we should not instead conclude that the synaesthetic experience both accurately categorises the letter as, say, a letter “D” whilst also inaccurately representing it as being green? Even though the inducer, be it a letter “D” or a sounding note “A”, does not have the property of the concurrent, if the synaesthete believes that the experience represents it as having such a property, then there is no real argument against representationalism.

Brogaard (2016) identifies a lack of empirical evidence as a problem with synaesthesia based arguments against representationalism to date, and calls for a different approach. Brogaard posits that some forms of projector synaesthesia might be considered as examples of where the phenomenology of the visual experience does not flow directly from the representational content. Such a case is given as in “M” a projector who experiences a terracotta brownish-orange volume in front of the letter “R”. The veridical colour of the letter is black and it never appears to “M” that it is anything other than black. The letter “R” itself does not appear to “M” at any time as terracotta brownish-orange. Hence the colours projected out into the world do not represent the mind-independent, physical object, “R”. In this case it can be argued that the phenomenology of visual perception is not exhausted by its representational content, and that representationalism is false (p. 312). Brogaard acknowledges that a representationalist might still attempt to dismiss synaesthesia by explaining the nature of such experiences as non-perceptual. However, Brogaard rejects this position by arguing that some forms of projector synaesthesia are a “kind of perceptual experience” (p. 313) based on results relating to grapheme-colour synaesthesia such as the Stroop effect (Mills et al., 1999; Mattingley et al., 2001) visual search paradigms (Ramachandran & Hubbard, 2001a) and brain imaging (Simner, 2012). Brogaard’s view is that from this standpoint a representationalist may not simply respond by arguing that projector synaesthesia is not a perceptual experience.

However, there are clearly difficulties in explaining some forms of music-colour synaesthesia in terms of musical qualia. Perhaps as suggested by Schiavio and van der Schyff (2016) an alternative embodied approach to the understanding of musical experience that does not seek to “reduce experience to inner mechanisms, representational recoveries, or neural firing” (p.375) would lead to a better understanding. Indeed, Schiavio and van der Schyff’s argument that engagement with music involves not just internal cognitive processes but real-time interactions between the individual and their environment is equally relevant to the phenomenal experiences presented by music-colour synaesthesia.

Conclusion

This review has examined the current literature concerning a form of coloured hearing, or chromesthesia, associated with music. It was found that music-colour synaesthesia has a broad scope encompassing not only tone-colour synaesthesia elicited on hearing individual tones, but a complex and idiosyncratic mixture of phenomenological experiences often mediated by timbre, tempo, emotion and differing musical style. The importance of the role of individual differences from synaesthete to synaesthete has also been highlighted. Without consideration being given to the distinction between the differing experiences of associators and projectors or higher and lower synaesthetes it is not possible to fully understand the mechanisms at work and experimental results may be misinterpreted.

The traditional view that synaesthesia is fundamentally a perceptual phenomenon has also been challenged here. The examination of eight neuroimaging studies were found to be largely inconclusive in respect of confirming the perceptual nature of music-colour synaesthesia. However, it should be noted that not all the studies distinguished between associators and projectors or higher and lower synaesthetes amongst their participants. Nonetheless, neither the hyperconnectivity (Grossenbacher & Lovelace, 2001) nor the disinhibited feedback theory (Ramachandran & Hubbard, 2001a) currently holds as a single categorical explanation for synaesthesia. Furthermore, comparisons made between cross-modal correspondences in non-synaesthetes and synaesthetes in respect of pairings made from colour, music, emotion, pitch-height and pitch-size suggest that non-synaesthetes employ similar mental processes to synaesthetes. Synaesthetes may not be pre-disposed to synaesthesia, per se, but may have developed a method of processing abstract concepts such as music unfolding over time afforded to them by the "extra qualia" (Wager, 1999) of their synaesthetic experience. Theories promoting the notion of "ideaesthesia" (Nikolić, 2009) have highlighted the importance of the role of concept and meaning in the understanding of synaesthesia (van Leeuwen et al., 2015) and have pushed for the move away from the purely perceptual sensory to sensory explanations for its cause and towards further research into the role of concept as inducer.

Music-colour synaesthesia demonstrates that a single mechanism is not sufficient to explain the phenomenological experiences that arise on hearing music, either from a sensory musical stimulus, or from a non-sensory musical concept. Stemming from this arises the need to reconsider the elevated position of consistency as the primary measure in synaesthesia studies. It has been shown in this review that inconsistency is not uncommon in music-colour synaesthesia and that the failure of a consistency test might result in the exclusion of a subject that may be able to reliably demonstrate synaesthetic experiences otherwise, such as through self-report or other behavioural tests. Whilst such batteries as the Eagleman Battery (Eagleman, et al., 2007) are very useful in determining grapheme-colour forms of synaesthesia, there is a risk that certain types of music-colour synaesthesia may be unnecessarily overlooked. If certain forms of synaesthesia can be discounted using current measures, alternative methods may reveal synaesthesia to be more prevalent in the general population than previously believed.

Finally, the difficulties in reconciling the phenomenological character of music-colour synaesthesia with established philosophical theories have also been discussed. The problem of the "extra qualia" (Wager, 1999) presented by music-colour synaesthesia remains and cannot be satisfactorily explained by the theories of physicalism, representationalism or functionalism. In his theses, "What is it like to be a bat?" Nagel (1974) states that because the way we perceive the world is so very different to that of a bat, we who are not bats cannot know what it is like to be a bat. Perhaps in the same way those who do not have synaesthesia just cannot know what it is like to experience colour on hearing music, illustrating further the difficulty in fully understanding the phenomenon.

Music-colour synaesthesia highlights the need for future research to extend to other forms of synaesthesia other than the more commonly examined, grapheme-colour synaesthesia or tone-colour synaesthesia. However, a full understanding of the mechanisms underlying synaesthesia may not be possible if researchers continue to attempt to contain the phenomenon within a distinct set of rules (Simner, 2012; Cohen Kadosh & Terhune, 2012) and do not reject a “one for all” explanation for its cause (Auvray & Deroy, 2015). Together with the recognition of the difference in experience between associators and projectors and higher and lower synaesthetes, and the similarities with cross-modal correspondences in non-synaesthetes, music-colour synaesthesia offers an opportunity to gain a better understanding of the processes of general cognition and consciousness from person to person.

CHAPTER THREE – THE ROLE OF SYNAESTHESIA IN READING WRITTEN MUSICAL KEY SIGNATURES

> *'She said that everything had colour in her thought; the months of the year ran through all the tints of the spectrum, the days of the week were arrayed as Solomon in his glory, morning was golden, noon orange, evening crystal blue, and night violet. Every idea came to her mind robed in its own especial hue. Perhaps that was why her voice and words had such a charm, conveying to the listeners' perception such fine shadings of meaning and tint and music.'*
>
> — L.M. Montgomery (1913), *The Golden Road*

Published as: Curwen, C. (2022). The role of synaesthesia in reading written musical key signatures. *Journal of Experimental Psychology: General.* Advance online publication. https://doi.org//10.1037/xge0001193

This chapter is produced in a slightly different format to that of the published journal paper referred to above, but is otherwise identical.

Linkage of Paper to Research Methodology and Development

The purpose of this paper is to provide empirical evidence that a synaesthetic response may be induced by a musical concept, and to demonstrate the precarity of consistency as a primary measure for synaesthesia. Five experiments investigate whether music-colour synaesthesia may be elicited from the concept of reading written musical keys. The examination tests whether a synaesthetic experience occurs without the need to sound out the key (i.e., without sensory stimulation), and whether it is affected by a change in the form of presentation (i.e., on the treble clef, the bass clef, or written in words).

Abstract

This study is the first empirical demonstration of synaesthesia for reading written musical keys signatures. Nine music-colour synaesthetes and nine controls took part in five experiments that aimed to confirm the authenticity of synaesthesia for reading musical keys, and to demonstrate that this type of synaesthesia is linked to conceptual rather than to purely perceptual processing of the inducing stimulus. First, the existence of a synaesthetic association with written musical keys was validated in an objective manner by employing two measures of consistency as diagnostic criteria. Second, the automaticity of the synaesthetes' responses was tested by demonstrating the presence of interference when naming synaesthetic colours for incongruent pairings of colour and musical key. To test whether a change in form altered the concept of the musical key, stimuli were randomly presented in three separate modes (words, treble clef or bass clef). Last, the interference of synaesthetic colours with veridical colours was assessed in a task-irrelevant manner, i.e., without the need for the explicit naming of synaesthetic colour. Findings showed synaesthesia for written musical keys to be a genuine form of synaesthesia elicited from the concept, or the idea, of the key.

Keywords: Stroop, synaesthesia, key signatures, music-colour, written notation

Notwithstanding a growing body of research, synaesthesia remains a phenomenon surrounded by uncertainties. The condition is believed to occur in approximately four percent of the population (Cytowic, 2018; Simner et al., 2006) and with great inter-individual variability but low intra-individuality. It is not uncommon for synaesthetes to be unaware that their experiences are not shared by others, and it is a phenomenon that can easily be misunderstood, and its different forms underrepresented (Day, 2005). This, coupled with its rarity in occurrence and variability from person to person, also presents the continuing challenge of low sample sizes in synaesthesia research.

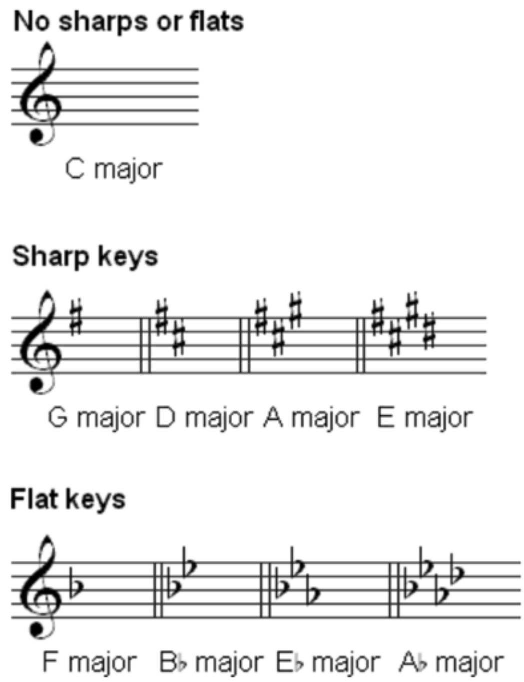
One form of synaesthesia associated with music (music-colour synaesthesia) falls under the umbrella term "chromesthesia" or "coloured hearing" (Ward, Tsakanikos & Bray, 2006). Yet scholarship interested in music-colour synaesthesia has a broad scope, encompassing not only the more frequently examined tone-colour synaesthesia but also phenomenal experiences mediated by style, timbre, and tonality (Peacock, 1985). Indeed, recent research argues that it is unlikely that a single mechanism underlies all forms of synaesthesia and rejects a "one for all" explanation for its cause (Auvray & Deroy, 2015; Simner, 2012). In this article, I focus on a single concept-driven form of music-colour synaesthesia that arises from reading written musical key signatures.

The association of colour with key signatures is not a new phenomenon (Day, 2008, p. 284). It is known to have been a cause for disagreement between the composers Scriabin and Rimsky-Korsakov: "Scriabin considered the tonality of F-sharp to be a bright saturated blue according to most sources. Rimsky-Korsakov perceived that key as an indefinite gray-green color" (Peacock, 1985, p. 495). This article provides the first empirical demonstration of music-colour synaesthesia for written key signatures and investigates its form of manifestation. Specifically, the present contribution demystifies the assumption that musical inducers are purely based on sound. Instead, it tests the hypothesis that musical *concepts* are at the heart of the synaesthetic experience, at least for this particular kind of synaesthesia associated with written key signatures (Curwen, 2018).

For the purpose of this paper the term "key signature" is used to relate to the indication of the key or tonic of the music. The tonal centre or tonic key of a melody is in the Western tonal tradition both a percept (Krumhansl, 2010) and a symbolic concept used in music theory and music notation. Reading a key signature is intrinsic to being able to read music, whilst being sensitive to the tonic key is a basic feature of tonal pitch perception irrespective of musical training (e.g., see Tillman, 2012). A musical key is denoted by a written key signature that appears immediately after the clef at the beginning of the first line of music with a set of up to seven sharp (♯) or seven flat (♭) symbols indicating the notes to be used when playing in each key. It is not necessary for the music to be sounded out for the concept of the intended key to be communicated, as shown in Figure 1.

Figure 1

Nine Major Key Signatures Written on the Treble Clef



Although historically described as a sensory-to-sensory phenomenon in which a sensation in one sense (an inducer) triggers a sensation in another unrelated sense (a concurrent) (Grossenbacher & Lovelace, 2001), there is evidence that in some forms of synaesthesia a non-sensory stimulus is enough to induce the condition (Chiou & Rich, 2014; van Leeuwen et al., 2015). For example, Dixon et al. (2000) demonstrated that when numerical additions such as 5 + 2 were followed by a colour patch, naming times were faster when the colour of the patch was congruent with the synaesthete's colour for the correct response; the physical presence of the inducer was not necessary (Meier, 2014). In music, the main factor in a newly described pitch class-colour synaesthesia was the name, and not the sound, of the pitch

(Itoh et al., 2017, 2019); and Ward, Tsakanikos and Bray's (2006) experimental investigation of synaesthesia for written musical notes demonstrated that the synaesthetic colour of a note was determined by musical context and was neither dependent on the mode of presentation nor on a change in form of the stimuli. This notion is supported by Lima (2020) in a grounded theory study that demonstrates a strong conceptual basis for music notation-colour synaesthesia. The synaesthetes in Lima's study reported that it was "the idea or notion of a particular music-notational percept that elicits a synesthetic color for them" (p. 185). Two participants in particular recognised that "they will not have a 'final' color for a given concept unless they" [were to] "consciously recognize it as such" (p. 185). For example, a note may hold the same position on the stave in the treble clef and on the bass clef, but its meaning is different: the middle line on the treble clef is a "B" and on the bass clef a "D". Should synaesthesia be elicited at a conceptual level, the same colour will be assigned to a "D" whether it is shown on the middle line of a bass stave or below the bottom line of a treble stave (Curwen, 2020a). In Ward, Tsakanikos and Bray's (2006) study, musical notes were printed in either congruent or incongruent colours with the participants' synaesthetic colours in words or on the stave (either in bass or treble clef). In a reverse Stroop design (Stroop, 1935), Ward and colleagues required synaesthetes to ignore the veridical colour and name their synaesthetic colour for the musical note. Significant interference was observed with longer reaction times for naming notes in incongruent colours. The authors suggest that the results show that interference occurred when the identity of the note was required to be processed (i.e., when suppressing its veridical colour).

Yet exactly how deeply the inducer needs to be processed remains uncertain. Smilek et al. (2001) concluded that although the meaning and concept needs to be activated to produce synaesthesia, conscious identification is not necessary: access to the meaning was enough, but there was no need for identification. In contrast, Mattingley et al. (2001) found that implicit processing (i.e., without conscious identification of the inducer) was not sufficient to produce synaesthesia. When letters and digits were presented briefly and then masked, synaesthesia could be eliminated if the stimuli were not made available for conscious report, even when there was evidence otherwise of the substantial processing of stimuli that would usually produce synaesthesia. Further studies (see Rich and Mattingley, 2003; Mattingley et al., 2006; Sagiv et al., 2006) have supported Mattingley and colleagues' (2001) results. Notably, these studies investigated only one form of synaesthesia: grapheme- colour synaesthesia. As mentioned earlier, recent research suggests that an explanation of a single operating mechanism for synaesthesia may be inadequate (Simner, 2012) and that it may be incorrect to assume that there is a unity between all types of synaesthesia. This brings into question not only the extent to which conscious report is required but also whether such findings may be extended to other forms of synaesthesia.

Can the concept of a written key signature be sufficient to induce a synaesthetic experience? The present study provides the first empirical demonstration of synaesthesia for reading written key signatures in five experiments. Similar paradigms to that of Ward, Tsakanikos and Bray's (2006) reverse Stroop design in their experiment "Stroop Interference for Naming Synaesthetic Colors", and Banno et al.'s (2017) experiment "Colour matching task" are employed to test the following hypotheses:

1. *The existence of a synaesthetic association with written key signatures.* Longer reaction times will be observed when naming synaesthetic colours if presented with incongruent pairings between colour and key signature, indicating the presence of synaesthesia for written key signatures.
2. *Synaesthetic association persists irrespective of presentation modality and form of key signatures.* A change in the form of the stimuli from a key signature written in words

to that of a key signature written on the stave (either in the treble or the bass clef) should not result in a change of synaesthetic colour.

The main objective of the study was to demonstrate that synaesthesia for written key signatures is a genuine form of synaesthesia and that it is linked to conceptual rather than to purely perceptual processing of the inducing stimulus**.** Consistency over time (Baron-Cohen et al., 1987) has been established as the primary measure when identifying synaesthesia. However, if employed as the only means of validation, a consistency test may lead to some forms of synaesthesia being overlooked. For example, the presence of some inconsistency and variation over time has been observed, particularly in children (Cytowic, 2002; Eagleman et al., 2007; Rogers, 1987), and it has been suggested that consistency might be better regarded as an "associated characteristic" rather than as an all-defining one (Ward & Mattingley, 2006, p. 130). Taking this into consideration, Experiment 1 employed two diagnostic measures for consistency, and Experiments 2 and 5 tested the presence of interference for incongruent pairings of colour and key signature. Experiment 2 also presented key signatures in three separate modes – words, treble clef and bass clef – to test whether a change in form altered the concept of the key signature resulting in an absence of, or a change to, the synaesthetic colour. Experiment 3 was supplementary to Experiment 2 and investigated whether the processing of key signatures was generally quicker when presented in words rather than in musical notation. Experiment 4 was a pre-test to Experiment 5 and tested the priming effect of achromatic key signatures.

Experiment 1: Verification of Synaesthesia for Reading Key Signatures

The aim of Experiment 1 was to verify the existence of synaesthesia for reading key signatures in a group of self-reporting synaesthetes by employing two measures of consistency as diagnostic criteria: vector distance in RGB choices and Euclidean distances in CIELUV colour space. Only keys with up to four sharps or four flats were selected to ensure that subitizing was possible (Kaufman et al., 1949).[1] Judgement for groups of items between one to four has been shown to be rapid (Saltzman & Garner, 1948), accurate (Jevons, 1871), and confident (Taves, 1941). Additionally, numbers of items beyond four have been demonstrated to increase response times by an extra 250 – 50ms per additional item (Trick & Pylyshyn, 1994). As participants were required to respond as quickly as they could in Experiments 2 to 5, keeping stimuli to a maximum of four flats or sharps controlled the time attributed to reading the key signature.

Method

Participants

Participants were recruited in two separate calls via social media – the first for synaesthetes and the second for controls – from the University of Sheffield, the Royal Northern College of Music, and the author's own contacts (see Table 1 for full Participant details). Ethical approval was obtained from the research ethics committee at the University of Sheffield. All respondents were required to complete an online Google form questionnaire to determine their level of musical ability and to identify any types of synaesthesia present. Self-reporting synaesthetes who experienced colours for key signatures were asked to specify whether they needed to sound out the key or not. Based on this initial assessment, the experimenter then arranged to meet with each participant in person to document the colours they associated with each key. All participants were provided with information about the study and were able to provide consent via a radial button on the Google form.

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[1] Subitizing is the process of immediately knowing the number of items presented visually without the need for estimation or counting.

Table 1

Participant Profiles

Participant ID	Syn/ Con	Age Range	Sex	Musical Training	AP	Fluency Key Sigs	Music-C Syn	Type	Other Forms
1	S	25-44	Male	> 15yrs	No	Yes	MKC/MT/T	A	D/M, SS
2	S	45-64	Male	> 15yrs	No	Yes	MKC/MT/T	A	GC, D/M, SS
3	S	25-44	Female	> 15yrs	No	Yes	MKC/MT/T	A	GC, D/M
4	S	15-24	Male	10-15 yrs	No	Yes	MKC/MT/CS/T	A	LG
5	S	15-24	Female	> 15yrs	No	Yes	MKC/MT/CS/T	A	None
6	S	45-64	Female	> 15yrs	Yes	Yes	MKC/MT/CS/T	A	None
7	S	25-44	Male	> 15yrs	Yes	Yes	MKC/MT/CS/T	A	None
8	S	15-24	Female	6-10 yrs	No	Yes	MKC/MT/CS/T	A	GC, D/M, AT, MT
9	S	15-24	Female	10-15 yrs	No	Yes	MKC/MT/CS/T	A	None
10	C	45-64	Female	6-10 yrs	No	No	None	N/A	None
11	C	25-44	Female	10-15 yrs	No	Yes	None	N/A	None
12	C	65+	Female	> 15yrs	No	Yes	None	N/A	None
13	C	15-24	Female	> 15yrs	D/K	Yes	None	N/A	None
14	C	25-44	Male	> 15yrs	No	Yes	None	N/A	None
15	C	25-44	Male	6-10 yrs	No	Yes	None	N/A	None
16	C	25-44	Female	> 15yrs	No	Yes	None	N/A	None
17	C	25-44	Female	> 15yrs	No	Yes	None	N/A	None
18	C	45-64	Male	> 15yrs	No	No	None	N/A	None
19	C	45-64	Female	6-10 yrs	No	Yes	None	N/A	GC
20	C	15-24	Female	> 15yrs	No	Yes	CS/T	N/A	GC

Note. Syn = synaesthete, Con = control, AP = absolute pitch, Fluency Key Sigs = ability to read key signature fluently, Music-C Syn = music-colour synaesthesia, MKC = concept of key signatures, MT = musical tones, T = Timbre, CS = compositional style, A = associator, GC = grapheme-colour synaesthesia, D/M = days/months, SS = spatial sequence, AT = auditory-tactile, MT = mirror-touch, LG = lexical-gustatory, D/K = do not know

Synaesthetes. Of the 12 self-reporting synaesthetes, only nine met the criteria for synaesthesia when reading written key signatures without needing to sound out the key (Participant numbers 1–9). Of those nine, only six had synaesthetic responses to all the nine major keys tested: of the other three, one had responses to eight keys, one to six keys, and one to five keys. All were classed as associators,[2] and all could fluently read key signatures written in both bass and treble clefs. Two possessed absolute pitch (Participants 6 and 7). Possession of absolute pitch was not independently verified but identified by self-report. All participants were able to indicate whether they possessed absolute pitch by responding “Yes”, “No”, or “Do not know” on the Google form. All participants had obtained a high musical standard (i.e., at least Grade 8 or equivalent of the Associated Board of the Royal Schools of Music), and so it was considered reasonable to assume that they were familiar with the condition and whether it was present or not.

Controls. Two of the 11 controls (Participant numbers 19 and 20) were identified as possessing strong grapheme-colour synaesthesia for letters. Both admitted to using letter names rather than key signatures to select their colours and were highly consistent in their selection. It was not possible to determine how this would influence their performance in respect of key signatures, so their results were not included. None of the controls reported possessing absolute pitch.

Materials

The materials used were the key signatures for nine major keys written on the treble clef: C major, G major, D major, A major, E major, F major, Bb major, Eb major and Ab major, as shown earlier in Figure 1.

Procedure

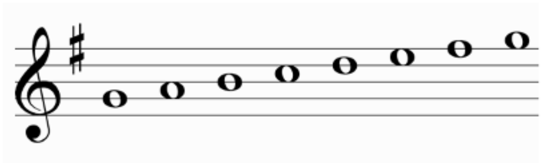
Synaesthetes were required to select as closely as possible their synaesthetic colour for the nine major keys without sounding out, or playing, the keys. Controls were asked to select the colours they felt made the best match for each key. Only major keys were used to avoid

[2] Synaesthetes are classed as associators or projectors according to their experience of the concurrent. Associators typically describe their experience as being in the mind’s eye (Dixon et al., 2004; Dixon & Smilek, 2005) or as knowing the colour (Ward et al., 2007), while projectors claim to see colours projected outside the body into external space (Smilek et al., 2001).

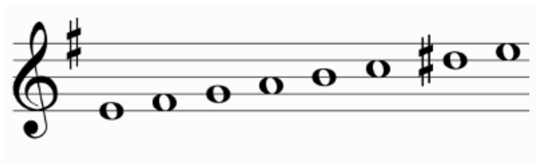
any ambiguity when reading from the stave. This is because pairs of major and minor keys are associated with the same key signature. In these instances when playing in the harmonic minor key it is required to also sharpen the seventh pitch. This is not indicated in the key signature, but instead on the stave. For example, a scale in G major on the treble clef will use the same key signature as its relative minor (E minor) but will also require a D♯ as shown in Figure 2. As it is not clear from the key signature alone whether the key should be major or minor, only major keys were used.

Figure 2

Example of Associated Keys G Major and E Minor Denoted on the Stave of the Treble Clef



G Major



E Minor

Colours were selected using www.w3schools.com developer website (w3schools, n.d.) and the standard "Colour Picker" Apple Mackintosh HD application. Participants were required to move a cross-hair cursor over a colour wheel and to adjust a vertical slider to control luminance on an Apple MacBook Air monitor. Previous studies have demonstrated in grapheme-colour synaesthesia that synaesthetes show more consistent answers than controls when both groups are retested at a later date (Baron-Cohen, et al., 1993; Dixon et al., 2000; Mattingley et al., 2001). To further verify the presence of synaesthesia for key signatures beyond self-report, the colour selection exercise was therefore repeated in a surprise retest one month later (though it was not possible to meet with Synaesthetes No. 1, 2 and 7 until five, eight and four months later respectively, nor to meet with Controls No. 12 and 13 until three months later). It was expected that synaesthetes would have a very precise selection of colours and would demonstrate a higher internal consistency for the colours selected at test and retest in comparison to controls.

Analysis

The colours selected were precisely identified in terms of RGB (red, green, blue) space and later transformed to representations in CIELUV space, as recommended by Rothen et al. (2013) where L stands for luminance, and U and V represent chromaticity values of colour images (Rahimzadeganasl & Sertel, 2017).[3] The website www.Colorhexa.com (ColorHexa, n.d.) was used to make the transformations. The main criticism of the use of RGB values is that it is device-specific. The digital representations for RGB may be the same across different devices, but they do not account for any difference between monitor outputs. This means that colours produced on one machine may not be quite the same as those on another. Although the use of standard RGB (sRGB) across devices has attempted to counter this, the distance measured within sRGB space between two colours does not relate to the perceptual distance of a human observer. Colour spaces generated by the International Commission on Illumination (CIE) account for the specific phosphor intensities of sRGB channels and can produce a large variety of colours taking into account the cone-response characteristics of human observers. Although converting sRGB values to CIE colours does not solve the problem of colour transformations between devices, it can help towards mitigating the problem (Hamilton-Fletcher, 2015, p. 33) by enabling distances between colour spaces to be measured more accurately as would be judged by human observers (Hunt & Pointer, 2011).

[3] Reasons for adopting representations in CIELUV space over RGB values are explained by Hamilton-Fletcher (2015).

Vector Distance in RGB Choices and Euclidean Distances in CIELUV Colour Space. The consistency of colours between one test and the second can be measured quantitatively by calculating separate vector distances in RGB and in CIELUV colour space choices using the following equation (Rothen et al., 2013; Ward et al., 2006) to produce a score for each participant (illustrated here with RGB dimensions):

$$d = \sum \sqrt{(R_1 - R_2)^2 + (G_1 - G_2)^2 + (B_1 - B_2)^2}$$

For example, if at the time of the first test the colour selected was R = 188, G = 248, B = 107, and at the second test it was R = 122, G = 255, B = 87, this would result in an absolute value of 69. The difference between mean RGB scores in the synaesthete and control groups was analysed with an independent groups *t*-test.

As colour selection is not necessarily identical, a cut-off value for synaesthesia for written key signatures was also calculated. Rothen and colleagues (2013) employed a cut-off of 135 for grapheme synaesthetes based on the sum of combinations of comparisons from their three tests per participant from CIELUV vector distance scores (i.e., trial 1 and trial 2, trial 2 and trial 3, trial 3 and trial 1). The authors noted that different synaesthetic inducers may require different cut-off values, as controls may have varying levels of consistency depending on the type of inducer. Yet similar principles were expected to apply to all other types of synaesthesia involving colour. Rothen's exact calculation could not be performed in the current study, as only one comparison was made here (i.e., between trial 1 and trial 2). Instead, the mean value of 52 was calculated from the total CIELUV vector distance scores for all the controls and synaesthetes and used as a cut-off point for synaesthesia associated with key signatures.

Linear Regression. Next, a simple linear regression was performed to compare and evaluate how well the CIELUV values in the first test predicted the CIELUV values in the retest. The dependent variable was the CIELUV values for the nine major key signatures obtained in the second test, and the CIELUV values in the first test served as the independent random variable – a similar method to that employed by Itoh et al. (2017). The software package SPSS Statistics V25 was used to carry out the analysis of the data collected.

Results and Discussion

RGB Vector Distance Analysis and Euclidean Distance in CIELUV Colour Space Analysis

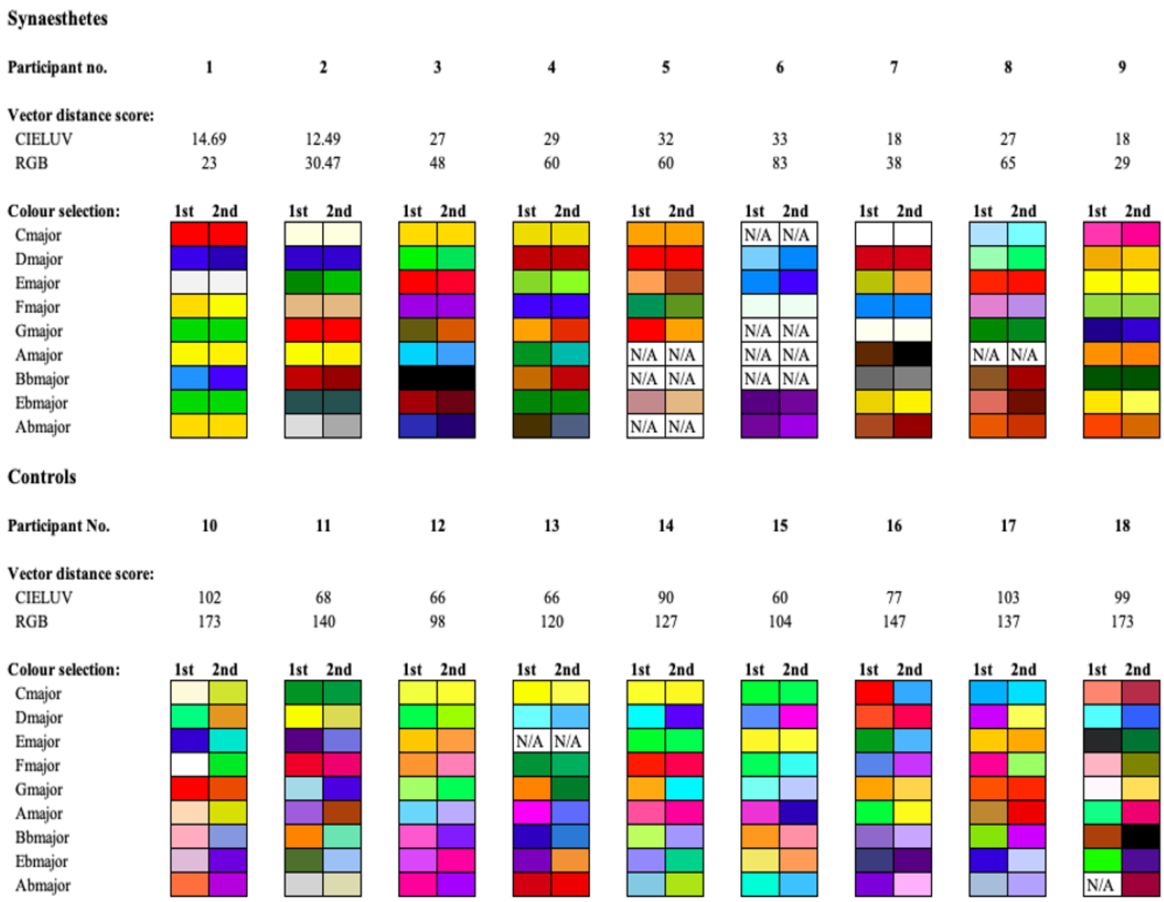
The independent groups *t*-test showed a statistically significant difference between the synaesthete and control groups on the mean RGB vector distance scores: $t(16) = -7.83$, $p < .001$. The effect size for this analysis ($d = 3.69$) was found to exceed Cohen's (1988) convention for a large effect ($d = .80$). Synaesthete scores were significantly lower than controls, indicating a much smaller vector difference between colour selections at test and retest and a higher level of consistency in synaesthetes than controls.

The calculated CIELUV cut-off score for the presence of synaesthesia of 52 was shown to be a reasonable assumption, as the nine participants classified as synaesthetes all had an average score below 34 using this method, whilst the nine controls scored in a range of 60 to 103 (see Figure 3).

However, it must be noted that while controls' scores fell into the higher range, not all the selections showed a lack of consistency across the two test conditions (e.g., Participant 12), and both synaesthetes and controls appeared to demonstrate a higher consistency for some keys (e.g., C major) than others (e.g., Bb major and Ab major). This highlights one of the shortcomings of using a consistency test as the primary measure in synaesthesia. Some controls are able to demonstrate a higher-than-chance level of consistency by choosing "red" again at retest, while synaesthetes may be searching for the precise texture, hue, colour (or mixture of colours) that they selected at the first test from a very limited palette.

Figure 3

Comparison of Synaesthetes' and Controls' Colour Selections for Nine Major Keys.



Note. RGB vector distance and Euclidean distance in CIELUV colour space scores are given for each participant as well as choice of colour. See the online article for the colour version of this figure.

Linear Regressions Analysis

The results of the linear regression analysis of the CIELUV data points are summarised in Table 2. Statistically significant models were revealed in both the synaesthete and control groups, indicating that the results are unlikely to have arisen by chance.

Table 2

Summary of Results of Linear Regression Analysis between First and Second CIELUV Colour Selections in Controls and Synaesthetes

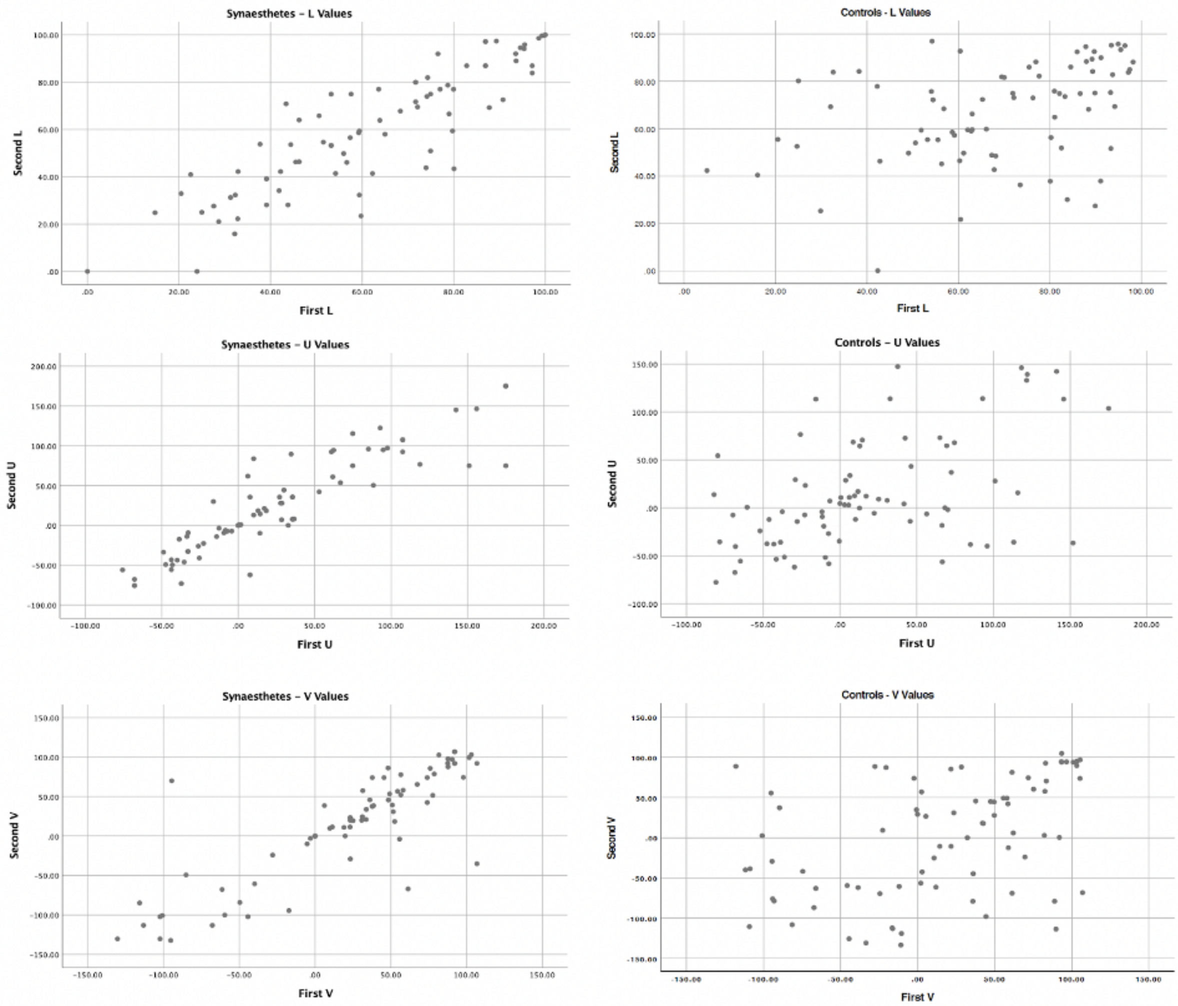
Colour Axes	Model	Adjusted R^2	Slope of Regression
		Synaesthetes	
L	F (1,78) = 232.78, p < .001	74.60%	B = .90, t = 15.26, p < .001
U	F (1,78) = 366.30, p < .001	82.20%	B = .89, t = 19.14, p < .001
V	F (1,78) = 162.02, p < .001	67.10%	B = .90, t = 12.73, p < .001
		Controls	
L	F (1,76) = 14.50, p < .001	14.90%	B = .38, t = 3.81, p < .001
U	F (1,76) = 26.06, p < .001	24.60%	B = .46, t = 5.11, p < .001
V	F (1,76) = 17.89, p < .001	18.00%	B = .48, t = 4.23, p < .001

Note. The analysis is along the three colour axes (L, U and V) between the first- and second-colour selections.

The correlations between the colour selections in the first test and those in the second test are also shown to be statistically significant in both the synaesthete and the control groups. The data displayed in the graphs at Figure 4 support this, illustrating that the colours selected by the control group are not entirely random and that a certain level of consistency exists: first-colour choices are a significant predictor of second-colour choices in both groups. This finding is less surprising considering that previous research has drawn attention to the similarities that exist between synaesthetic pairings and some common cross-modal associations in the general population from colour, music, emotion, pitch-height and pitch-size (Gallace & Spence, 2006; Isbilen & Krumhansl, 2016; Marks, 1987, 2004; Mondloch & Maurer, 2004; Palmer et al., 2013, 2016 Walker et al., 2010; Ward, Tsakanikos & Bray, 2006). Yet the graphs in Figure 4 also highlight the different level of variability in selection between the two groups. The low R^2 values in all three control colour dimensions reflect the far less precise colour selection of non-synaesthetes, while in the synaesthete group narrower prediction intervals provide evidence for their typically specific and precise choices.

Figure 4

Graphs of Regression Analysis Highlighting Difference in Variability in Colour Selection between Synaesthetes and Controls



At least 67.1% of the variance in second-colour choices can be predicted by variances in first-colour in the synaesthete group, while the highest percentage is only 24.6% in the control group. The regression coefficient (*B*) would be 1 if the results of two tests were identical and zero if random. The coefficient approaches 1 in the synaesthete group in all dimensions but falls below .5 in the control group. Notwithstanding the significant correlations in both groups, these results support the expectation that synaesthetes would demonstrate very precise selection of colours and a much higher internal consistency for the colours selected at test and retest than controls.

Experiment 2: Stroop Interference for the Naming of Synaesthetic Colours of Written Key Signatures

The aim of Experiment 2 was to demonstrate the presence of interference when naming synaesthetic colours for incongruent pairings of colour and key signature beyond self-report, and to test whether synaesthetic responses exist irrespective of mode of presentation (Hypothesis 1 and Hypothesis 2 respectively). As posited by Ward, Tsakanikos and Bray (2006), identifying the printed colour of a key signature may not necessarily require the identification of the key signature itself. A reverse Stroop approach was therefore adopted that required synaesthetes to name their synaesthetic colour for the key signature rather than veridical colour of the stimuli. By asking synaesthetes to ignore the colour on the screen and to name their synaesthetic colour instead, they are required to "process the identity of the note more deeply" (2006, p. 32).

A further point that strongly influences the adoption of a reverse Stroop design is the fact that all nine synaesthetes in this study were classed as associators. Dixon et al. (2004) showed that the performance of associators and projectors in Stroop tests revealed different patterns of interference. Projectors showed a significantly larger Stroop effect compared to associators and were faster at naming their synaesthetic colours than associators. These findings suggest a difference in the automaticity of synaesthetic processing between projectors and associators. Gatti and Egeth (1978) also posit that a projector's synaesthetic colour experience might simply be more difficult to ignore than that of an associator. As the synaesthetic colour is projected out into the world rather than held in the "mind's eye", its physical proximity to the veridical colour may make it harder to overlook. An associator may more easily be able to ignore their synaesthetic colour as it is held internally and spatially away from the target colour patch and name the veridical colour in a standard Stroop test with little interference.

It was expected that a longer reaction time would be observed when naming synaesthetic colours if synaesthetes were presented with incongruent pairings between colour and key signature, but that the change in the form of the stimuli from a key signature written in words to that of a key signature written on the stave (either in the treble or the bass clef) would not affect a change in synaesthetic experience (Chiou & Rich, 2014).

Method

Participants

Participants comprised the nine synaesthetes (Participants 1–9) verified as synaesthete in Experiment 1.

Materials

Three sets of stimuli in the form of coloured key signatures for the nine major keys were created for each individual participant in accordance with their synaesthetic colour for each key. The first set was written in words, and the second and third set notated on the stave in the treble clef and the bass clef respectively. Again, no minor keys were used to avoid ambiguity when reading from the stave. Incongruent pairings were then created from these colours for each participant and matched with other keys so that there were nine congruent pairings and nine incongruent pairings for each set. Each pairing was presented once in random order comprising 18 trials for each set, totalling 54 trials. Examples of the type of stimuli are shown in Figure 5.

Figure 5

Example of Congruent (Middle) and Incongruent (Top and Bottom) Stimuli Written in Words or Musical Representations

Note. Participants were required to ignore the veridical colour and name their synaesthetic colour (e.g., blue). The Word and Bass Clef stimuli are printed in red (see the online article for the colour version of this figure).

Procedure

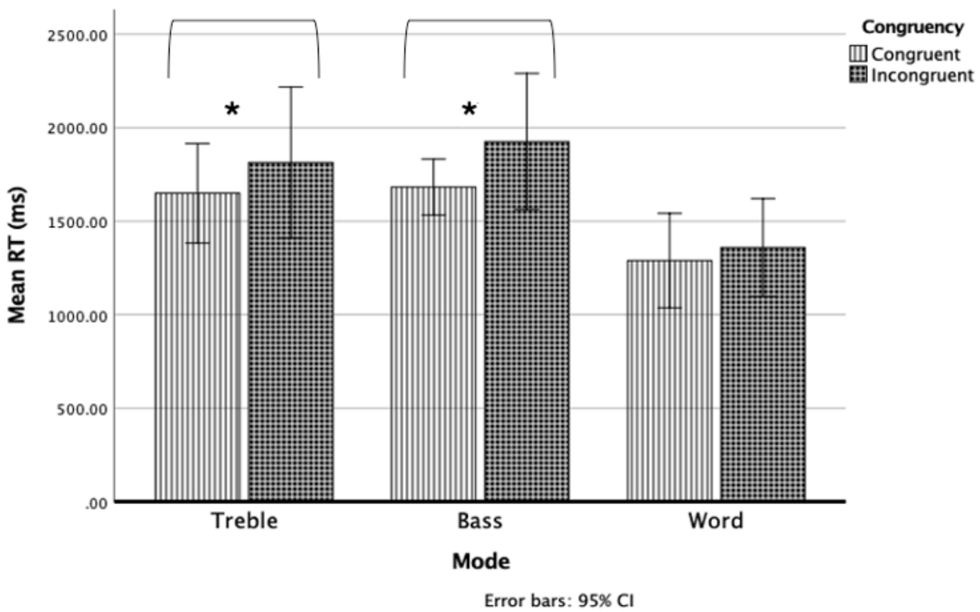
The synaesthetes were presented with coloured key signatures written either in words, on the stave in the treble clef, or in the bass clef. Each stimulus was preceded by a fixation cross for 1000ms, after which the stimuli remained on the screen for 4000ms during which time a verbal response was recorded. No auditory stimuli were used. Participants were asked to ignore the veridical colour of the stimulus and to name out loud their synaesthetic colour for each key as quickly and as accurately as they could into a microphone. Participants were presented with on-screen instructions and were allowed a short practice trial before the experiment began. The reaction time for each response per participant was measured in milliseconds and recorded in a Waveform audio format (.WAV). The test was run using the open-source software package PsychoPy3 Experiment Builder (v3.0.5).

Analysis

Synaesthetes' performances were analysed by calculating mean reaction times (RT), as illustrated in Figure 6. Each RT measurement was verified by comparing it to the recording on the corresponding .WAV file. Any discrepancies were adjusted accordingly and incorrect responses noted. To reduce the effect of outlier RTs, incorrect responses and errors in timings when the microphone was inappropriately triggered were excluded from the reaction time analysis, together with RTs of more than three standard deviations from the mean. Data was compared using a repeated measures two-way 2 x 3 ANOVA with congruency between veridical colour and synaesthetic colour (Yes, No) and mode of presentation (Treble Clef, Bass Clef, Words) as within-subjects factors. The software package SPSS Statistics V25 was used to carry out the analysis of the data collected.

Figure 6

Stroop Interference in Synaesthetes when Naming Synaesthetic Colour



Note. Stroop interference is found when synaesthetes have to name their synaesthetic colour [* p < .05.]

Results and Discussion

The ANOVA with congruency and mode as independent variables showed a statistically significant main effect of congruency on RTs; $F(1,8) = 6.63$, $p = .03$, $\eta^2 = .45$. A statistically significant main effect of mode was also observed on RT; $F(2,16) = 32.99$, $p = .001$, $\eta^2 = .81$. Post hoc Bonferroni tests indicated that the Word condition ($M = 1320$, $SD = 334$) had significantly ($p = .001$) faster RTs than the Treble condition ($M = 1730$, $SD = 436$) and significantly ($p = .001$) faster RTs than the Bass condition ($M = 1804$, $SD = 334$). There was no significant difference between Treble and Bass scores. No statistically significant interaction was observed between the effects of congruency and mode on reaction time; $F(2,16) = .538$, $p = .594$, $\eta^2 = .06$.

However, although overall the reaction times are faster in Word condition, the mean reaction times in the Congruent Word condition are only marginally faster than the Incongruent condition. Paired *t*-tests indicated a statistically significant difference on mean reaction times in the Treble condition, $t(61) = 2.25$, $p = .027$, and Bass condition, $t(61) = 2.042$, $p = .046$, but not in the Word condition, $t(64) = 1.13$, $p = .261$.

As expected, synaesthetes displayed significant Stroop interference in the form of longer reaction times when they were required to name their synaesthetic colour and ignore the veridical colour of presented key signatures. Post hoc Bonferroni tests indicated that the significant main effect for mode was the result of faster naming times for the Word condition only. The presence of Stroop interference was observed across all modes of presentation, indicating that the change in the form of the stimuli from a key signature written in words to that of a key signature written on the stave (either in the treble or the bass clef) in Experiment 2 did not result in a change of synaesthetic colour, particularly as no interaction between congruency and mode was observed. However, paired *t*-tests revealed that the effect of congruence was not significant in the Word condition. The reasons for this unexpected result may be various. First, three of the nine synaesthetes also experienced grapheme-colour synaesthesia. It is possible that the colours elicited from reading the letters comprising the name of the key written in words were incongruent with the colours elicited from the concept of the key signature itself. Second, notation on the stave may provide more sensorimotor information about the concept of key rather than the written word – i.e., thoughts about production or hand shape (Curwen, 2020a). Confirmation of these hypotheses would require further experimentation beyond the scope of the present study.

The presence of Stroop interference observed across all three modes of presentation when synaesthetes were asked to name their synaesthetic colour provides evidence to support the existence of synaesthesia for the concept of key signatures. It was hypothesised that there would be no interaction between congruency and mode, which was positively evidenced in the data collected. This suggests that the meaning of the stimulus was more important in eliciting a synaesthetic response than the shape or form of the stimulus itself. However, there was a significant main effect for mode. On further investigation this was revealed to be due to one mode: Word. RTs were faster for both Congruent and Incongruent words, than those of Treble and Bass. Treble and Bass RTs for each of the conditions were very similar to each other. A possible explanation for this could be that the processing of the meaning of words may be quicker generally than that of musical notation. Ward, Tsakanikos and Bray (2006) hypothesised that "synaesthesia may take longer to appear for musical notation than for graphemes because musical notation is likely to be less familiar even to the musically trained" (p. 30). This hypothesis was tested in a separate task (Experiment 3) to compare the general processing time of musical notation with words.

Experiment 3: Processing of Musical Notation and Words

The aim of this task was to investigate whether the processing of the meaning of achromatic key signatures was generally quicker in the general population when presented in words rather than in musical notation, as suggested by the results of Experiment 2.

Method

Participants

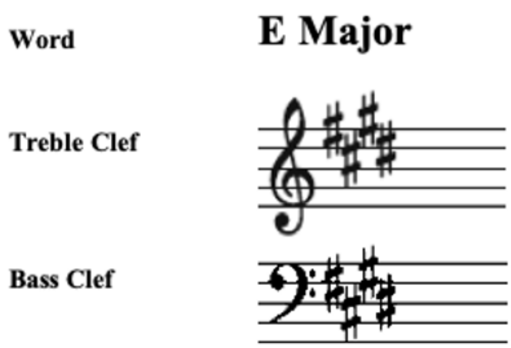
Participants comprised seven controls (Participants 11–17). Participants 10 and 18 could not be included as they were not able to read key signatures sufficiently fluently.

Materials

The same nine major key signatures were used to create three sets of monochromatic stimuli written in words, or on the stave in the treble clef or the bass clef. Examples of the type of stimuli are shown in Figure 7.

Figure 7

Example of Monochromatic Stimuli for E Major



Procedure

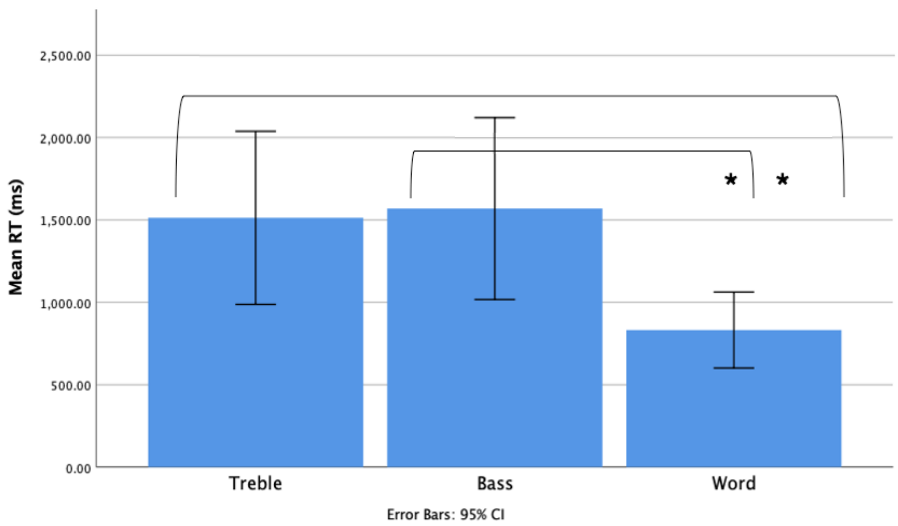
The processing task was in the same format as Experiment 2: participants were asked to identify out loud each key by name as quickly and as accurately as they could into a microphone, and no auditory stimuli was used. Participants were presented with on screen instructions and were allowed a short practice trial before the experiment began. Each key signature was presented twice in random order comprising 18 trials for each set, totalling 54 trials. The reaction time for each response per participant was measured in milliseconds and recorded in a Waveform audio format (.WAV), and the test was run using the open-source software package PsychoPy3 Experiment Builder (v3.0.5).

Analysis

Participants' performances were analysed by calculating the mean RTs as illustrated in Figure 8. Each RT measurement was verified by comparing it to the recording on the corresponding .WAV file. Any discrepancies were adjusted accordingly and incorrect answers recorded. As before, incorrect responses were excluded together with RTs more than three standard deviations from the mean RT to reduce the effect of outlier RTs. Data was compared using a one-way repeated measures ANOVA with mode of presentation (Treble Clef, Bass Clef, Words) as a within-participant variable. The software package SPSS Statistics V25 was used to carry out the analysis of the data collected.

Figure 8

Controls' Naming Times–Monochromatic Key Signatures in Different Modalities



Note. In the control group, Word naming times were significantly faster than in the Treble or the Bass condition [* $p < .05$].

Results and Discussion

The repeated measures ANOVA indicated a statistically significant main effect of mode on RT; $F(2,12) = 22.6$, $p = .001$, $\eta^2 = .79$. Post hoc Bonferroni tests indicated that the Word condition ($M = 832$, $SD = 249$) had significantly ($p = .006$) faster RTs than the Treble condition ($M = 1513$, $SD = 568$) and significantly ($p = .008$) faster RTs than the Bass condition ($M = 1569$, $SD = 597$). There was no significant difference between Treble and Bass scores.

The hypothesis that the processing of the meaning of a key signature is quicker when written in words than when musically notated is supported here. A similar mean RT for each of the Treble and Bass conditions was recorded ($M = 1513$ and $M = 1569$, respectively) and these were approximately 85% slower than the mean RT for the Word condition ($M = 832$). In Experiment 2, mean RTs were slower than those in Experiment 3 in all conditions, but the mean RTs for the Treble and Bass conditions ($M = 1730$ and $M = 1804$ respectively) were only approximately 31% slower than the Word condition ($M = 1320$). Yet despite the smaller difference between the Word condition and the Treble and Bass conditions, a similar pattern was observed.

This offers a possible explanation for the unexpected significant main effect of mode in Experiment 2, independent of participants' synaesthesia. In conclusion the results of Experiments 2 and 3 provide support for Hypothesis 1 (the existence of a synaesthetic association with written key signatures). With regard to Hypothesis 2 (synaesthetic association persists irrespective of presentation modality and form of key signatures), synaesthesia was shown to persist regardless of whether the key signature was presented on the stave in the Treble Clef or Bass Clef, but not in the Word condition. Overall, evidence supports the existence of synaesthesia for reading written key signatures as a genuine form of synaesthesia likely linked to conceptual rather than to purely perceptual processing of the inducing stimulus (Dixon et al., 2000, 2005).

Experiment 4: Verification of the Existence of a Priming Effect for Achromatic Key Signatures

As mentioned previously, how deeply an inducer needs to be processed to elicit synaesthesia remains unclear (Chiou & Rich, 2014; Mattingley et al., 2001; Smilek et al., 2001). Mattingley et al. (2001) presented stimuli to synaesthetes for 500ms, 56ms or 28ms in a masked priming experiment and concluded that the inducer in grapheme-colour synaesthesia must be available for conscious report for synaesthesia to arise, whilst Smilek et al. (2001) reported implicit processing without conscious identification to be sufficient. Experiment 5 was designed to test Hypothesis 1 by assessing the interference of synaesthetic colours with veridical colours in a task-irrelevant manner by measuring the congruency effect on reaction times without the need for the explicit naming of synaesthetic colour. Participants were required to select whether an achromatic key signature target superimposed over a colour patch was the same or different to an achromatic key signature prime. The colour patch would be either congruent or incongruent with the participant's synaesthetic colour for the target key signature, though the colour of the patch would be irrelevant to the task. Experiment 4 was designed as a pre-test to verify the existence of a priming effect for achromatic key signatures in the general population. Employing a similar paradigm to Mattingley et al. (2001), primes were presented for durations of 500ms, 56ms and 28ms in separate blocks of trials prior to testing synaesthetes in Experiment 5.

Method

Participants

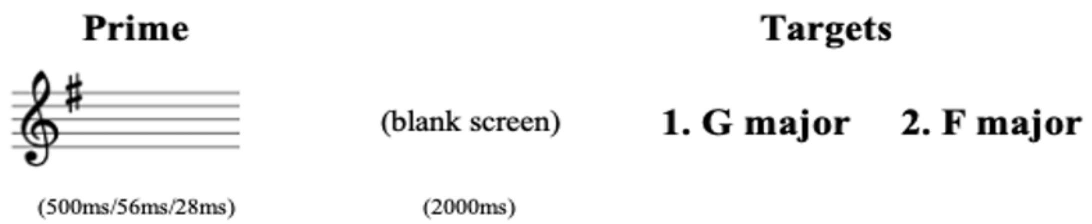
Data was collected and analysed from six synaesthetes (Participants 1, 3–6, and 8). Unfortunately, a technical malfunction meant that the data from Participants 2, 7 and 9 was not recorded.

Materials and Procedure

A set of stimuli (primes) was created from nine achromatic major key signatures notated on the stave in the treble clef: C major, G major, D major, A major, E major, F major, Bb major, Eb major and Ab major. Again, no minor keys were used to avoid ambiguity when reading from the stave, and no auditory stimuli was used. Targets were in the form of written key signatures in words. Examples of achromatic stimuli and targets are shown in Figure 9.

Figure 9

Stimuli and Targets in Experiment 4



Note: The example prime is the achromatic key signature of G major notated on the treble clef. Targets are key signatures written in words (one correct and one incorrect).

The task was conducted in three separate blocks of trials. In each block a fixation cross was shown for 2000ms, followed by a prime in the form of an achromatic key signature written on the stave in treble clef. The prime was presented briefly and then followed by a blank screen for 2000ms. In the first block the prime was presented for 500ms, and then for 56ms and 28ms in blocks 2 and 3 respectively. The name of two major keys were then displayed in words, and the participant was asked to choose the correct name for the prime key signature, selecting a key press for Option 1 or Option 2 as quickly as they could. Participants were shown on-screen instructions and were allowed a short practice trial before the experiment began. The test was run using the open-source software package PsychoPy3 Experiment Builder (v3.0.5).

Analysis

Participants' performances were analysed by calculating RTs and error rates (ERs). As in Experiment 2, incorrect responses were excluded together with RTs more than three standard deviations from the mean RT, comprising 6.58% of the total data, to reduce the effect of outlier RTs. The data was analysed using a one-way repeated measures ANOVA with presentation time (500ms, 56ms, 28ms) as a within-participant variable. Owing to the repetitive nature of the extended testing across three blocks of trials, the correlation coefficients between mean RTs and ERs from combinations of the three presentation times were calculated to assess whether a speed–accuracy trade-off existed affecting response speed. The software package SPSS Statistics V25 was used to carry out the analysis of the data collected (see Table 3).

Table 3

Mean Error Rates and Reaction Times in Experiment 4

Measure	500ms	56ms	28ms
ER (%)	1.23	3.09	3.09
Errors (No)	2	5	5
RT (ms)	685	637	683
SD (ms)	230	160	146

Note: ER = Error rate

Results and Discussion

No main effect on reaction time was observed due to the difference in presentation times; $F(2,10) = 607, p = .564, \eta^2 = .11$. This suggests that the prime was presented long enough in all presentation conditions to be available for identification. A speed–accuracy trade-off was not observed. ERs were very low and the mean ERs and RTs across the three presentation conditions from the 18 data points (6 participants x 3 conditions) were not significantly correlated (Spearman's rank correlation); $p(17) = .183$, $p = .468$. Additionally, ERs were not significantly correlated with the presentation time; $\rho(17) = .172$ $p = .495$. It was concluded that the presentation times of 28ms, 56ms and 500ms are appropriate to examine the effects of priming in the following Experiment 5.

Experiment 5: Interference for the Matching of Key Signatures (Synaesthetes)

The aim of Experiment 5 was to further test Hypothesis 1 by assessing the interference of synaesthetic colours with veridical colours in a task-irrelevant manner. The design was a sequential matching paradigm adapted from Banno et al.'s (2017) Experiment "Colour matching task". Banno's experiment measured the congruency effect on reaction times without the need for the explicit naming of synaesthetic colour. The advantage of this design is that, in Experiment 2, synaesthetes indicated that a simple "red" or "blue" often did not adequately describe a synaesthetic colour. This led to less confident responses from some synaesthetes. Removing the requirement to name a synaesthetic colour limited this effect.

Method

Participants

Nine synaesthetes took part as in Experiment 2, but data from only eight participants was analysed. Participant 2 had to be excluded owing to a failure to follow experimental instructions.

Materials

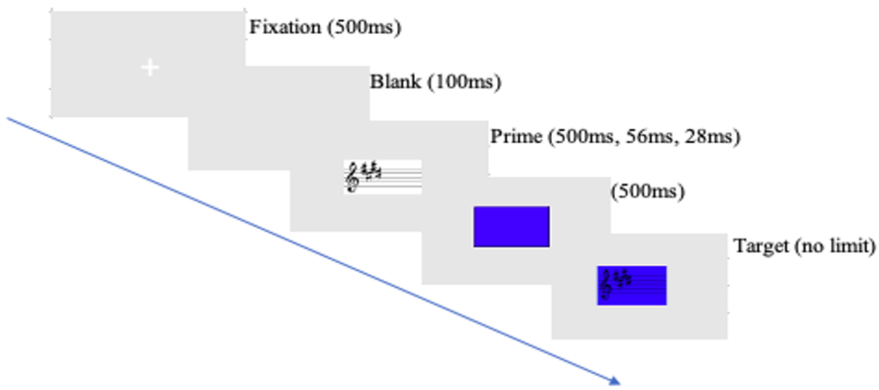
A set of stimuli was created for each synaesthete in accordance with their synaesthetic colours for each key. The stimuli comprised coloured key signatures in the treble clef only. As the aim of this experiment was to further test Hypothesis 1 by assessing the interference of synaesthetic colours with veridical colours in a task-irrelevant manner, different modes of presentation were not used, and all key signatures were presented on the treble clef. No minor keys were used to avoid ambiguity when reading from the stave. Incongruent pairings were created from the colours for each participant and matched with other keys so that there were nine congruent pairings and nine incongruent pairings per set. Half of the set of trials required a "SAME" response, and the other half required a "DIFFERENT" response. It was expected that synaesthetes would be significantly affected by veridical and synaesthetic colour congruency even though the colour was task irrelevant.

Procedure

The experiment began with a fixation point for 500ms. After a blank space for 100ms an achromatic major key signature was presented for variable durations (500ms, 56ms or 28ms) in separate blocks of trials. After this, a colour patch was presented for 500ms, followed by a target key signature superimposed over the same colour patch until a response was made. No auditory stimuli were used. Participants were asked whether the target key signature was the "SAME" or "DIFFERENT" to the first key signature, which they indicated with a key press of the left or right arrow key for "SAME" or "DIFFERENT" respectively. A schematic of the experiment is shown in Figure 10, and the types of stimuli used are shown in Figure 11. Participants were shown on-screen instructions and were allowed a short practice trial before the experiment began. Participants were presented with three blocks of 36 stimuli in random order. The test was run using the open-source software package, PsychoPy3 Experiment Builder (v3.0.5).

Figure 10

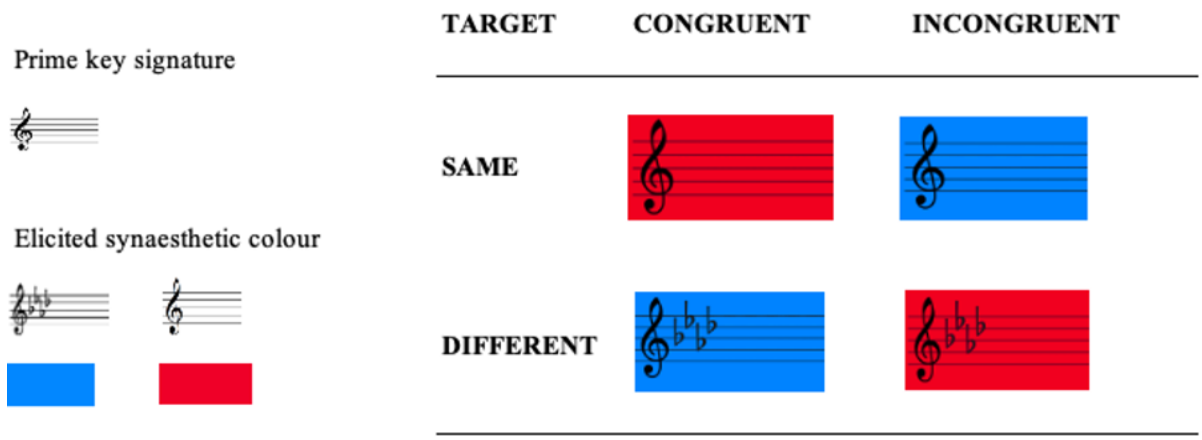
Schematic—Presentation of Prime Key Signature (500ms)



Note. Trial schematic for Experiment 5. See the online article for the colour version of this figure.

Figure 11

Sample Display for a Synaesthete who Experiences Ab Major as Blue and C Major as Red



Note. In the example, the prime is C major, and the Target can be the same in a congruent or incongruent colour, or different in a congruent or incongruent colour, to the presented target key. Four possible patterns are illustrated (2 congruence x 2 response types).

Analysis

In order to focus solely on the effect of congruency and not on the effect of whether the same or a different key was presented, only responses for "SAME" conditions were analysed. Performance was measured by analysing reaction times. Data for conditions with a "SAME" response was compared using a two-way repeated measures 2 x 3 ANOVA with congruency of colour and target key signature (Yes, No), and the presentation of the prime (500ms, 56ms, 28ms) as within-subjects factors. Incorrect responses and RTs more than three standard deviations from the mean were excluded (i.e., 7.29% of "SAME" response data). Data for conditions with a "DIFFERENT" response was not analysed because at least one of the colours, veridical or synaesthetic, would always be incongruent with one of the key signatures. To assess whether a speed–accuracy trade-off existed affecting response speed, "SAME" response ERs were calculated, together with the correlation coefficients between mean RTs and ERs from combinations of the two congruence conditions and the three presentation times. The software package SPSS Statistics V25 was used to carry out the analysis of the data collected.

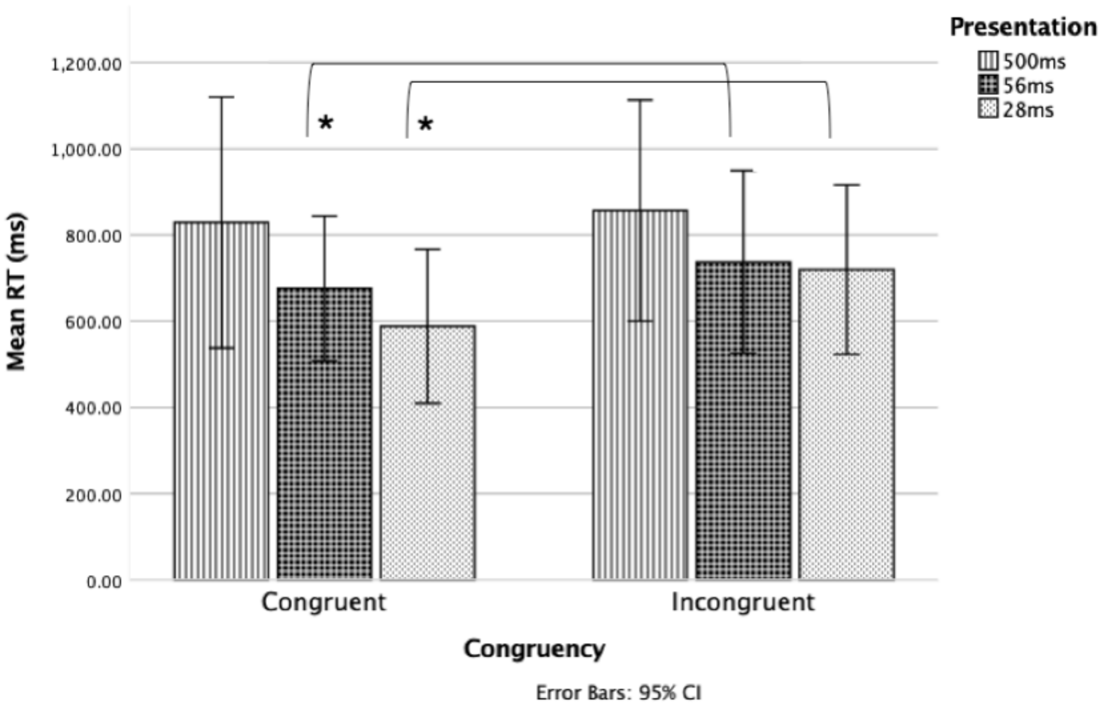
Results and Discussion

The repeated measures ANOVA indicated a statistically significant main effect of congruency on RTs; $F(1,7) = 29.51$, $p = .001$, $\eta^2 = .81$ and an effect of presentation times; $F(2,14) = 7.84$, $p = .005$, $\eta^2 = .53$. Post hoc Bonferroni tests revealed that there was no significant difference between the individual presentation times. However, the mean reaction times in the Congruent 500ms condition were not significantly faster than in the Incongruent condition. Paired *t*-tests indicated a statistically significant difference on mean reactions times in the 28ms condition; $t(70) = -3.916$, $p = .001$, and 56ms condition; $t(70) = -2.549$, $p = .013$; but not in the 500ms condition; $t(70) = -.745$, $p = .459$. A statistically significant interaction was not observed between congruency and presentation on RT; $F(2,14) = 2.83$, $p = .093$, $\eta^2 = .29$. A comparative graph of the data collected in the Incongruent and Congruent conditions is shown in Figure 12. It shows that there was a trend for RTs to be slower for the Incongruent conditions, as expected.

Mean error rates and reaction times from 48 data points (8 synaesthetes x 6 conditions) are shown in Table 4. No speed-accuracy trade-off was observed as response speed and ER were not significantly correlated; $\rho(47) = -.251$ $p = .086$ (Spearman's rank correlation), neither was ER significantly correlated to presentation; $\rho(47) = -.250$ $p = .086$ (Spearman's rank correlation). No correlation was observed between ER and congruency; $\rho(47) = -.031$, $p = .832$. These results are in concurrence with those of Experiment 4. The results support the presence of Stroop interference even when the colour is task-irrelevant across all presentation times, suggesting that access to the meaning of the stimuli was accessible across all presentation times, even when the key signature was not clearly visible. However, paired *t*-tests revealed that the effect of congruence was very weak in the 500ms presentation time. This may be due to the small sample size. Nevertheless, the depth of processing required to elicit synaesthesia for key signatures remains uncertain and requires further testing.

Figure 12

Synaesthete—Response Data



Note. Naming times were significantly faster in the Congruent Bass and Congruent Word conditions than in the Incongruent Bass and Incongruent Word conditions [*p = .05].

Table 4

Mean Error Rates and Reaction Times in Experiment 5

	500ms		56ms		28ms	
Measure	Con	Inc	Con	Inc	Con	Inc
ER (%)	0	1.56	6.25	4.69	4.69	6.25
Errors (No.)	0	1	5	4	4	5
RT (ms)	829	856	676	738	589	720
SD (ms)	348	307	201	254	214	235

Note: Con = Congruent; Inc = Incongruent, ER = Error Rate

General Discussion and Conclusion

This study is the first to provide empirical evidence for the existence of a form of synaesthesia associated with reading key signatures. Notwithstanding the small sample size of synaesthetes with this type of synaesthesia, results were significant and effect sizes were large. However, there were some limitations to the study. Difficulties associated with the confirmation of genuine synaesthesia is well documented (Eagleman et al., 2007; Rothen et al., 2013) and continues to be problematic in synaesthesia research. The identification of true synaesthetes from amongst the 12 self-reporting participants was not clear-cut, and an indication of high consistency in colour selection was not an absolute means of verification (Cohen Kadosh & Terhune, 2012; Simner, 2012). For example, two participants' results were excluded even though they returned a high consistency score. This decision was based on a very low percentage of correct responses given when naming their synaesthetic colour in Experiment 2, calling into scrutiny the automaticity of response normally present in synaesthesia.

A further complication was that some synaesthetes experienced a specific mixture of colours for certain keys. A "greeny-purple with inflections of red" was neither easy to find at first selection nor to recreate at retest. For these keys the consistency score was lower than expected, and the description given to the colour in Experiment 2 was often ambiguous and at risk of experimenter interpretation. It was also necessary to adjust the consistency scores of those synaesthetes that did not have synaesthetic colours for all nine major keys tested. Their colour associations were highly consistent and specific for certain keys, but their average consistency scores across all nine keys were lower than expected.

Two synaesthetes also reported the possession of absolute pitch (Participants 6 and 7). It cannot be absolutely certain that the "pitch" of the key was not heard in their head as a result of reading the key signatures. If so, the task of colour selection at test and retest may have been made easier and their choices not primarily conceptual. However, notwithstanding their absolute pitch, Participants 6 and 7 did not demonstrate the highest consistency scores in Experiment 1. In Experiments 2 and 5 the stimuli were presented so briefly; it might be the case that any additional processing time required to translate pitch naming to synaesthetic colour would be observed as an increase in reaction time rather than being advantageous. It is possible that this could have contributed to the lack of a significant difference between reaction times in Congruent and Incongruent conditions at 500ms in Experiment 5, but further experimentation would be required to confirm this.

The control group also presented unexpected results at retest. Although scores were lower and not as precise as in the synaesthete group, choices were not entirely random. The danger that some synaesthetes may be overlooked and that a high score may be misinterpreted as a synaesthetic association supports the argument that consistency should be better considered as an "associated characteristic" of synaesthesia rather than as a definitive measure (Ward & Mattingley, 2006).

The participation of controls in Stroop-type behavioural tests also poses problems simply because controls do not experience synaesthetic colours. This raises the question of exactly what was being tested. In Experiment 2, participants were asked to explicitly name their *synaesthetic* colour, a request that was absent in the control group. In the pilot, it was clear that although the controls' colour selection was not entirely random and that a certain level of consistency existed (as shown in Experiment 1), they were not able to reliably name the colour they had previously selected (or often any colour at all) within the 4000ms response time. This was particularly the case for controls who had to be encouraged to make any sort of colour choice for the keys in the first place. As incorrect responses and errors in timings when the microphone was inappropriately triggered were excluded from the reaction time analysis, together with RTs of more than three standard deviations from the mean, very little data was collectable. Consequently, controls were not requested to do this experiment, and a comparison with synaesthetes was not possible.

Controls were not compared to synaesthetes in Experiment 5 as controls did not make precise enough selections at Test and Retest in Experiment 1 to determine a categorical colour for each key. It might be argued that an experiment could have been run if it had been assumed that the “Congruent” condition for the controls was the colour for each key selected at first test, and the colour selected at retest was ignored. Incongruent conditions could therefore have been created with any colour at all that was not either of the colours selected at first or second test. Again, this raises the question of exactly what was being tested. Even if synaesthetes were presented with a period of time to become familiar with a set of colours, reaction times would most likely reflect the effects of short-term memory rather than the consistency and automaticity typically associated with synaesthesia.

Additionally, although the results of Experiment 5 suggest that the meaning of the stimuli was accessible even when the key signature was not clearly visible, Experiment 5 was not explicitly designed to investigate unconscious priming. Further experimentation would be required to confirm the depth an inducer would need to be processed in this form of synaesthesia (Mattingley et al., 2001; Smilek et al., 2001). Nevertheless, this is an interesting indication that there is no need for long exposure to the inducer for synaesthesia to arise, and that even a brief presentation may be sufficient.

Despite these limitations, the importance of this study is that it evidences synaesthetic experiences associated with music are not confined to a response on hearing an individual tone or chord (Mills et al., 2003) as much of the research to date has assumed and focussed on. Music-colour synaesthesia has a broad scope and not all types are cross-sensory (Curwen, 2018). The results challenge the traditional view that synaesthesia is fundamentally a perceptual phenomenon and support the argument that some forms of synaesthesia can arise from a conceptual stimulus (Dixon et al., 2000; Mroczko-Wąsowicz & Werning, 2012; Mroczko-Wąsowicz & Nikolić, 2014; Ward, Tsakanikos & Bray, 2006).

Empirical evidence has shown that a synaesthetic experience may be elicited without the necessity of sounding out the key, and that the concept of the key is sufficient to produce a synaesthetic response. For example, the richness of concept-driven forms of music-colour synaesthesia may be mediated by timbre, tempo or emotional meaning (Mroczko-Wąsowicz & Nikolić, 2014). The synaesthetic colours associated with a key signature provide information about the concept of the key, irrespective of its mode of presentation either as a written key signature on a musical stave or in words. Emerging from the results of Experiment 2 is the hypothesis that synaesthesia associated with music may be mediated by concept but grounded in sensorimotor action, and that notation on the stave may provide more sensorimotor information about the concept of key rather than the written word – i.e., thoughts about production or hand shape (Curwen, 2020a). This presents an opportunity for future empirical research. For example, a group of non-synaesthete musicians (controls) might be given sufficient training until they could use a keyboard to silently play a selection of chords in different keys notated either on the stave (bass and treble clef) or written in words, and reliably associate a colour with each key. The group of controls would then be compared to a group of synaesthete musicians. Each group would be presented with coloured chords in different keys (notated on the stave or written in words) and asked to play them as quickly as possible. It might be expected that chords presented to synaesthetes in incongruent colours would result in slower reaction times, but not in the control group. In addition, should synaesthesia have a sensorimotor grounding, it might be expected that there would be no effect for congruency in the word condition in either group, as words may not carry the same sensorimotor information as chords notated on the stave.

In conclusion, this study supports the likelihood that separate mechanisms underlie different forms of music-colour synaesthesia, and that to gain a full understanding of the phenomenon it is important to extend investigations beyond the more commonly examined tone-colour synaesthesia.

CHAPTER FOUR – MUSIC-COLOUR SYNAESTHESIA: A SENSORIMOTOR ACCOUNT

'I study synaesthesia because it's one of the few conditions in which it's clear that someone else's experience of reality is measurably different from mine. And it makes it obvious that how we perceive the world is not one-size-fits-all.'

— D. Eagleman (2015), *The Brain: The Story of You*

Published as: Curwen, C. (2020). Music-colour synaesthesia: A sensorimotor account. *Musicae Scientiae*. https://doi.org/10.1177/1029864920956295

This chapter is produced in a slightly different format to that of the published journal paper referred to above, but is otherwise identical.

Linkage of Paper to Research Methodology and Development

I have argued in previous chapters that music-colour synaesthesia should be examined not as a separate and distinct condition, but as a continuation of typical musical perception and cognition. The results of Experiment 2 in Chapter 3 suggested that the notation of a musical key on the stave may provide more sensorimotor information about the concept of key rather than the written word, i.e., thoughts about production or hand shape (Curwen, 2020a). Before testing this hypothesis in Chapter 5, the current chapter sets out a theoretical framework for a sensorimotor explanation for music-colour synaesthesia, which stems from embodied and enactive accounts of typical music cognition and includes an active role for the body and its situated power of action.

Abstract

This paper presents a sensorimotor account of music-colour synaesthesia, proposing a radically different perspective than is commonly provided. Recent empirical and theoretical work in music cognition moves away from cognitivist accounts, rejects representationalism, and embraces an embodied standpoint. It has been shown that some forms of synaesthesia may be elicited from a concept alone and are often accompanied by shapes and textures. It is from this perspective that a skilful engagement with the environment and relevant sensorimotor contingencies may be identified. Here the role of embodied and enactive perception in general music cognition is extended to music-colour synaesthesia, and an argument is made for how the attributes of "bodiliness" and "grabbiness" might be found in a sonic environment, and how music listening might be perceived as an "act of doing".

Keywords: synaesthesia; music; music-colour; sensorimotor; cognition

"Coloured hearing", or chromesthesia, is an umbrella term that includes music-colour synaesthesia (Ward, Huckstep & Tsakanikos, 2006). Synaesthesia has been described as "a union of the senses" (Cytowic, 2002, p. 325) arising from the stimulation of one sense (an inducer) triggering a reaction in an unstimulated second sense (a concurrent; Grossenbacher & Lovelace, 2001). This article examines the congruence between general music cognition and synaesthesia, interpreting music-colour synaesthesia within the broader frameworks of embodied and extended music cognition, in which action and interaction with the environment are central to music perception. It argues that music-colour synaesthesia is best understood as a sensorimotor phenomenon, rather than understanding it as a particular neurological condition. This view resonates with recent research in embodied and enactive music cognition, moves away from traditional cognitivist accounts, rejects "representationalism", and embraces a more situated standpoint (Krueger, 2009, 2011, 2014; Loaiza, 2016; Maes et al., 2014; Reybrouck, 2014, 2017; Schiavio et al., 2017; Schiavio et al., 2019; van der Schyff et al., 2018).

In order to come to a balanced perspective on music-colour synaesthesia as a sensorimotor phenomenon, this article provides, first, a brief overview of the phenomenon of synaesthesia, focusing on music-colour synaesthesia. Next, developments of research in general music cognition are outlined that describe engagement with music, including music listening, as an "act of doing". The third section discusses how music-colour synaesthesia may indeed be explained from a sensorimotor perspective. The final section discusses challenges presented by synaesthesia to sensorimotor theory, and how these may be resolved arguing for a shift in perspective of music-colour synaesthesia from being regarded as special to being illustrative of how typical, but individualised music cognition may develop.

Synaesthesia

Researchers are beginning to challenge the assumption that a single mechanism underlies all forms of synaesthesia (Auvray & Deroy, 2015), and Simner (2012), for example, rejects a one-for-all explanation. Although synaesthesia has been described as a merging of the senses, not all types are cross-sensory. Evidence shows that it can be activated by a concept alone (van Leeuwen et al., 2015); the inducer does not have to be physically present (Meier, 2014). For example, Dixon and colleagues (2000) found that synaesthetes responded to the concept of "7" triggered by the presentation of 5+2 in the absence of the actual number, and Ward, Tsakanikos, and Bray (2006) found that the concept of musical notation was enough to elicit a synaesthetic response. These findings have led to the development of alternative theories such as "ideaesthesia" (Jürgens & Nikolić, 2012; Nikolić, 2009), meaning "sensing concepts" (Mroczko-Wąsowicz & Nikolić, 2014, p. 4), connecting sensation and phenomenal experiences, or *qualia,* with their conceptual triggers or semantic inducers. Qualia is the term used to describe the qualities of subjective experience associated with certain sensory stimuli (see Jackson, 1982). In music, this might include the difference in experience between a melody played on a piano and the same melody played on a French horn (see also Curwen, 2018).

Synaesthetic experiences have been described by Wager (1999) as “extra qualia” (p. 264) that manifest themselves differently from synaesthete to synaesthete. Attempts to explain extra qualia associated with synaesthesia challenge philosophies of mind such as representationalism: “the view that the phenomenal character of an experience supervenes on its representational content [or] the way an experience seems to its subject is . . . the way the experience represents the world as being” (Wager, 1999, p. 263). Tye (1998) ventures that phenomenal character must be identical to its representational content. The challenge to representationalism posed by synaesthesia is that it appears at odds with reality. Experiencing green in response to music does not mean the music is actually green, nor that the synaesthete is experiencing green-ness (Auvray & Deroy, 2015). There is much disagreement on this topic (see Curwen, 2018).

Differences between “higher” and “lower” synaesthetes, and between “associators” and “projectors”, further highlight the diversity of synaesthetic manifestations. The distinction between higher and lower synaesthetes was first proposed by Ramachandran and Hubbard (2001), based on evidence of cross-activation mechanisms operating at different times and in different locations in the brain. Lower synaesthetes were thought to process information at an early stage in the fusiform areas that manage form and colour perception, while higher synaesthetes were thought to process information at a later stage in areas that manage the conceptual aspects of colour. Associators describe their experience as being in the mind’s eye (Dixon et al., 2004; Dixon & Smilek, 2005) or as knowing the colour (Ward et al., 2007), while projectors claim to see colours projected outside the body into external space (Smilek et al., 2001). It appears reasonable to consider associators as higher synaesthetes and projectors as lower synaesthetes, but this has not been substantiated by research and in some studies the two dimensions of synaesthesia are shown to be orthogonal (Ward et al., 2007). The crucial distinction between associators and projectors lies in the experience of the concurrent, while that between higher and lower synaesthetes lies in the nature of the inducer. Lower synaesthetes can perceive colours in their mind's eye, and higher synaesthetes can be projectors. These examples, among many others, illustrate that the potential scope of music-colour synaesthesia is very wide.

Coloured Hearing

"Tone-colour synaesthesia" is the type of music-colour synaesthesia examined most often: single tones and chords, isolated from any musical context, elicit specific colours. It has been attributed to neurological mechanisms, specifically bottom-up processing (see Music-Colour Synaesthesia below). However, the synaesthetic experience of music is not just about the ability to assign a colour to individual tones or chords, nor is it just about sound (Mills et al., 2003). Timbre, tempo, and emotion mediate the experience, and some synaesthetes have to hear an entire musical piece to produce a synaesthetic response (Curwen, 2018). In this article I focus on higher, concept-driven, forms of music-colour synaesthesia.

According to Peacock (1985) there are four broad categories of musical inducer: compositional style, timbre, tonality, and pitch (tone). Concurrents are almost always experienced as colour, but can also be experienced as shapes, spatial layouts, and textures (Eagleman & Goodale, 2009). Synaesthetes often experience more than one form simultaneously and in various combinations. For example, GS, the sole participant in Mills et al.'s (2003) study, experienced large blocks of darker colours when hearing heavy metal music, and unpleasant colour combinations when hearing music she disliked. The particular colours were influenced by changes in instrumentation or timbre, and higher and lower pitches were associated with lighter and darker colours respectively. She also experienced shapes, texture, and movement creating landscapes that she referred to as maps, that moved at speeds in accordance with the tempo of the music and were often easier for GS to follow than standard musical notation.

There are some similarities between synaesthetic experiences and typical non-synaesthetic cross-modal associations, such as those between pitch height and lightness (Eitan & Timmers, 2010; Ward, Huckstep, & Tsakanikos, 2006) and pitch height, size, and brightness (von Hornbostel, 1925; Marks, 1974; Marks, 1987). Marks (1975) argues that the cross-modal mechanisms underlying synaesthesia and general cognition are so similar that the former can be seen as a kind of shorthand for the latter (p. 325).

Music-Colour Synaesthesia and General Cognition

Krueger (2011, 2014) argues that music helps individuals realise emotional and social experiences in everyday life. According to the original *extended mind thesis* (EMT), cognitive processes are not confined to the head, nor even the body, but extend into the external world (Clark & Chalmers, 1998): a pen and paper aids calculation, a cane helps the blind navigate, and musical instruments facilitate music production (Chemero, 2018). The EMT has been expanded to propose a dynamic coupling system between subject and environment (Sutton, 2010; Kirchhoff, 2012). Colombetti and Roberts (2015) explain that a "self-stimulating, coupled relationship is instantiated" (p. 1259) between a saxophonist and their instrument demonstrating that the relationship extends beyond "skull and skin" (p. 1244) to affective states: the sound produced by the instrument affects the player's emotional experience, influencing what they play next. Reybrouck (2017) suggests that musical sense making derives from the mediation of cognitive events by sensorimotor interactions with the physical world, which may be multimodal. The addition of a visual modality to an auditory modality may make a listener aware of previously hidden auditory information, modifying their perceptual experience. Interpreting synaesthesia in similar terms challenges the prevailing view that music-colour synaesthesia is a form of cross-sensory imagery with neurological origins.

Notwithstanding the rarity of synaesthetic experiences, and their characteristic automaticity and consistency, music-colour synaesthesia may not be so different from typical music cognition. Barsalou's *perceptual symbol systems* theory (PSS) explains how a conceptual system grounded in perception might work (1999, 2003). When people perceive objects, their basic sensorimotor experiences are captured as sensory symbols so that patterns of activation established during early sensory processing can be re-enacted subsequently. Conceptual systems derive from category knowledge, each category relating to a different component of experience (Barsalou, 2003). Individual concepts are the product of repeated re-enactments of the pattern of activation established when the object was perceived for the first time. These re-enactments are only partial, however; certain elements of the original pattern of activation evoked by the perception of the object remain, but context determines the nature of each subsequent re-enactment, adding further multimodal sensorimotor information to previous perceptions of the object (Jacobson, 2013). As Zbikowski (2010) explains:

> …a simulator for the category of conjoined musical events associated with the term "perfect authentic cadence" could be established simply through multiple encounters with exemplars of the category . . . such a simulator would not only include auditory information, but also extend to sensorimotor information about the feeling of performing these events . . . introspective states associated with such cadences, and physical responses to hearing them (Zbikowski, 2010, pp. 35–36).

In music-colour synaesthesia, the concurrent might be mediated by new information that influences the conceptual content of the stimulus. This information might consist of timbre, emotion, tonality or musical style (Mroczko-Wąsowicz & Danko, 2014). There are many different types of synaesthesia, however, and in accordance with Simner (2012) who argues against a one-for-all explanation, and Auvray and Deroy (2015) who suggest that each type be considered separately, my aim here is not to propose a single underlying mechanism. Some synaesthesias may be of neurological origin, others genetic. Nevertheless, it is likely that higher, concept-driven forms of music-colour synaesthesia are based on experience, albeit to varying extents.

Music Cognition

Cognitivist Approaches

Cognitivist accounts of musical experience propose representations and computations based on an input-output model (Lerdahl & Jackendoff, 1983; Nussbaum 2007): the sensory system receives a stream of external information from which internal representations of the real world are created (i.e., music processing). They do not consider the role of the body; Fodor (1983) argued for the modularity of mind, while more recent neurological explanations focus on the role of areas of the brain thought to be specialised for music (e.g., Peretz & Coltheart, 2003). These explanations are criticised (e.g., Di Paola et al., 2017; Fuchs, 2017; Gallagher, 2017; Varela et al., 1991) yet their core tenets are still endorsed. For example, Huron (2006) explains musical experience in terms of an internal appraisal mechanism based on “some sort of weighted sum” (p. 110) of different representations of listeners’ expectations, while Sloboda and Juslin (2010) explored the relationship between real emotions and their representation in the form of emotional responses elicited from music. Yet musical experience is intersubjective and influenced by what individual listeners feel and what they do (Leman, 2008; Reybrouck, 2006). People fulfil their social needs and experience well-being through musical engagement not by processing internal representations but by exploring the external, musical, environment (Krueger, 2009, 2011; Reybrouck 2010; Schiavio et al., 2017).

Ecological Approaches

Clarke (2005) applied ecological psychology, based on Gibson’s (1966, 1979) theory of *affordances*, to music perception. Affordances, according to Gibson, are what the environment "offers the animal, what it provides or furnishes, either for good or ill . . . I mean by it something that refers to both the environment and the animal . . . it implies the complementarity of the animal and the environment" (1979, p. 127). Consequently, perception is seen not as an internal process but as the result of the ongoing relationship between the animal's, or agent's, whole perceptual system, rather than isolated receptors such as the ear or the eye, and its environment.

But what are musical affordances? Most scholars agree that music affords movement or some form of entrainment (e.g., Clarke, 2005; Leman, 2008; Krueger, 2014; Reybrouck, 2005, 2012). DeNora describes musical affordances as "moods, messages, energy levels, and situation" (2000, p. 44). A musical event may be an interactive exploration of different "sonic affordances", and a provider of emotional and social affordances without which our ability to relate to others would be significantly diminished (Krueger, 2011). Krueger (2014) subsequently put forward a model of the musically extended mind, explaining that music affords not just movement but also entrainment, observed as moving in time to the beat and sharing the experience with others. As an "emotion-extending resource" (2014, p. 9) musical affordances offer access to extended experiences and expressivity beyond those available to us in non-musical situations.

In their theory of musical affordance, Menin and Schiavio (2012) propose an embodied, motor-based account emphasising the intentional nature of the relationship between musical subjects and objects. When a skilled guitarist demonstrates a motor form of intentionality by using their fingers on the strings in such a way as to reproduce a musical sequence, "this sensory-motor process not only represents the basis of musical understanding, but it can also shed light on the notion of musical affordance, relying on a sub-cognitive, pre-linguistic, intrinsically motor form of intentionality" (p. 210). Applying Ramstead et al. 's (2016) cultural affordances framework to music performance, Einarsson and Ziemke (2017) argue that it is "the situation as a whole that has affordances" (p. 10), offering a still broader perspective.

Embodied Approaches

The rejection of the distinction between action and perception is at the heart of Gibson's ecological theory, and key to theories of embodiment (Chemero, 2009; Leitan & Chaffey, 2014; Wilson & Golonka, 2013). Their proponents acknowledge the constitutive (i.e., essential) role of the body in driving cognitive processes and dismiss the key role of mental representations in the cognitive economy of the living system (Thompson, 2007; Varela et al., 1991). Should information be there for the taking in the environment, why would nature build an internal mechanism to do the same job (Rowlands, 2003)? Nevertheless, those who propose embodied approaches to music cognition have struggled to discard all aspects of representation. For example, representational structures are retained in Leman's (2008) theory of embodied music cognition, which otherwise describes the relationship between agent and environment, to capture the richness of musical experience (see Schiavio & Menin, 2013). Recent research frames more "radically embodied" (van der Schyff et al., 2018, p.13) and enactive approaches to musical engagement in the context of musical emotion, communication, and meaning in community music making, and musical creativity (Schiavio et al., 2017, 2019; van der Schyff et al., 2018). In contrast to approaches presenting music cognition as a series of internal (i.e., computational, neural) processes and representations, these approaches propose the direct, circular interaction between the agent's body and its social, cultural, and physical environment (Reybrouck, 2014; van der Schyff et al., 2018).

Sensorimotor Theory

Matyja (2010) highlights the importance of O'Regan and Noë's (2001) *sensorimotor contingency theory* (SCT) in an enactive approach to music cognition. SCT is an account of perceptual consciousness that attempts to explain qualia without reference to representation. It presents a new approach to perception emphasising the influence of motor actions on changes in sensory stimulation (Bishop & Martin, 2014). Focusing on visual experience, "the central idea of our new approach is that *vision is a mode of exploration of the world that is mediated by knowledge of what we call sensorimotor contingencies* [emphasis in original]" (O'Regan and Noë, 2001, p. 940).

SCT explains how an agent explores the environment, and how their attention is attracted by (unpredictable) attributes of the environment described as *bodiliness*, *grabbiness* and *insubordinateness*. The extent to which an agent makes use of sensorimotor contingencies determines the quality of their experience:

> Bodiliness refers to the objectively quantifiable way in which bodily changes modify sensory input; for example, turning your head alters visual input, but has no effect on thoughts. Insubordinateness is the fact that bodily changes, though they have a systematic effect, do not completely determine sensory changes (sensory input can change without bodily changes occurring). Grabbiness concerns the fact that, due to basic properties of sensory systems, sudden transitory changes in sensory input strongly grab our attention and cause perceptual processing to be focused on the sudden event (Degenaar & O'Regan, 2015, p. 2).

Sensorimotor Theory and Music

How can we relate this to music? If an act of listening to music is an interaction with the sonic environment (Krueger, 2009), relevant sensorimotor contingencies may be obtained in the following ways: bodiliness: turning towards the sound we hear; grabbiness: being alerted at a key or instrumentation change; insubordinateness (relating to aspects of the sonic world beyond our control): music stopping unexpectedly; equipment failure; instrument failure.

If SCT is about actively exploring the environment, doing and interacting, how can it be applied to music listening when we appear not to be doing anything? Yet doing denotes not only bodily movement, but also thinking, imagining, and standing still (Beaton, 2013).

Listening to music offers affordances in the form of our memory of previous experiences of musical engagement (Myin, 2016).

Stewart et al. (2003) report empirical evidence for a sensorimotor role in reading and playing music in a functional imaging study with non-musicians. Twelve learners undertook 15 weeks of musical training and carried out an explicit music reading task requiring them to press keys on an electronic keyboard. Their results were compared with those of a control group. Activation in the superior parietal lobe (SPL) was observed in the learners but not the control group. The researchers conclude that reading music involves a sensorimotor translation of the notation to appropriate keypresses.

Some have argued that formal musical training is needed to achieve deep musical understanding (e.g., Kivy, 2002), whilst others have shown that an implicit understanding of the structure of western tonal music can be acquired through exposure alone (Krumhansl, 2010). Importantly, formal musical training is not needed to obtain relevant sensorimotor knowledge. For example, Peñalba-Acitores illustrates how bodiliness and grabbiness might emerge during typical musical engagement (2011, p. 222):

> . . . our perception roams around different aspects of the material, exploring melodies, instruments, chords, structure, and style; and we are aware of that exploration through bodiliness . . . we will know that we are experiencing a *crescendo* because of increasing tension in the muscles; and we will experience rhythm because of the way that it allows us to synchronize our movements (virtual or actual) with the beat; This constitutes bodiliness.
>
> Grabbiness, by contrast, captures the idea that the environment guides the subject in perception . . . In an orchestral piece, a listener might be more likely to be 'grabbed' by timbre . . . Or we may be "grabbed" by the unexpected change from minor to major in a

tierce de Picardie. [4]

Peñalba-Acitores also suggests that listeners unfamiliar with Indian music find it difficult to listen to at first because they attempt to apply the sensorimotor skills they have learned from listening to Western tonal music.

Music-Colour Synaesthesia

Neurological Theories

There are two primary neurological explanations for the cause of synaesthesia, the *disinhibited feedback theory* (Grossenbacher & Lovelace, 2001) and the *hyperconnectivity theory* (Ramachandran & Hubbard, 2001a). The disinhibited feedback theory suggests that a breakdown of the barriers that normally keep modules and their processing completely separate permits a free flow of information from primary sensory areas to associated areas such as the parietal lobe or limbic system. In this way, if feedback signals are not inhibited, later stages of processing can influence earlier stages of processing (Neufeld, Sinke, Zedler et al., 2012). According to the hyperconnectivity theory, both intermodal and intramodal synaesthesias are caused by a bottom-up process arising from unusual direct connections between different modules of the brain such as visual and auditory areas. In infancy, there are many more connections between brain areas than in adulthood. These extra connections are normally pruned as the brain matures, yet in synaesthesia it is thought that this process is not completed fully, leaving some unusual connections behind (see Ramachandran & Hubbard, 2001a, pp 9–10). Both theories emphasise the role of genetic factors for the cause of synaesthesia and provide little role learning in its development. Yet synaesthesia may not just arise from inadequate neural pruning and weakened inhibitory re-entrant feedback. The reasons for such disinhibition or connectivity may be various.

[4] A tierce de Picardie (meaning a Picardy third) is the term given to the use of a major chord in the final tonic chord of a piece of music in a minor key.

Role of Concept

As previously mentioned, some synaesthesias can arise from a conceptual stimulus (Dixon et al., 2000; Mroczko-Wąsowicz & Werning, 2012; Mroczko-Wąsowicz & Nikolić, 2014; Ward, Tsakanikos and Bray; 2006) implying that synaesthetes may not be predisposed to synaesthesia but, rather, have learned to assign meanings to certain stimuli for the purpose of strengthening their knowledge and understanding of abstract concepts (van Leeuwen et al., 2015). Individual synaesthetes frequently disagree as to the specific colours and imagery associated with musical inducers, suggesting that the learned meanings assigned to stimuli are neither random nor universally applied.

Role of Body, Action and Environment

The similarities that exist between synaesthetic pairings and the cross-modal associations commonly made by the general population between colour, music, emotion, pitch-height and pitch size indicate that synaesthetes and non-synaesthetes employ comparable mental processes (Gallace & Spence, 2006; Isbilen & Krumhansl, 2016; Marks, 1987, 2004; Mondloch & Maurer, 2004; Palmer et al., 2016; Palmer et al., 2013; Tsiounta et al., 2013; Walker et al., 2010; Ward, Huckstep, & Tsakanikos, 2006). Both groups are exposed to similar learned cultural and environmental associations. For example, large objects make bigger and louder sounds on impact than smaller ones, and higher pitches are associated with smaller animals (Spence, 2011). Parise and Spence (2009) hypothesise that, according to Bayesian theory, pairings such as those between pitch and size are based on the individual's prior knowledge that these cross-modal associations "go together" (p. 2) in the natural environment. Music-colour synaesthesia may simply be a typical musical experience with "extra qualia", as described by Wager (1999, p. 264), for some people. Nevertheless, as we have seen, the phenomenological experience of seeing the colour green when hearing the pitch class "A" presents a challenge to representationalism (Alter, 2006; Auvray & Deroy, 2015; Brogaard, 2016; Curwen, 2018; Rosenberg, 2004; Wager, 1999). Embodied and enactive music cognition research rejects explanations of musical experience as a series of internal cognitive processes (Reybrouck, 2005, 2012) and argues rather that "musical experience . . . is not something that is done *to* us" [but instead is] "something we *do*" (Krueger, 2011, p. 2). A more holistic and embodied approach to understanding musical experience (Schiavio & van der Schyff, 2016) can be applied to the development of a sensorimotor explanation for music-colour synaesthesia.

Synaesthesia and Sensorimotor Contingency Theory

Deroy and Spence (2013) suggest that the cross-modal correspondences underlying synaesthesia may be grounded in sensorimotor associations:

> …most people match angular shapes with the word "takete" while matching rounded shapes with the word "maluma" . . . it is the sharp vocal transitions made by the mouth when uttering the plosive sounds in "takete" that people map onto the sharp/angular shape . . . this cross-modal correspondence would then become "embodied" and grounded in sensorimotor associations (p. 1249).

However, it is important to acknowledge the challenges that synaesthesia poses to the basic assumptions of sensorimotor theory, which Mroczko-Wąsowicz (2015) highlights in the following three objections:

1. Synaesthetic concurrents are generated internally, and do not arise from light reflecting from a surface, changing the angle of the head, or eye saccades.
2. Synaesthetic colour does not adapt away as in colour inversion in normal vision. It is generally consistent and unchanging.
3. Synaesthetes can tell the difference between synaesthetic colours and veridical colours, suggesting that synaesthetic colours lack perceptual presence (i.e., of being real and existing in the world).

However, higher, concept-driven forms of music-colour synaesthesia can be reconciled to sensorimotor theory and the above objections resolved, as discussed below.

Synaesthetic Colours are Generated Internally

Synaesthesia has little to do with vision per se: “synesthetic visual responses to music aren’t affected by shutting or moving the eyes” (Ward, 2013, p. 51) and concurrents do not arise from normal vision. The colours experienced by associators are often described as being in the mind’s eye, or of knowing a colour. Yet this does not mean that a synaesthetic experience is not the result of an individual’s interaction with their direct environment. Affordances derived from interactive patterns in previous experiences of musical engagement can be understood as “something we do now, in the light of what we have done before” (Myin, 2016, p. 100). Similarly, Barsalou’s PSS theory proposes that a pattern of activation established during early basic sensorimotor processing can be re-enacted subsequently (1999, 2003). For example, in other synaesthesia research, Mroczko-Wąsowicz and Werning’s (2012) presented two semi-professional swimmers who associated synaesthetic colours with four swimming strokes (breaststroke, crawl, butterfly and backstroke). In a Stroop-like task (Stroop, 1935) both named colours faster when shown photographs of swimmers in stroke-congruent colours. Simply thinking about or imagining the swimming stroke was enough to re-enact the original activation pattern and elicit a colour response; the strokes did not have to be executed physically.

Beaton (2013) argues that colour does not exist independently in the external world, nor just in our minds, but as the result of our interaction with the world (see also Varela et al., 1991) emphasising that learned associations are an important part of individuals’ personal experience with colour, and what it means to them. For example, Gilbert et al. (2016) found that participants deliberately matched similar colours to similarly valenced emotion terms. Participants’ choices differed significantly as a function of emotion and were moderated by sex and age. When participants in another study were asked to judge the effects of colour on emotion (Wilms & Oberfield, 2018), the combination of hue, saturation, and brightness was important, and Palmer and Schloss (2016) found that preferences for a particular colour were influenced by interaction with an object of the same colour. Barsalou (2003) also emphasises the role of personal experience when re-enactments of original sensorimotor patterns are tailored to the context of the individual's current situation. Personal experience may explain disagreements between synaesthetes as to the colours associated with the same inducer.

Visual perceptual experiences can be obtained from stimuli other than those produced by light reflecting from a surface, as demonstrated by the visually impaired with tactile-vision substitution systems (TVSS), as described by Bach-y-Rita and Kercel (2003), or other forms of sensory substitution such as The vOICe (e.g., Pasqualotto & Esenkaya, 2016). For example, the profoundly deaf Scottish virtuoso percussionist, Dame Evelyn Glennie, writes of how "my whole body is similar to an ear, every surface has learnt to become a conduit, bringing meaning and sense to my brain" (2016, para.11).

It can therefore be argued that what underpins music-colour synaesthesia is the development of a conceptual system, in the form of sensorimotor features associated with a musical inducer the first time it is heard, and enriched through repeated exposure. For example, the individual may experience, either as an instrumentalist or a listener, an intense emotional response to the music, associated with a certain group of colours that in turn become associated with it. Different individuals presented with the same inducer experience it in different contexts, however, which would explain why different synaesthetes see different colours. A synaesthetic colour experience might be the result of subsequent re-enactments of the conceptual system while remembering, producing or listening to the music. For example, Ward, Tsakanikos and Bray (2006) showed that synaesthetic colour was determined by musical context rather than mode of presentation or form of stimulus. In the notation of Western music, a dot presented on the middle line of a five-line stave has different meanings depending on the clef (e.g., B in treble, D in bass). Synaesthesia is elicited at the conceptual level, so the same colour will be assigned to a D whether it is shown on the middle line of a bass stave, below the bottom line of a treble stave or as a letter, whether upper- or lower-case.

The variation in colour preferences from synaesthete to synaesthete for the same stimuli reflects the differences in the meaning of the concept surrounding the stimuli for each individual. According to Gardenfors (2004), concepts "are intrinsically dynamic entities, arising and adapting continuously as the agent engages with its environment . . . concepts are never free-floating entities but are always concepts for a particular agent, who comes with her own perspectival biases" (p. 170). Barrett (2011) makes an interesting link between Gibson's affordances and Jacob von Uexküll's *Umwelt* (1992). The notion of *Umwelt* is described by Barrett as "the world as it is experienced by a particular organism" (p. 80) implying, as in Gibson's theory, that the same environment will not offer the same affordances to each animal. An agent is only sensitive to those stimuli relevant to it from within its own environmental niche. For example, humans do not need to see ultraviolet light or hear very high-pitched sounds, nor do we need a heightened sense of smell to detect and avoid other predators in the same environment. None of these things forms part of our *Umwelt*.

Reybrouck (2001, 2005) considers music listening relevant to *Umwelt* research, arguing that "dealing with music can be considered as a process of knowledge acquisition" (2001, p. 623) dependent on the individual listener's previous interactions with their sonic environment and the meanings that listener might attribute to the sounds. Reybrouck claims that "what is really important is not the acoustical description of the sound, but the sounds as they are experienced by the listener" (2001, p. 618). Non-synaesthetes are happy to accept reality as it is presented to them: without unobtainable synaesthetic experiences (Eagleman, 2012).

Similarly, synaesthetes, whose phenomenal experience of music includes colours, accept their wider *Umwelt*.

Synaesthetic Colours Do Not Adapt Away

Kohler's (1964) study describes the experience of wearers of coloured goggles who report an adaptation over time until the goggles no longer interfere with their normal vision. Yet, as Ward (2012) points out, it is often overlooked that the adaptation does not mean that the colours have returned to normal. The colours are still inverted, but the wearer has had to adjust to them to be able to navigate their environment with relative ease. In the case of synaesthesia, seeing a synaesthetic colour does not impair the synaesthete's ability to see veridical colour. An associator's colours held in the mind's eye, do not arise from light reflecting off a surface (Ward, 2012) and so there is no need for them to disappear to accommodate veridical colours. Synaesthetes can see both veridical, and synaesthetic colours, just as well. For example, in Ward, Tsakanikos and Bray's (2006) study synaesthetes were shown musical notes in congruent and incongruent colours and asked to name their synaesthetic colour, ignoring the veridical colour. Although a Stroop effect was observed, naming synaesthetic colours did not interfere with the synaesthetes' normal vision. At no time did they see the written notation as anything other than its veridical colour, black. Notably, Mroczko-Wąsowicz (2015) suggests that there is no real need for synaesthetic colours to adapt away, as they do not carry the same colour information about the objects within the synaesthete's environment as veridical colours (see p. 10). Synaesthetic colours associated with a musical event may instead provide information about a concept, emotion, meaning, property or a previous action.

Synaesthetic Colours Lack Perceptual Presence

If a synaesthete is aware that the colours they see are not veridical, how can their experience be viewed as an interaction with the real world, and how can the potential lack of perceptual presence (of being or existing in the world) be responded to? According to Noë (2001), perceptual presence can be explained by the practical mastery of sensorimotor contingencies. For example, we know what the reverse side of a tomato looks like even though we cannot see it. Our sensory responses, elicited by the tomato, are such that we know how the tomato will behave in a variety of situations.

But how can we account for phenomena such as synaesthesia, in which "raw sensory experience ('qualia') remains but perceptual presence is lacking" (Seth, 2014, p. 98)? Seth's Predictive Perception account of Sensorimotor Contingencies (PPSMC) accounts for normal perception and synaesthesia through the interpretation of *counterfactuals* and *predictive processing*. Generative models predict an outcome based on how sensory inputs would change in various action situations, even if those actions did not actually happen. The richness of these counterfactually encoded sensorimotor contingencies determines the degree of perceptual presence. Counterfactuals might be understood as statements of what would occur if something other than the present state of affairs happened (e.g., the glass would break if I were to drop it on the floor). A predictive model based on counterfactuals takes into account not just the likely cause of a sensory input, but the likely cause of a sensory input based on a repertoire of possible actions (Seth, 2014). Used in everyday science (Beaton, 2013), counterfactuals inform us how an interaction might occur between an agent and its environment in various scenarios. The interaction may, or may not, be carried out, but it could possibly happen in reality. Seth's theory claims that the lack of perceptual presence in synaesthesia is due to poor counterfactuals owing to a smaller, or non-existent, repertoire of likely real world sensory inputs.

This interesting account has received a number of responses (Froese, 2014; Hohwy, 2014; Madary, 2014; Metzinger, 2014; O'Regan & Degenaar, 2014; Rouw & Ridderinkhof, 2014; van Leeuwen, 2014). Madary (2014) compares counterfactual richness in visual and other sensory modalities where, in the latter cases, only some counterfactual information may be required for perceptual presence. For example, there are far more counterfactual possibilities available to us in vision than from sound. We can visually observe an object from many different angles by moving our eyes alone, but fewer options are available to us from an auditory perspective. This might suggest that auditory input need be far less counterfactually rich than visual input to achieve perceptual presence. Madary proposes a modification to Seth's proposal. Instead of the degree of presence depending upon the degree of richness of counterfactual information, "*some* counterfactual information" regarding sensorimotor contingencies is required for perceptual presence (p. 132). However, Madary questions whether even this modification might explain the apparent lack of presence in synaesthetic concurrents asking whether there are any sensorimotor contingencies in synaesthetic concurrents at all? Madary suspects not, but one might argue otherwise.

Froese's (2014) main challenge to Seth's explanation is that counterfactual predictive processing only appears to address perceptual presence and not the appearance of reality, and that it is "the absence of the latter, and not of the former, that is an essential property of synesthetic experience" (p. 126). By not distinguishing sufficiently between the two, Froese argues that Seth does not account for types of synaesthesia that in fact might present some kind of perceptual presence. While it may be more difficult to attribute sensorimotor contingencies to some forms of synaesthesia than others, music-colour synaesthesia is often accompanied by shapes, textures and moving landscapes (Eagleman & Goodale, 2009) similar to the tunnels reported in spatial sequence synaesthesia (Gould et al., 2014). Although "this contextual space appears as distinct from the real world" (Froese, 2014, p. 127) counterfactuals by themselves cannot explain the lack of reality of concurrents, as the experience of counterfactuals may remain surprisingly rich. An enactive account of perception does not attempt to explain veridical experience in terms of internal representation, but by how that experience "is shaped by the real world" (p. 127). Indeed, such phenomenal experience, as reported in music-colour synaesthesia, might offer a perceptual presence in a similar form to those Beaton (2013) attributes to visual memory. Counterfactuals may operate even in imaginary contexts, and it is only the lack of reality that distinguishes synaesthetic colour from veridical. Beaton (2013) claims that both visual memory and visual imagination are themselves types of interaction with the world and gives examples of how we are "poised to act" (p. 306) even when encountering hallucinations of a unicorn, or an illusion of a tomato. Although the unicorn does not and cannot exist in the world, we can gain an understanding, by using counterfactuals, of how we would act if these objects were actually present (Shoemaker, 1994). For example, O'Regan and Degenaar compare a synaesthetic experience to the ability "to vividly imagine things that are absent" suggesting that the relevant cortical activity remains "dangling" (2014, p. 131): in the sense that the cortical activity is not related to current sensorimotor events happening in the environment (Hurley & Noë, 2003). Indeed, Schubotz (2007) provides evidence supporting an explanation as to how a simulation of events, including auditory events, may be realised in our sensory-motor system, even those that we are unable to reproduce ourselves.

According to O'Regan & Degenaar (2014) "sensorimotor theory itself already has the resources to explain synaesthesia" (2014, p. 131). Bodiliness, grabbiness and insubordinateness are able to go beyond the idea of explaining perceptual presence in terms of counterfactual richness, and are equipped to explain all sensory experience. The argument here is that sensorimotor contingencies can be attributed to cases of music-colour synaesthesia. We can imagine our interaction with tunnels and shapes in a moving spatial landscape or the expected feel of certain textures. Resonating with Barsalou's PSS theory, a fragment of the original sensorimotor state might be placed in memory (Jacobson, 2013) explaining why a synaesthetic concurrent may appear disembodied from the original sensorimotor qualities of its inducer. It may appear that a synaesthetic concurrent "seems to have little to do with the SMCs underwriting the perception of the inducer" (Seth, 2014, p. 105), but once the sensorimotor contingencies of experiencing red have been mastered, then red can be re-enacted in an atypical way.

Music-Colour Synaesthesia as a Variant of General Human Cognition

Although never directly referring to an enactive or sensorimotor approach, Sollberger (2013) stresses that the extent to which an individual is able to interact with their environment has an important functional role when characterising a perceptual experience as veridical. Furthermore, if the perceiver is able to distinguish and interact with external objects in the world, then how the experience is embodied, whether as a taste or a coloured sound, is irrelevant (Sollberger, 2009, pp. 151–152). Acknowledging that different types of synaesthesia might require different explanations for their cause, Sollberger argues that not all forms of synaesthesia should be viewed as a non-veridical experience, and that some synaesthesias should be viewed as a "normal variant of human perception" (2013, p. 171). Sollberger refers to music-colour synaesthesia as a form that presents to the perceiver something about their real-world environment. Specifically, synaesthetes with this type of synaesthesia are able to meet the following two conditions:

> They literally attribute the sensory properties of the synesthetic experiences to the *distal* stimulus itself.
>
> They do not take their synesthetic experiences to be *nonveridical*, e.g., illusory or hallucinatory (2013, p. 173).

Sollberger (2013, p. 174) cites experiences from music-colour synaesthetes collected by Cytowic (2002):

> A person who sings with little phrasing or variation in volume has a straight line voice. A baritone has a round shape that I feel. This is so obvious, it's all very logical. I thought everyone felt this way. When people tell me they don't, it's as if they were saying they don't know how to walk or run or breathe. (Cytowic, 2002, p. 28)

> The shapes are not distinct from hearing them—they are part of what hearing is. The vibraphone, the musical instrument, makes a round shape. Each is like a little gold ball falling. That's what the sound *is*; it couldn't possibly be anything else. (Cytowic, 2002, p. 69)

The colours and shapes experienced in music-colour synaesthesia are a fundamental part of the phenomenal character of musical experience, or the "what it is like" (Nagel, 1974, p. 437) to hear music, for synaesthetes (Chalmers, 1996; Shoemaker, 1994). Synaesthetes are often surprised to learn that not everyone experiences music as they do and can not imagine experiencing music in any other way. Perhaps the question we should be asking is not, "what is it like to have synaesthesia" but, "what is it like *not* to have synaesthesia?"

Historically, synaesthesia has been examined as a sensory/perceptual condition distinct from typical cognition. Yet, many different types and sub-categories of synaesthesia exist, and purely neurological explanations remain inconclusive. The similar mental processes employed by synaesthetes and non-synaesthetes (Simner, 2012) suggest that certain synaesthesias can be described in terms of typical cognition. Recent research in general music cognition has moved away from a cognitivist approach, and explains musical experience via embodied and enactive theories (Schiavio et al., 2017; Schiavio et al., 2019). It is possible that certain forms of synaesthesia may arise from purely neurological or genetic factors. However, the direction of research in general music cognition and in synaesthesia point to a sensorimotor approach as a promising next step in explaining the phenomena of synaesthesia associated with music.

Conclusion

I have argued that music-colour synaesthesia should be examined not as a separate and distinct condition, but as a continuation of typical perception and cognition. Research in general music cognition has embraced embodied and enactive accounts that include an active role for the body and its situated power of action. Central to these accounts is how engagement with music might be regarded as an act of doing, in accordance with Gibson's theory of affordances and sensorimotor theory, and how certain attributes of a musical environment attract a subject's attention in the form of their bodiliness, grabbiness and insubordinateness (Peñalba-Acitores, 2011; Krueger, 2009). Yet actively exploring and interacting with a musical environment should not be restricted to physical acts of engagement we more commonly associate with doing, but can extend to imagining and thinking (Beaton, 2013; Myin, 2016). Deep musical understanding can be acquired without formal musical training through attentive everyday listening (Krumhansl, 2010). I have described how a synaesthete can obtain a mastery of sensorimotor contingencies and become *poised to act* (Beaton, 2013), and how the quality of the synaesthetic experience is governed by a level of "dangling cortical activity" (Hurley & Noë, 2003, p. 158). The similarities in the progression of research in synaesthesia and general music cognition show how music-colour synaesthesia might be reconciled with a sensorimotor account and viewed as a "normal variant of human perception" (Sollberger, 2013, p. 171). The phenomenon of shapes, colours and textures experienced on hearing music represents something about the real-world environment for the synaesthete, and is integral to their perception, experience, knowledge, and musical understanding.

These claims present an opportunity for future empirical research. Starting from the hypothesis that synaesthesia associated with music is mediated by concept and context but grounded in sensorimotor action, the commonalities between the mechanisms underlying music-colour synaesthesia and general music cognition, might be tested. A group of non-synaesthete musicians could undertake sufficient training until they were able to produce a series of triads on a keyboard to which they could reliably assign a specific colour. A Stroop-like task would verify that congruent colour-triad trials were produced with faster times and with fewer errors than incongruent colour-triad trials. In a second study, the newly trained group might be compared to a group with pre-existing music-colour synaesthesia. Ward, Tsakanikos, and Bray (2006) suggest that the involvement of the superior parietal lobe (SPL) in sensorimotor transformations is likely to be important in synaesthesia. The application of transcranial magnetic stimulation (TMS) disrupts neural processing in the SPL. Both groups would undertake the Stroop task whilst receiving TMS over the right intraparietal cortex. It is expected that in the non-congruent trials, interference would no longer be observed in either group as the TMS would un-bind the colour-triad associations.

I hope this article will encourage a shift in thinking about music-colour synaesthesia as well as promote investigations of the role of our sensorimotor system and actual as well as imagined interactions with the environment in various forms of synaesthesia.

CHAPTER FIVE – SYNAESTHETIC RESPONSES TO MUSIC IN NON-SYNAESTHETES: FROM MULTIMODALITY TO EMOTION AND SYNAESTHESIA

> *'We perceive the world around us, and ourselves within it, with, through, and because of our living bodies.'*
>
> — A. Seth (2021), *Being you: A new science of consciousness*

Forthcoming: Curwen, C., Timmers, R., & Schiavio, A., *Synaesthetic responses to music in non-synaesthetes: From multimodality to emotion and synaesthesia*. [Manuscript in preparation]. Department of Music, The University of Sheffield.

Chapter Five is presented in a format suitable for submission to a journal.

Statement of Contribution of Joint Authorship

Curwen, C. – (Candidate)

Writing and compilation of manuscript, established methodology and research design, data collection and analysis, preparation of tables and figures.

Timmers, R. – (Principal Supervisor)

Supervised and assisted with research design, conceptualisation of the study, manuscript compilation, interpretation of results, and editing and co-author of manuscript.

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Assisted with conceptualising of the study, editing and co-author of manuscript.

Linkage of Paper to Research Methodology and Development

Building on the findings from the previous studies, Chapter Five presents an empirical investigation of the role of sensorimotor features in music-colour synaesthesia with the objective of demonstrating that certain forms of music-colour synaesthesia may be mediated by concept and context, but grounded in action.

In particular the study tests whether synaesthetic instrumentalists present stronger synaesthetic experiences when listening to music played on an instrument for which they have high sensorimotor knowledge (i.e., an instrument that they are able to play proficiently) compared to one that they do not. Emotional and sensorimotor responses to musical stimuli played on familiar and unfamiliar instruments are tested in both the synaesthete and the control group to see if similar processing mechanisms can be identified.

Abstract

The paper provides an empirical investigation that compares the role of action and multimodality to the role of emotion as an inducer of music-colour synaesthesia and tests the following hypotheses:1) changes to action-related qualities of a musical stimulus affect the resulting synaesthetic experience; 2) a relationship exists between multimodal and emotional responses to music in the general population and with synaesthesia in synaesthetes. 29 synaesthetes and 33 non-synaesthetes were asked to listen to 12 musical excerpts performed on a familiar instrument, an unfamiliar instrument and deadpan on an electronic instrument. They evaluated the applicability of a multimodal, emotional or synaesthetic term to describe their experience of the music. The study demonstrated that the most influential effect on the intensity of listeners' multimodal, emotional or synaesthetic responses was whether or not music is performed by a human, more so than familiarity with a particular instrument. Synaesthetes and non-synaesthetes were shown to share a relationship between the intensity of emotional and multimodal responses, yet it was multimodal/sensorimotor intensity that was

shown to be fundamentally associated with the intensity of the synaesthetic response. Overall, the results highlighted commonalities between the mechanisms underlying music-colour synaesthesia and general music cognition, and demonstrated that some forms of music-colour synaesthesia are grounded in action.

Keywords: synaesthesia, music-colour, multimodal, emotional, action, perception

Music-colour synaesthesia is included under the umbrella term "coloured hearing", or "chromesthesia" (Ward et al., 2006). The four broad categories of musical inducer[5] include compositional style, timbre, tonality, and pitch (tone) (Peacock, 1985). A synaesthetic experience induced from musical stimuli most commonly includes colour but can also extend to multimodal features such shapes, spatial layouts, and textures (Eagleman & Goodale, 2009). Although synaesthesia is often described as being cross-sensory or "a union of the senses" (Cytowic, 2002, p. 325), it has also been shown that in some forms of the condition activation is triggered by concepts (van Leeuwen et al., 2015) which has led to the development of alternative theories such as *ideaesthesia*[6] (Jürgens & Nikolić, 2012; Nikolić, 2009). For example, Dixon and colleagues (2000) found in grapheme synaesthesia[7] that the presentation of 5+2 triggered a synaesthetic response, even in the physical absence of the number "7". Similarly, Ward, Tsakanikos, and Bray (2006) demonstrated that the concept of musical notation was sufficient to elicit a synaesthetic response without necessitating the "sounding out" of the tone. Moreover, mediators such as emotion, action or musical style are intrinsically linked with the perceived qualities of music and as such likely to affect or in fact may play a

[5] "Inducer" – a percept or concept (such as sound, or an idea) that triggers an experience in another modality (such as colour or texture) (Grossenbacher & Lovelace, 2001).
[6] "Ideaesthesia" was introduced by Danko Nikolić as an alternative to the sensory to sensory explanation for synaesthesia. Ideaesthesia describes the phenomenon of a percept-like experience induced by mental activation of a non-sensory inducer such as a concept, or an idea.
[7] Grapheme synaesthesia is the experience of colour associated with written graphemes such as numbers or letters (Simner et al., 2006).

crucial role in shaping the resulting synaesthetic experience (Curwen, 2020a). Such observations have encouraged recent challenges to the assumption that a single mechanism underlies all forms of synaesthesia (Auvray & Deroy, 2015).

Similarities between synaesthetic experience and typical cognition can be observed through common non-synaesthetic cross-modal associations in the general population. Pitch height, lightness, size, and brightness are frequently correlated (Eitan & Timmers, 2010; Marks, 1974, 1987, von Hornbostel, 1925, Ward, Huckstep, & Tsakanikos, 2006). The influence of emotion on music to colour associations may also be an important factor in music-colour synaesthesia (Isbilen & Krumhansl, 2016; Palmer et al., 2016, 2013). Isbilen & Krumhansl (2016) tested musicians, non-musicians, absolute pitch possessors, and music-colour synaesthetes and their results suggest that there may be similarities on a general level in the way that people conceptualise emotions associated with music and those associated with colours, which in some forms of music-colour synaesthesia may also be represented by a corresponding change in colour. Although the phenomenon of synaesthesia is typically considered to be separate from general cognition, the shared mental processes of synaesthetes and non-synaesthetes (Simner, 2012) suggest that there may be certain similarities and differences are a matter of degree, at least in some forms of synaesthesia.

Research in general music cognition has embraced embodied and enactive accounts that highlight the importance of an acting body and its engagement with a material context for music cognition (Krueger, 2009, 2011, 2014; Loaiza, 2016; Maes et al., 2014; Reybrouck, 2014, 2017; Schiavio et al., 2017, 2019; van der Schyff et al., 2018).

For example, Clarke (2005) remarks in his *Ways of Listening* about the general relationship between a player and their instrument:

> The intimate relationship between perception and action in the ways that players listen takes many forms, depending — among other factors . . . on the specific physical characteristics of the instruments in relation to the human body. . . (p. 152).

This relationship is further evidenced in neuroimaging research. Margulis et al. (2009) found that expert flautists showed more motor activity when listening to Bach's Partitas for solo flute than when they were listening to Bach's Partitas for solo violin. The same was true for expert violinists listening to the flute Partitas. Neither group was asked to engage in any motor activity or to play their instrument, but to only passively listen, illustrating the "special experience instrumentalists have with music for their instrument of expertise" (p. 271). Influences of instrumental expertise on multimodal correspondences have also been shown when comparing flautists and pianists and their mapping of pitch in horizontal space (Timmers & Li, 2016).

It is argued here that music-colour synaesthesia may share a similar grounding in action to general music cognition (Curwen, 2020a) which leads to a number of predictions that are examined in this paper. We predict a difference in strength of synaesthetic experience depending on familiarity with playing an instrument and whether or not an instrument is performed by a human. We also predict synaesthetic experience to have a strong relationship with induced drives for action and multimodal experiences. This relates to the expert's sensorimotor knowledge of an instrument (e.g., about sound production or hand shape), but also more generally to multimodal correspondences with sounds, e.g., associations between sound properties and physical properties including size, shape, and energy.

The present study provides an empirical investigation that tests the following hypotheses related to the role of action and multimodality and compares these to the role of emotion as an inducer of synaesthesia:

Changes to action-related qualities of a musical stimulus affect the resulting synaesthetic experience: H1) the intensity of a listener's synaesthetic experience will be influenced by a change of instrument (i.e., a change from their own instrument, to one with which they have no expertise); H2) performance (i.e., whether or not the instrument is played by a human).

A relationship exists between multimodal and emotional responses to music in the general population: H3) there will not be a significant difference between synaesthetes and non-synaesthetes when rating emotional and multimodal factors across different listening conditions; H4) emotional responses will feed into synaesthetic responses; H5) a supposed continuity between multimodal and synaesthetic responses predicts a stronger relationship between these two factors irrespective of emotion.

The main aim and objective of this study is to highlight the commonalities between the mechanisms underlying music-colour synaesthesia and general music cognition, and to demonstrate that some forms of music-colour synaesthesia are grounded in action.

Method

Participants

A total of 62 volunteer instrumentalists (29 music-colour synaesthetes and 33 controls) took part in the study (see Table 1). Participants were recruited via various social media platforms (e.g., Facebook, Twitter), The University of Sheffield volunteers list, and the first author's own contacts. Music-colour synaesthesia was described to participants as spontaneously seeing colours and shapes on hearing music, and the identification of synaesthetes was by self-report and not independently verified. Ethical approval was obtained from the departmental research ethics committee at the University of Sheffield.

Table 1

Summary of Participant Characteristics: Gender, Age, Absolute Pitch, and Level of Musicianship

Characteristic	Synaesthetes	Controls
Male	16	12
Female	13	21
Age	18-65	16-67
AP	7	4
Professional	11	15
Very high level amateur	7	7
Grade 8	6	8
Intermediate	3	3
Beginner	2	-

Note. AP = absolute pitch, Grade 8 = Grade 8 of the Associated Board of the Royal Schools of Music

Materials

SmartSurvey was used to collect demographic information, including whether participants experienced synaesthesia for music (Part 1). Self-reported responses to presented musical excerpts were collected in Part 2 and included questions about perceived emotion, perceived multimodal associations, and for the synaesthetes perceived synaesthetic responses (see Appendices A–D).

Terms used to evaluate each musical excerpt comprised seven pairs of emotional dimensions (Cowen et al., 2020), nine pairs of multimodal dimensions (Eitan & Timmers, 2010), five synaesthetic experience questions derived from observations by Eagleman and Goodale (2009), and four drive towards action questions (Janata et al., 2011) – see Table 2.

Table 2

Overview of Terms Used to Evaluate Each Musical Excerpt Assessing Emotional, Multimodal and Synaesthetic Responses and Drive Towards Action

Emotional	Multimodal	Synaesthetic	Drive towards action
Positive|Negative	Rough|Smooth	Dark/Light shades	Actually sing/hum along?
Excited|Calm	Light|Heavy	Textures	Imagined sing/hum along?
Weak|Strong	Spiky|Round	Movement	Actually move/dance along?
Tense|Relaxed	Bright|Dark	Colour	Imagined move/dance along?
Happy|Sad	Dynamic|Static	Shapes	
Angry|Tender	Thick|Thin		
Pleasant/Unpleasant	Warm/Cold		
	Spatially High/ Spatially Low		

Musical material consisted of four contrasting dances[8] (Prelude, Courante, Sarabande and Gigue) from J.S. Bach's Cello Suite No.1 BWV 1007 in G Major. These were presented on three instruments totalling twelve musical excerpts:

Set 1: four excerpts (one from each dance) played on a familiar instrument (Principal)
Set 2: as in Set 1 but played on an unfamiliar instrument (Unknown)
Set 3: as in Set 1 but produced on an electronic instrument, with no expression (Electronic)

Choice of Material

J.S. Bach's Cello Suite No.1 was chosen because it has been transcribed for a variety of instruments (see Appendix A), which allowed performances of the excerpts to be presented on a familiar instrument (Principal Instrument), and an unfamiliar instrument (Unknown Instrument). Professional recordings, readily available from Spotify and YouTube, were converted to MP3 files and trimmed to be between 30–60 seconds in length from the beginning of the dance and to stop at the end of a phrase. MP3 files of the Electronic Instrument version

[8] The movements of a Baroque Suite are also known as dances.

of the excerpts were created using Muse Score 3.5. A list of all the recordings used are detailed in Appendix A.

Procedure

All participants gave informed consent at the start of the survey, followed by demographic information and details related to their level of musicianship (see Appendix D), the main instrument they played, and whether or not they had synaesthesia. This was followed by a pre-trial of the main section of the study in which an excerpt of the Bach Cello Suite was performed on a Marimba. This was used to assess whether participants were sufficiently accepting towards this music performed on an instrument other than a cello before they continued with the main part of the study (Part 2).

Part 2 of the experiment was tailored to participants' instrumental choices. Those participants whose familiar and unfamiliar instrument did not fit the instrument pairing selections presented were able to request a bespoke Part 2. Participants were asked to use headphones to listen to the twelve excerpts presented in pseudo-randomized order, such that no version of the same excerpt was directly preceded or followed by the other.

After each excerpt, they evaluated the applicability of a term (see Table 2) to describe their experience of the music on a five-point scale representing 1(*not at all*), 2 (*weakly*), 3 (*moderately*), 4 (*strongly*) and 5 (*very strongly*). To limit the number of scales necessary, bidirectional scales were employed with a nine-point scale placing 1 (*not at all*) in the middle. Terms referred to emotional experiences, multimodal experiences and their drive to hum/sing or move along. The synaesthete group was also asked for a rating of the strength of their synaesthetic experience in terms of colour, texture, location and movement (Eagleman & Goodale, 2009, p. 4). No time limit was applied and participants were permitted to play the excerpt multiple times if necessary. The experiment lasted around 30 minutes.

Data Processing and Analysis

The ratings were all treated as unipolar ratings from 1 (*not at all*) to 5 (*very strongly*). This enabled us to calculate the strength of the experience per type of dimension (emotional, multimodal, synaesthetic), irrespective of the individual dimension that was most strongly perceived to be applicable. As the data approximated an interval scale measuring the strength of response per participant, these Likert scale responses were summed and a mean score calculated for the strength of three ratings in the synaesthete group (multimodal, emotional, and strength of synaesthetic response) and two ratings in the control group (multimodal and emotional).

The data analysis was split into two parts — the first looks at the data that is shared between the controls and synaesthetes and analyses emotional and multimodal ratings by these groups. The second examines the responses of the synaesthetes only including all three types of responses: emotion, multimodal and drive towards action and synaesthesia.

Part I – Synaesthetes and Controls

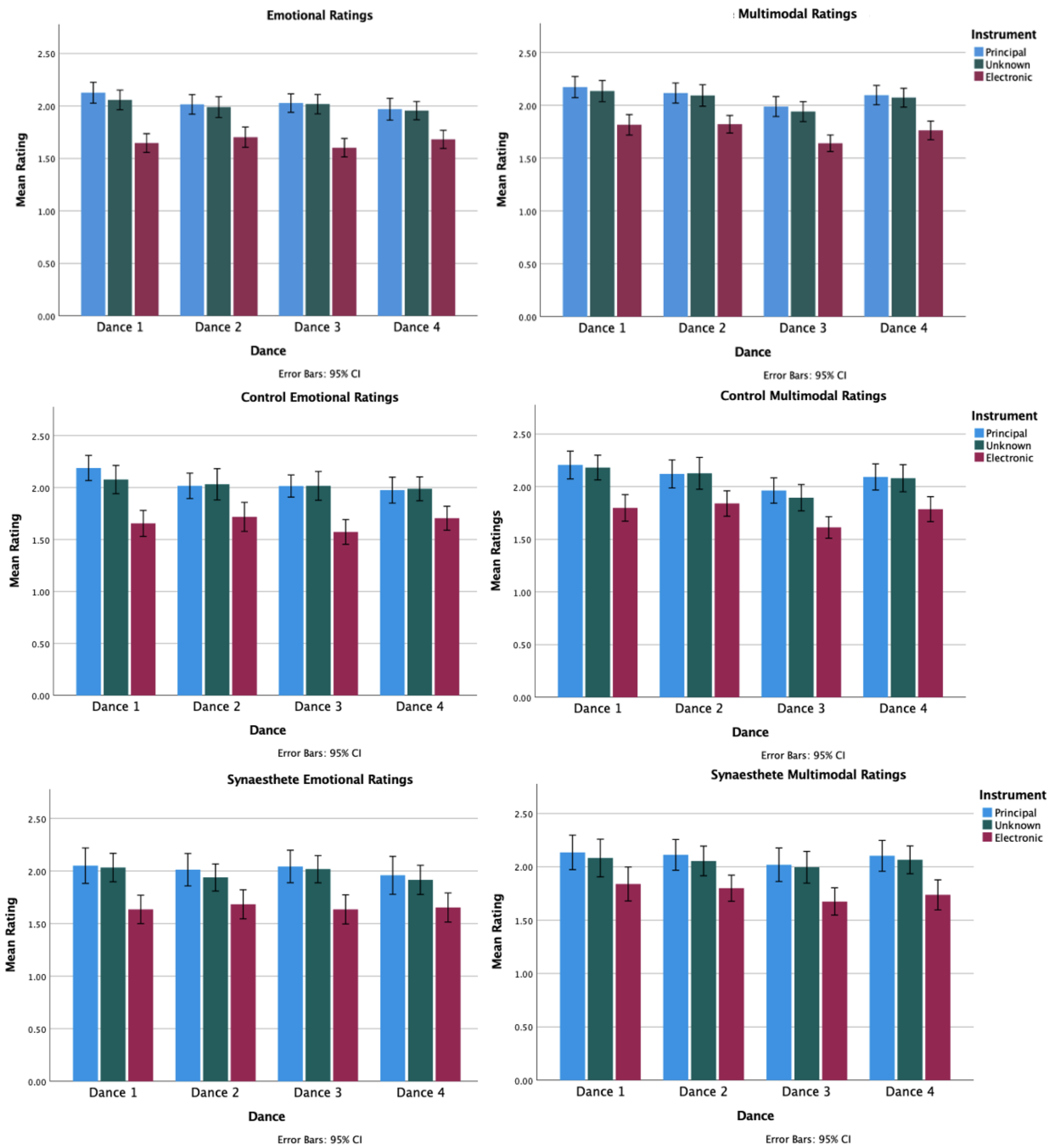
The emotional and multimodal data was subject to four types of analysis. First, a repeated measures ANOVA was performed to test whether a change of instrument would have an effect on the mean strength of the emotional and multimodal ratings across each dance condition. In particular we wanted to examine whether a change from an instrument that participants were very familiar with to one that they did not have any experience playing would significantly diminish the strength of ratings. Moreover, would there be an observable difference in ratings between the synaesthete and the control groups or not, and would a deadpan performance on an electronic instrument still produce emotional and multimodal responses? Second, we carried out a Principal Component Analysis to test for any corroboration in the clustering of, or the relationship between, multimodal and emotional dimensions in synaesthetes and non-synaesthetes as an indication of similarities in terms of their emotional and multisensory processing of music. An independent *t*-test was also performed on component scores to test for any difference in the strength of the ratings in each cluster between the two groups. Last, a Pearson's correlation analysis was performed to see whether a relationship between multimodal and emotional responses existed, and to test for any difference between controls and synaesthetes. It was expected that there would be an observable relationship between emotional and multimodal response in both groups, and that any difference between controls and synaesthetes would not be significant.

Descriptive Statistics

A visual inspection of Figure 1 shows that mean emotional and multimodal ratings in the control group and in the synaesthete group share a similar pattern. Multimodal and emotional responses are weaker across all four dances in the Electronic Instrument condition compared to the Principal and Unknown Instrument conditions, and the difference in ratings between the Principal Instrument condition and the Unknown Instrument condition per dance is minimal. In general, the Principal Instrument condition exhibits similar or slightly higher ratings for emotional and multimodal responses to those in the Unknown Instrument condition, with the exception of the Control group's emotional ratings for Dance 1 (Prelude), for which the difference is greatest. Overall, the apparent similarity in ratings for emotional and multimodal responses in the synaesthete group and in the control group is as expected.

Figure 1

Mean Emotional and Multimodal Ratings in the Control Group and Synaesthete Groups by Instrument and Dance Condition



Note. Principal = Principal Instrument, Unknown = Unknown Instrument, Electronic = Electronic Instrument, Dance 1 = Prelude, Dance 2 = Courante, Dance 3 = Sarabande, Dance 4 = Gigue

Three-Way Mixed Measures ANOVA

A 2 x 3 x 4 mixed measures ANOVA was conducted with the presence of music-colour synaesthesia (Yes, No) as a between-subjects factor, and instrumental conditions (Principal Instrument, Unknown Instrument, Electronic Instrument), Dance (Dance 1, Dance 2, Dance 3, Dance 4) as within-subjects factors to test the effect of a change of instrument across four dance conditions. There were no outliers and the data was normally distributed as assessed by box plot and a Kolmogorov-Smirnov test ($p > .05$), respectively. Mauchly's test indicated that the assumption of sphericity had been violated for Instrument and Multimodal ratings (χ^2 (2) = 8.79, $p = .012$) and for the interaction between Dance and Instrument on Emotional ratings (χ^2 (20) = 32.48, $p = .039$). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .878$) and ($\varepsilon = .852$), respectively. The software package SPSS Statistics V27 was used to carry out the analysis of the data collected.

Table 3

Results for Multimodal and Emotional Response in a Three-Way 2 x 3 x 4 Mixed Measures ANOVA

	Multimodal Response				Emotional Response			
Condition	*df*	*F*	η^2	*p*	*df*	*F*	η^2	*p*
Syn	(1,60)	.183	.003	.670	(1,60)	.480	.008	.491
Syn/Instr	(2,120)	.076	.001	.927	(2,120)	.202	.003	.818
Instr	(2,120)	31.230	**.342**	.001**	(2,120)	57.060	**.487**	.001**
Syn/Dance	(3,180)	2.641	.042	.051	(3,180)	1.420	.023	.239
Dance	(3,180)	20.140	**.251**	.001**	(3,180)	4.636	.072	.004*
Instr/Dance	(6,360)	.251	.004	.940	(6,360)	3.500	.055	.002*
Instr/Dance/Syn	(6,360)	.750	.012	.610	(6,360)	.550	.009	.770

Note. Syn – synaesthesia, Instr – instrument, *df* – degrees of freedom, *F*- F ratio , η^2 - effect size, *p* – significance [** $p < .001$, * $p < .05$]. Larger effect sizes are bolded.

Results

The results are presented in Table 3. The lack of a main effect for the presence of synaesthesia, and a lack of interactions apart from emotional ratings between Instrument and Dance, confirms the visual inspection of Figure 1 and indicates that emotional and multimodal ratings in the Control and Synaesthete groups were generally the same in all conditions.

Instrument Type on Emotional Ratings. The main effect of Instrumental type on Emotional ratings was the result of differences between Principal Instrument ratings and Electronic Instrument ratings, and the Unknown Instrument and Electronic Instrument conditions. Post hoc Bonferroni tests indicated that the Electronic Instrument condition (M = 1.655, SD = .414) had significantly (p = .001) lower Emotional ratings than the Principal Instrumental condition (M = 2.033, SD = .444) and significantly (p = .001) lower ratings than the Unknown Instrument condition (M = 1.996, SD = .422). There was no significant difference between the Principal Instrument condition (M = 2.033, SD = .444) and the Unknown Instrument (M = 1.996, SD = .422) emotional ratings.

Instrument Type on Multimodal Ratings. The main effect of Instrument type on Multimodal ratings was also the result of differences between Principal Instrument ratings and Electronic Instrument ratings, and the Unknown Instrument and the Electronic Instrument conditions. Post hoc Bonferroni tests indicated that the Electronic Instrument condition (M = 1.756, SD = .421) had significantly (p = .001) lower Multimodal ratings than the Principal Instrumental condition (M = 2.08, SD = .464) and significantly (p = .001) lower ratings than the Unknown Instrument condition (M = 2.052, SD = .471). There was no significant difference between the Principal Instrument condition (M = 2.08, SD = .464) and the Unknown Instrument condition (M = 2.052, SD = .471).

Dance Type on Emotional Ratings. The main effect of Dance type on Emotional ratings was the result of the difference in ratings between Dance 1 (Prelude) and Dance 3

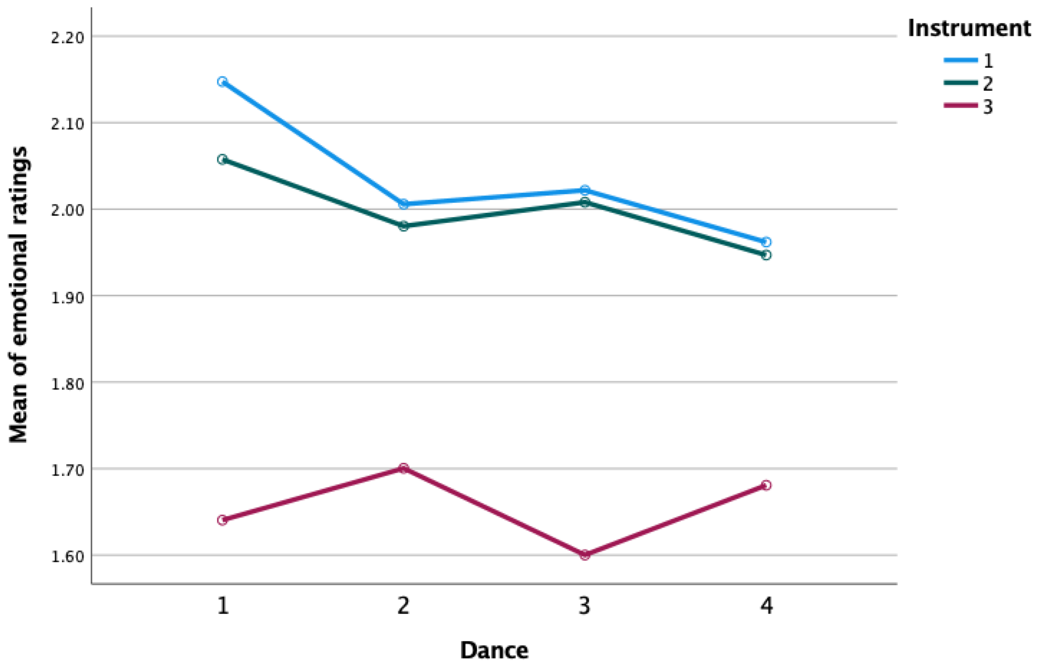
(Sarabande), and Dance 1 (Prelude) and Dance 4 (Gigue). Post hoc Bonferroni tests indicated that Dance 1 (Prelude, *M* = 1.946, *SD* = .449) had significantly (*p* = .001) stronger Emotional ratings than Dance 3 (Sarabande, *M* = 1.877, *SD* = .468) significantly (*p* = .005) stronger Emotional ratings than Dance 4 (Gigue, *M* = 1.861, *SD* = .529).

There was no significant difference between Dance 1 (Prelude, *M* = 1.946, *SD* = .449) and Dance 2 (Courante, *M* = 1.894, *SD* = .0485), Dance 1 (Prelude, *M* = 1.946, *SD* = .449) and Dance 4 (Gigue, *M* = 1.861, *SD* = .529), Dance 2 (Courante, *M* = 1.894, *SD* = .0485) and Dance 3 (Sarabande, *M* = 1.877, *SD* = .468), or Dance 2 (Courante, *M* = 1.894, *SD* = .0485) and Dance 4 (Gigue, *M* = 1.861, *SD* = .529).

Dance Type on Multimodal Ratings. The main effect of Dance type on Multimodal ratings was shown to be the result of the difference in ratings between Dance 1 (Prelude) and Dance 3 (Sarabande), and Dance 2 (Courante) and Dance 3 (Sarabande), and Dance 4 (Gigue) and Dance 3 (Sarabande). Post hoc Bonferroni tests indicated that Dance 3 (Sarabande, *M* = 1.852, *SD* = .445) had significantly (*p* = .001) weaker Multimodal ratings than Dance 1 (Prelude, *M* = 2.032, *SD* = .529) and significantly (*p* = .001) weaker Multimodal ratings than Dance 2 (Courante, *M* = 1.998, *SD* = .272) and significantly (*p* = .001) weaker Multimodal ratings than Dance 4 (Gigue, *M* = 1.969, *SD* = .473). There was no significant difference between Dance 1 (Prelude, *M* = 2.032, *SD* = .529) and Dance 2 (Courante, *M* = 1.998, *SD* = .272), Dance 1 (Prelude, *M* = 2.032, *SD* = .529) and Dance 4 (Gigue), and Dance 2 (Courante, *M* = 1.998, *SD* = .272) and Dance 4 (Gigue, *M* = 1.969, *SD* = .473).

Figure 2

Changes in Emotional Rating as a Function of Instrumental and Dance Type for Both Synaesthetes and Controls



Note. Dance 1 = Prelude, Dance 2 = Courante, Dance 3 = Sarabande, Dance 4 = Gigue, Instrument 1 = Principal Instrument, Instrument 2 = Unknown Instrument, Instrument 3 = Electronic Instrument.

Interaction. The interaction between Instrument and Dance for emotional responses is illustrated in Figure 2. The graph indicates an ordinal interaction between the Principal Instrument condition and the Electronic Instrument condition, and the Unknown Instrument condition and the Electronic Instrument condition. The difference in emotional ratings in the Electronic Instrument condition is greater in the slower excerpts Dance 1 (Prelude) and Dance 3 (Sarabande) than in the more upbeat excerpts, Dance 2 (Courante) and Dance 4 (Gigue). A small difference can also be seen between the Principal Instrument condition and the Unknown Instrument condition in Dance 1 (Prelude) but nothing notable in Dances 2, 3 and 4.

In summary the cause of the main effect of Instrument type on multimodal ratings and emotional ratings was the performance of the excerpts on the Electronic Instrument, played without expression. Although both ratings are slightly higher in the Principal Instrument condition than in the Unknown Instrument condition, the difference is not significant and it is unlikely that familiarity with a particular instrument is the cause of the higher rating. Across the Dance conditions, multimodal ratings were significantly different between the Sarabande and all the other dances (Prelude, Courante and Gigue) reflecting the lower levels of arousal associated with the character of the sombre slower dance. Differences in emotional ratings were mainly observed again between Dance 1 (Prelude) and Dance 3 (Sarabande), and also between Dance 1 (Prelude) and Dance 4 (Gigue), reflecting the higher level of arousal and valence elicited by the lively character and faster tempo of Gigue compared to the sedate Prelude. Difference in valence was not significant between Dance 2 (Courante) and any of the other dances.

Principal Component Analysis

Next a principal component analysis (PCA) was performed to explore the interrelation, or clustering, of multimodal and emotional dimensions. The suitability of the data for PCA was assessed prior to analysis. Inspection of the correlation matrix showed that all but one of the variables had at least one correlation coefficient greater than 0.3. This variable (Actually Singing Along) was removed from the analysis. Kaiser-Meyer-Olkin (KMO) measures for individual variables were then inspected and nine variables were identified that measured less than .500 (Static, Angry, Weak, Thick, Thin, Tender, Imagine Singing Along, Imagine Moving, Actually Moving). These variables were also removed from the analysis. The overall KMO measure was 0.723 with individual KMO measures all greater than 0.6: classifications of ‘mediocre’ to 'middling' according to Kaiser (1974). Bartlett's test of sphericity was statistically significant ($p < .001$), indicating that the data was likely to be factorisable.

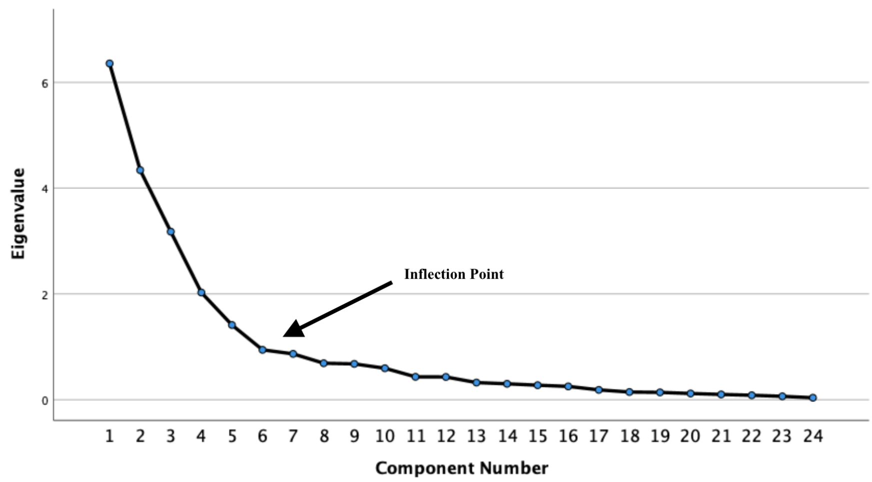
Results

PCA revealed five components that had eigenvalues greater than one and which explained 26.50%, 18.10%, 13.23%, 8.44% and 5.89% of the total variance, respectively.

Visual inspection of the scree plot (see Figure 3) also indicated that six components should be retained (Cattell, 1966).

Figure 3

Scree Plot



However, a four-component solution met the interpretability criterion. As such, four components were retained. The four-component solution explained 66.27% of the total variance and a Varimax orthogonal rotation was employed to aid interpretability. The rotated solution exhibited "simple structure" (Thurstone, 1947). The interpretation of the data was consistent with emotional (valence and arousal) attributes and multimodal characteristics that partially aligned and were independent of the emotional characteristics. Component 1 appears to index positive valence and to a lesser degree high arousal, and had particularly strong loadings on *positive* and *pleasant*, followed by *happy* and *warm*. It loaded negatively with negative valence *sadness*. Component 2 had high loadings on a mixture of emotional and multimodal items indexing low arousal and positive valence: *relaxed*, *smooth*, *calm* and *round*. Component 3 had high loadings primarily on multimodal items, but nevertheless with emotional connotations of negative valence and high arousal: *rough, tense, spiky*, and *cold*. Component 4 related strongly to multimodal characteristics, but not to emotional characteristics. These are commonly observed cross-modal correspondences that index pitch height with brightness and lightness (Gallace & Spence, 2006; Marks, 1987, 2004; Mondloch & Maurer, 2004). *Heavy* and *dark* indicated the reverse and were indeed negatively loaded together with *spatially low* that had a negative cross-loading of over .4. Component loadings and communalities of the rotated solution are presented in Table 4.

Table 4

Rotated Structure Matrix for PCA with Varimax Rotation for a Four Component Solution for Multimodal and Emotional Ratings in Synaesthetes and Controls

	Rotated Components Coefficients				
Item	Component 1	Component 2	Component 3	Component 4	Communalities
Positive	**0.896**	0.171	0.009	0.170	0.665
Pleasant	**0.846**	0.175	-0.084	0.197	0.552
Happy	**0.845**	0.142	-0.011	0.284	0.479
Warm	**0.840**	0.150	-0.101	-0.018	0.730
Dynamic	**0.716**	-0.038	0.231	0.137	0.663
Excited	**0.685**	-0.096	0.473	-0.029	0.615
Unpleasant	**-0.551**	0.374	0.414	0.026	0.862
Negative	**-0.544**	0.449	0.387	-0.133	0.704
Sad	**-0.494**	0.472	0.308	-0.318	0.814
Relaxed	0.147	**0.791**	-0.281	0.058	0.793
Smooth	0.297	**0.749**	-0.167	0.084	0.685
Calm	-0.092	**0.717**	-0.157	-0.073	0.496
Round	0.349	**0.573**	-0.143	-0.158	0.675
Spatially Low	-0.029	**0.553**	0.124	**-0.467**	0.672
Strong	0.433	**0.435**	-0.001	-0.321	0.540
Rough	-0.026	-0.163	**0.792**	-0.056	0.658
Tense	0.155	-0.178	**0.780**	-0.094	0.754
Spiky	-0.019	-0.138	**0.744**	0.135	0.591
Cold	-0.310	0.505	**0.567**	0.017	0.786
Light	0.296	0.198	0.142	**0.779**	0.586
Heavy	0.163	0.308	0.200	**-0.761**	0.739
Bright	0.520	0.057	0.076	**0.711**	0.433
Dark	-0.102	**0.467**	0.189	**-0.641**	0.673
Spatially High	0.256	-0.009	0.345	**0.498**	0.740

Note. Major loadings for each item are bolded

Independent Samples *t*-Tests

The PCA was followed with three independent samples *t*-tests to determine whether there were differences in component scores between synaesthetes and controls for Components 1, 3 and 4 for which scores were normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). A Mann-Whitney test was run for data relating to Component 2.

Results

Table 5 shows that a statistically significant difference was not observed between controls and synaesthetes for any ~~Components~~. The lack of a significant difference is as expected and further supports the similar observable relationship between emotional and multimodal response common to both synaesthete and control groups.

Table 5

Results of Independent t-Tests (Components 1, 3 and 4) and a Mann-Whitney Test (Component 2) for Component Scores Between Synaesthetes and Controls

	Synaesthetes				Controls				
Component	Mean	*SD*	Med	*IQR*	Mean	*SD*	Med	*IQR*	Results
				t-Tests					
1	-0.15	1.09			0.13	0.91			$t = -1.101, p < .275$
3	-0.04	0.92			0.03	1.08			$t = -0.438, p < .663$
4	0.001	0.89			-0.001	1.10			$t = 0.009, p < .993$
				Mann-Whitney Test					
2			-0.13	1.54			-0.04	.907	$U = 512, p < .636$

Note. SD = Standard deviation, IQR = Interquartile range, Med = Median

Pearson's Correlation Analysis

Finally, a correlation analysis was carried out to further test the hypothesis that a relationship exists between multimodal and emotional responses to music in all participants, and to examine the relationship between multimodal dimensions and synaesthetic responses, and emotional dimensions and synaesthetic responses. It was expected that the correlation between multimodal and emotional responses to music in the synaesthete group will not be significantly different to that of non-synaesthetes.

The results of the linear regression analysis of multimodal and emotional ratings are summarised in Table 6 and the correlations are illustrated in Figure 4.

Table 6

Summary of Results of Linear Regression Analysis Across all Dances and all Instruments Between Multimodal Scores and Emotional Scores for Controls and Synaesthetes

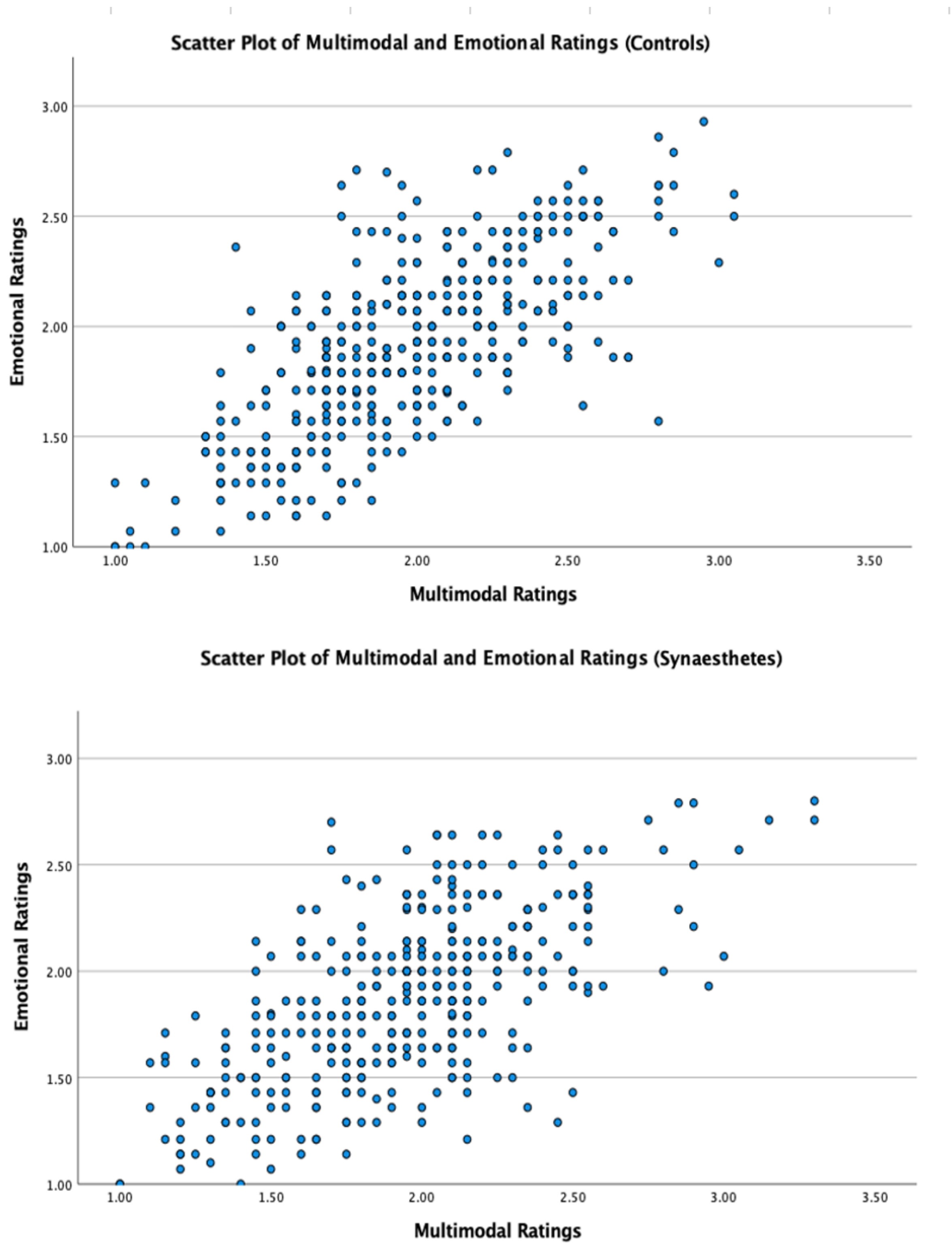
Participants	Model	Adjusted R^2	Slope of Regression
Synaesthetes	F (1,346) = 245.72, $p < .001$**	41.40%	$B = .644$, $t = 15.676$, $p < .001$**
Controls	F (1,394) = 391.16, $p < .001$**	49.70%	$B = .706$, $t = 19.778$, $p < .001$**

Note. [* $p < .05$, ** $p < .001$].

The higher R^2 value in the control group is reflected in the narrower distribution of data points, compared to that of the synaesthete group. 49.7% of the variance in emotional ratings can be predicted by variances in multimodal ratings in the control group, but only 41.4% of the variance in emotional ratings can be predicted by variance in multimodal ratings in the synaesthete group. Notwithstanding the difference in variability, the statistical significance in both groups further highlights the commonalities between the mechanisms that underlie music-colour synaesthesia and typical music cognition.

Figure 4

Scatter Plots Highlighting the Difference in Variability Between Multimodal and Emotional Ratings Between Synaesthetes and Controls



Part II: Synaesthetes

Next the emotional, multimodal and synaesthetic response data in the synaesthete group was subject to three types of analysis to examine the relationship between emotional ratings, multimodal ratings, and the strength of synaesthetic response. First a repeated measures ANOVA was performed to test the mean of the strength of synaesthetic responses across the different listening conditions of Instrument and Dance. Second, a Pearson's correlation analysis was performed to measure the influence of emotional ratings and multimodal ratings on the intensity of synaesthetic response. Third, Pearson's partial correlations were run across all Dance and Instrument conditions to assess the strength and direction of the relationship between multimodal ratings and the strength of synaesthetic experience after adjusting for correlations with emotional ratings, and between emotional ratings and the strength of synaesthetic experience after adjusting for correlations with multimodal ratings. Unfortunately, it was not possible to conduct a PCA as KMO measures for adequate sampling could not be met for the smaller number of participants in the synaesthete group.

Descriptive Statistics

Table 7 shows the means, standard deviations and standard errors for the strength of synaesthetic response, emotional ratings, and multimodal ratings in the synaesthete group across the Dance and Instrument conditions. A visual inspection of Figure 5 shows that mean synaesthetic response ratings exhibit a different pattern to that in Figure 1. Although the Electronic Instrument still displays the lowest ratings overall, the prediction that synaesthetes would report the highest level of intensity for synaesthetic experience in the Principal Instrument condition is not supported here.

Table 7

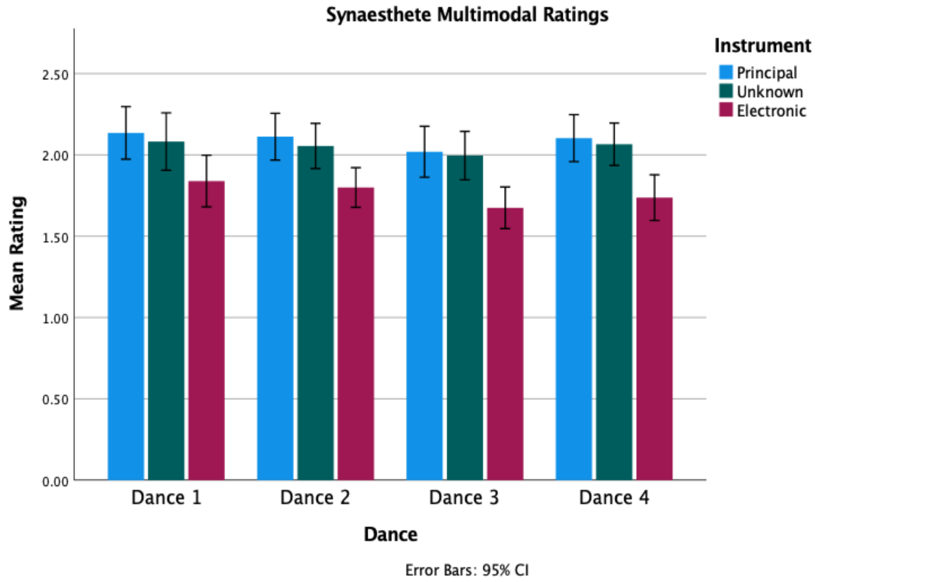
Means, Standard Deviations and Standard Errors for Synaesthetic, Emotional and Multimodal Response in the Synaesthete Group Only

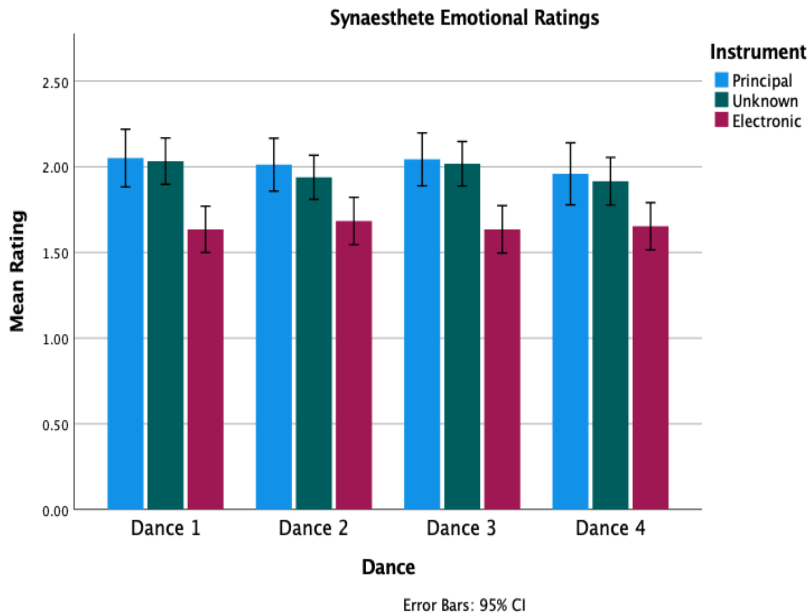
	Synaesthetic			Emotional			Multimodal		
Condition	*M*	*SD*	*SE*	*M*	*SD*	*SE*	*M*	*SD*	*SE*
Principal	3.105	1.693	0.157	2.010	0.720	0.067	2.065	0.706	0.066
Unknown	3.147	1.614	0.150	1.963	0.578	0.054	2.029	0.705	0.065
Electronic	2.547	1.752	0.163	1.647	0.580	0.054	1.753	0.621	0.058
Dance 1	2.991	1.261	0.135	1.910	0.430	0.046	2.002	0.581	0.062
Dance 2	2.977	1.429	0.153	1.865	0.467	0.050	1.966	0.481	0.052
Dance 3	2.839	1.488	0.160	1.886	0.499	0.053	1.880	0.483	0.052
Dance 4	2.924	1.355	0.145	1.833	0.474	0.051	1.948	0.445	0.048

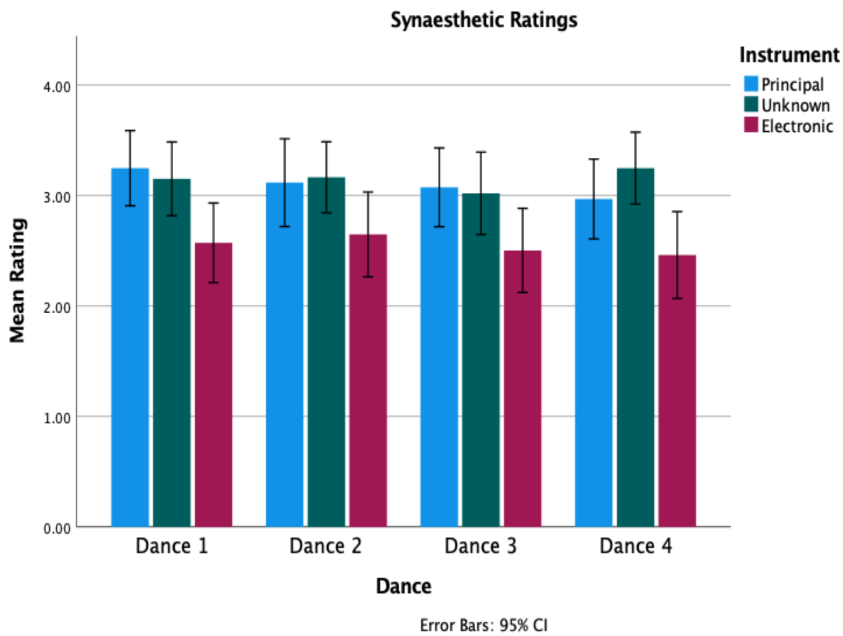
Note. M = Mean rating, *SD* = Standard Deviation, *SE* = Standard Error, Principal = Principal Instrument, Unknown = Unknown Instrument, Electronic = Electronic Instrument, Dance 1 = Prelude, Dance 2 = Courante, Dance 3 = Sarabande, Dance 4 = Gigue

Figure 5

Multimodal Ratings, Emotional Ratings, and Strength of Synaesthetic Experience in the Synaesthete Group by Instrument and Dance Condition







Note. Principal = Principal Instrument, Unknown = Unknown Instrument, Electronic = Electronic Instrument, Dance 1 = Prelude, Dance 2 = Courante, Dance 3 = Sarabande, Dance 4 = Gigue

Two-Way 3 x 4 Repeated Measures ANOVA on Synaesthetic Intensity Rating

To examine this further the mean of the strength of synaesthetic responses was analysed using a two-way 3 x 4 repeated measures ANOVA with Instrument (Principal Instrument, Unknown Instrument, Electronic Instrument) and Dance (Dance 1, Dance 2, Dance 3, Dance 4) as within-subjects factors. There were no outliers and the data was normally distributed as assessed by box plot and a Kolmogorov-Smirnov test ($p > .05$), respectively. Mauchly's test indicated that the assumption of sphericity had been violated for the interactions between Instrument and Dance for Multimodal ratings (χ^2 (2) = 7.55, p = .023), Emotional ratings (χ^2 (2) = 8.44, p = .015) and Synaesthesia (χ^2 (2) = 15.959, p = .001). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .804) and (ε = .788) and (ε = .691), respectively. Mauchly's test also indicated that the assumption of sphericity had been violated for the interaction between Instrument, Dance and Synaesthetic experience (χ^2 (20) = 36.85, p = .013), the interaction between Instrument, Dance and Emotional ratings (χ^2 (20) = 38.40, p = .008) and the interaction between Instrument, Dance and Multimodal ratings (χ^2 (20) = 43.00, p = .002). Therefore, degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity (ε = .686) and (ε = .699) and (ε = .651), respectively. The software package SPSS Statistics V27 was used to carry out the analysis of the data collected.

Results

Table 8 illustrates the results for the strength of synaesthetic response, emotional rating and multimodal rating across all Dance and Instrument conditions. There was no significant main effect of Dance Condition for synaesthetic or emotional responses, but there was a significant main effect for multimodal responses. Yet, post hoc Bonferroni tests did not indicate significant differences between the Dances. The effect size was very weak (η^2 = 0.115) and it is probable that the reduction in sample size as a result of the paired comparisons further reduced the power, and consequently the likelihood of detecting differences between the groups. However, there was a significant main effect of Instrument for synaesthetic responses, emotional ratings and multimodal ratings for which post hoc Bonferroni tests were also performed.

Table 8

Results for the Strength of Synaesthetic Response, Emotional Ratings and Multimodal Ratings in a Two Way 3 x 4 Repeated Measures ANOVA

		Synaesthetic			Emotional			Multimodal		
Condition	*df*	*F*	η^2	*p*	*F*	η^2	*p*	*F*	η^2	*p*
Dance	(3,84)	1.39	.05	.251	1.74	.06	.165	3.63	.11	.016*
Instr	(2,56)	14.92	.45	.001**	19.16	.41	.001**	11.99	.30	.001**
Dance/Instr	(6,168)	0.79	.01	.535	1.28	.41	.280	0.23	.01	.922

Note. Instr– Instrument, *df* – degrees of freedom, *F*- F ratio, η^2 - effect size, *p* – significance [** $p < .001$, * $p < .05$].

Instrument Type on Synaesthetic Responses. The main effect of Instrumental type on synaesthetic responses was shown to be the result of differences between the Electronic Instrument ratings and the Principal and Unknown Instrument conditions. Post hoc Bonferroni tests indicated that the Electronic Instrument condition (*M* = 2.547, *SD* = 1.24) had significantly weaker (*p* = .001) synaesthetic responses than the Principal Instrument condition (*M* = 3.105, *SD* = 1.20) and significantly (*p* = .001) weaker synaesthetic responses than the Unknown Instrument condition (*M* = 3.147, *SD* = 1.14). There was no significant difference between the Principal Instrument condition (*M* = 3.105, *SD* = 1.20) and the Unknown Instrument condition (*M* = 3.147, *SD* = 1.14).

Instrument Type on Emotional Ratings. The main effect of Instrumental type on emotional responses was shown to be the result of differences between the Electronic Instrument ratings and the Principal and Unknown Instrument conditions. Post hoc Bonferroni tests indicated that the Electronic Condition (*M* = 1.647, *SD* = .41) had significantly weaker (*p* = .001) emotional ratings than in the Principal Instrument condition (*M* = 2.01, *SD* = .51) and significantly (*p* = .001) weaker emotional ratings than in the Unknown Instrument condition (*M* = 1.963, *SD* = .41). There was no significant difference between the Principal Instrument condition (*M* = 2.01 , *SD* = .51) and the Unknown Instrument condition (*M* = 1.963, *SD* = .41).

Instrument Type on Multimodal Ratings. The main effect of Instrumental type on multimodal responses was shown to be the result of differences between the Electronic Instrument ratings and the Principal and Unknown Instrument conditions. Post hoc Bonferroni tests indicated that the Electronic Instrument condition ($M = 1.753$, $SD = .44$) had significantly weaker ($p = .002$) multimodal ratings than the Principal Instrument condition ($M = 2.065$, $SD = .50$) and significantly ($p = .001$) weaker multimodal ratings than the Unknown Instrument condition ($M = 2.03$, $SD = .50$). There was no significant difference between the Principal Instrument condition ($M = 2.065$, $SD = .50$) and the Unknown Instrument condition ($M = 2.03$, $SD = .50$).

Dance and Instrument. The lack of a significant interaction between Dance and Instrument for any measure indicated that the strength of synaesthetic responses, emotional ratings or multimodal ratings for each dance was not affected by the change of instrument.

In summary, the main effects of Instrument for emotional, multimodal, and synaesthetic responses were shown to be solely a result of the performance of the excerpts on an Electronic Instrument played without expression. These results support the visual inspection of Figure 4 and indicate that should multimodal or emotional responses drive the strength of synaesthetic responses, the relationship is not likely to be grounded in familiarity with a particular instrument.

Pearson's Correlation Analysis

Next a linear regression analysis was performed to assess whether emotional ratings and multimodal ratings can account for variance in the intensity of synaesthetic responses.

Results

The results of the linear regression analysis are summarised in Table 9. Statistically significant models were revealed for both multimodal and synaesthetic ratings, and emotional and synaesthetic ratings, indicating that the results are unlikely to have arisen by chance. The correlations between multimodal and synaesthetic ratings and emotional and synaesthetic ratings are also shown to be statistically significant across all Dance and Instrument conditions.

Table 9

Correlations Across all Dances and all Instruments Between Multimodal Ratings and Strength of Synaesthetic Experience, and Emotional Ratings and Strength of Synaesthetic Experience

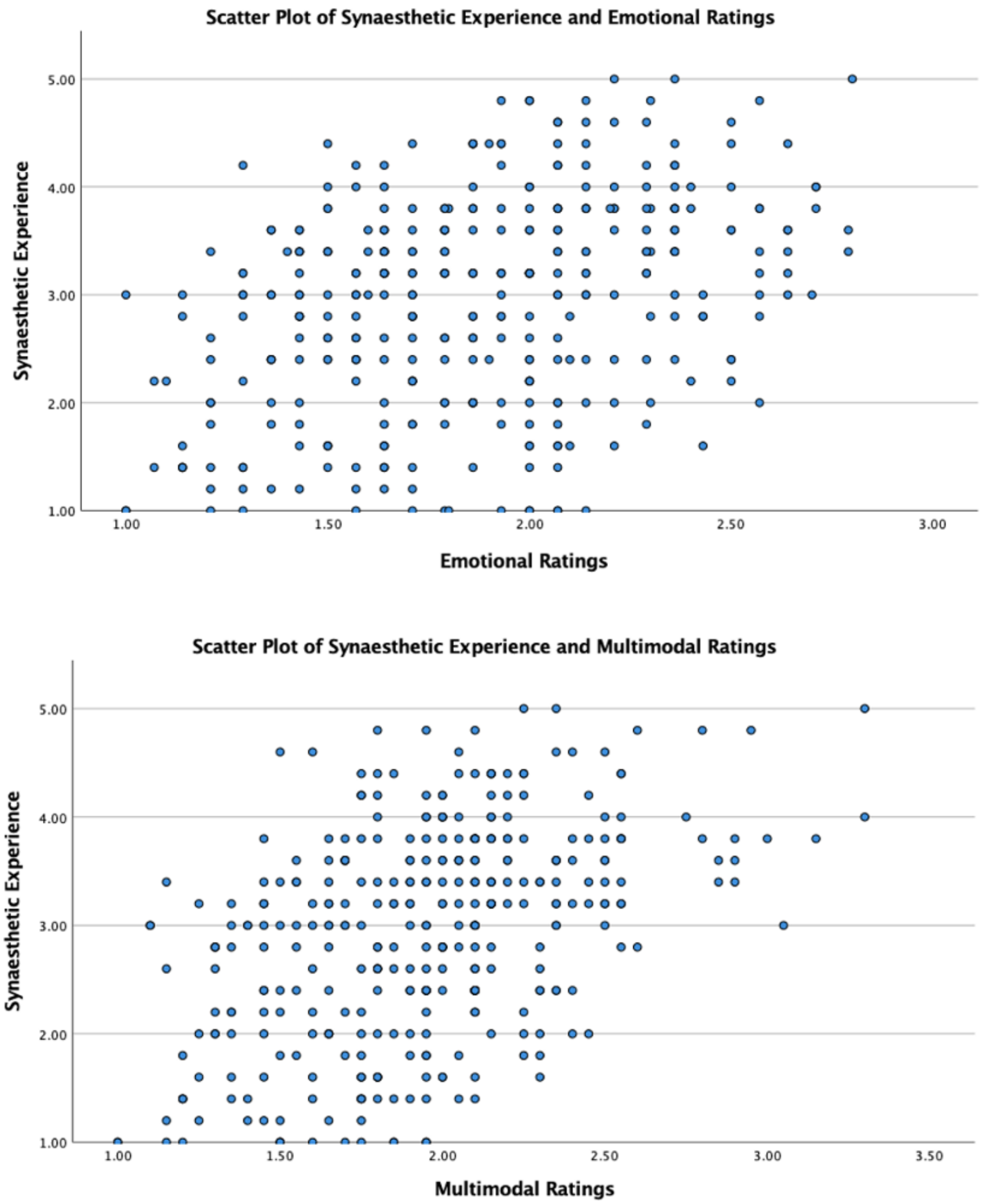
Experience	Model	Adjusted R^2	Slope of Regression
Emotion	F (1,346) = 56.338, p < .001 **	13.8%	B = .374, t = 7.51, p < .001 **
Multimodal	F (1,346) = 94.288, p < .001 **	21.4%	B = .463, t = 9.71, p < .001 **

Note. [* p < .05, ** p < .001]

The graphs in Figure 6 support this, illustrating that emotional and multimodal ratings are individually correlated to the strength of synaesthetic response. Yet the difference in variability between the two groups is also highlighted. The R^2 value of the correlation between multimodal ratings and synaesthetic strength, compared to the R^2 value of emotional ratings and synaesthetic strength is reflected in the narrower distribution of data points. 21.4% of the variance in synaesthetic strength can be predicted by variances in multimodal ratings, but only 13.8% of the variance in synaesthetic strength can be predicted by variance in emotional ratings. This indicates a linear relationship between multimodal ratings and synaesthetic responses, and emotional ratings and synaesthetic responses, but it does not take account of the potential influence multimodal response may have on emotional response, and vice versa.

Figure 6

Scatter Plots Highlighting the Difference in Variability Between Synaesthetic and Emotional Ratings, and Synaesthetic and Multimodal Ratings



Pearson's Partial Correlations

To assess the strength and direction of the relationship between multimodal ratings and synaesthetic experience, and the strength and direction of the relationship between emotional ratings and synaesthetic experience, Pearson's partial correlations were run across all Dance and Instrument conditions.

Results

Relationship Between Multimodal Ratings and Synaesthetic Experience. First, Pearson's partial correlations were run across all Dance and Instrument conditions to assess the relationship between multimodal ratings and the strength of synaesthetic experience after adjusting for correlations with emotional ratings. There was univariate normality, as assessed by Shapiro-Wilk's test ($p > .05$), and there were no univariate or multivariate outliers, as assessed by boxplots and Mahalanobis Distance, respectively. A bivariate Pearson's correlation established that there was a strong, statistically significant linear relationship between multimodal rating and the strength of synaesthetic experience in all conditions as shown in Table 10. A Pearson's partial correlation shows that the strength of this linear relationship was less when controlling for correlations with emotion, but remained significant in all but one condition (Courante, Dance 2, $p < .052$) suggesting that the strength of synaesthetic response has a strong and unique multimodal grounding.

Table 10

Relationship Between the Strength of Multimodal Ratings and Synaesthetic Response after Controlling for Emotional Responses

	Multimodal and Synaesthesia		Controlling for Emotion	
Condition	Zero Order	R^2	First Order PC	R^2
Principal	$r(114) = .463,\ p < .001^{**}$	21.44	$r(113) = .346,\ p < .001^{**}$	11.97
Unknown	$r(114) = .443,\ p < .001^{**}$	19.62	$r(113) = .395,\ p < .001^{**}$	15.60
Electronic	$r(114) = .320,\ p < .001^{**}$	10.24	$r(113) = .193,\ p < .039^{*}$	3.72
Dance 1	$r(85) = .459,\ p < .001^{**}$	21.07	$r(84) = .237,\ p < .028^{*}$	5.62
Dance 2	$r(85) = .404,\ p < .001^{**}$	16.32	$r(84) = .211,\ p < .052$	4.45
Dance 3	$r(85) = .486,\ p < .001^{**}$	23.62	$r(84) = .368,\ p < .001^{**}$	13.54
Dance 4	$r(85) = .492,\ p < .001^{**}$	24.21	$r(84) = .403,\ p < .001^{**}$	16.24

Note. Dance 1 = Prelude, Dance 2 = Courante, Dance 3 = Sarabande, Dance 4 = Gigue. Significant correlations remained between multimodal and synaesthetic response after controlling for emotion in all conditions apart from the Courante [* $p < .05$, ** $p < .001$].

Relationship Between Emotional Ratings and Synaesthetic Experience. Next Pearson's partial correlations were run to assess the relationship between emotional ratings and the strength of synaesthetic experience after adjusting for correlations with multimodal ratings. A bivariate Pearson's correlation established that there was a strong linear relationship between emotional ratings and the strength of synaesthetic experience in all conditions as shown in Table 11. However, a Pearson's partial correlation shows that the strength of this linear relationship was less when multimodal was controlled for, becoming insignificant in all but two conditions (Electronic and Dance 2) suggesting that only a weak relationship exists between the strength of synaesthetic response and emotional ratings.

Table 11

Relationship Between Strength of Emotional Ratings and Synaesthetic Response after Controlling for Multimodal Responses

	Emotion and Synaesthesia		Controlling for Multimodal	
Condition	Zero Order	R^2	First Order PC	R^2
Principal	$r(114) = .544, p < .001$**	29.59	$r(113) = .056, p < .549$	0.31
Unknown	$r(114) = .227, p < .001$**	5.15	$r(113) = -.067, p < .474$	0.45
Electronic	$r(114) = .495, p < .001$**	24.50	$r(113) = .204, p < .029$*	4.16
Dance 1	$r(85) = .442, p < .001$**	19.54	$r(84) = .197, p < .069$	3.88
Dance 2	$r(85) = .408, p < .001$**	16.65	$r(84) = .219, p < .043$*	4.80
Dance 3	$r(85) = .344, p < .001$**	11.83	$r(84) = .034, p < .754$	0.12
Dance 4	$r(85) = .308, p < .004$*	9.49	$r(84) = .006, p < .959$	0.00

Note. Dance 1 = Prelude, Dance 2 = Courante, Dance 3 = Sarabande, Dance 4 = Gigue.

[* $p < .05$, ** $p < .001$].

This shows that multimodal ratings have a significantly stronger influence on the strength of synaesthetic response than emotional ratings. Although ANOVA results did not support the hypothesis that the strength of synaesthetic responses would be related to familiarity with a particular instrument, the result of the partial correlation provides evidence that music-colour synaesthesia may have a grounding in action.

General Discussion and Conclusion

We have argued that music-colour synaesthesia shares a similar grounding in action to typical music cognition and perception and that mediators such as emotion and action may influence the strength of the resulting synaesthetic experience. We asked two groups of musicians (one with music-colour synaesthesia and one without) to rate their emotional and multimodal responses to 12 musical excerpts. The synaesthete group was also invited to rate the strength of their synaesthetic experience. H3 predicted that there would be no significant difference between synaesthetes or non-synaesthetes when rating emotional and multimodal factors across different listening conditions, and H1 predicted that changes to action-related qualities of a musical stimulus would affect the resulting synaesthetic experience (i.e., a change from their own instrument, to one with which they have no expertise). Parallel results and no differences were found between the synaesthete and non-synaesthete groups when rating emotional and multimodal responses to music. Both groups showed a main effect for differences in both multimodal and emotional scores relating to the type of instrument, and this was also observed for synaesthetic responses. It was expected that this would be because participants would score higher ratings for the instrument in which they had the greatest expertise. However, although ratings for the Principal Instrument condition were found to be slightly higher than those for the Unknown Instrument condition, the difference was not significant. H2 predicted that the intensity of a listener's synaesthetic experience would be influenced by performance (i.e., whether or not the instrument is played by a human), and this was also supported for emotional and multimodal responses. Further investigation showed that the cause of the main effect for Instrument was the lower scores for emotional, multimodal and synaesthetic ratings in the Electronic Instrument condition. These results suggest that it is relevant whether music is performed by a human for emotional and multimodal responses to arise, more so than familiarity with a particular instrument. This was also confirmed for synesthetic responses.

Although the type of Dance was not the focus of this study, there were some noticeable effects to emotional and multimodal responses on change of dance. The slow and sombre Sarabande attracted significantly lower multimodal responses than the other dances, and emotional ratings were significantly different between the Prelude and the Sarabande, and the Prelude and the Gigue. However, in the synaesthete group differences in synaesthetic or emotional responses with Dance were not significant, and the weak effect of Dance on multimodal responses was eliminated after performing post hoc Bonferroni tests. No interaction was found between Dance and Instrument, for multimodal, emotional, or synaesthetic responses. Although it could be argued that this might have been because of the reduction in sample size and power as a result of the paired comparisons, the strong main effect of Instrument persisted for synaesthetic, emotional and multimodal responses under the same examination.

The relationship between multimodal and emotional (valence and arousal) attributes in synaesthetes and non-synaesthetes was further explored by Principal Component Analysis. Component 1 indicated positive valence and high arousal with notably strong loadings on *positive* and *pleasant*, and then on *happy* and *warm*. Component 2 indexed low arousal and positive valence with high loadings on a combination of emotional and multimodal items: *relaxed*, *smooth*, *calm* and *round*. Component 3 had particularly high loadings on multimodal items but also indexed emotional attributes of negative valence and high arousal: *rough*, *tense*, *spiky*, *cold*. Component 4 was the only one that did not involve a combination of emotion and multimodal attributes, but indexed the cross-modal correspondences of pitch height with brightness and lightness commonly observed in the general population (Gallace & Spence, 2006; Marks, 1987, 2004; Mondloch & Maurer, 2004). Independent *t*-tests revealed no difference in Component scores between the synaesthete and non-synaesthete groups corroborating the commonalities between the two groups in terms of their emotional and multisensory processing of music.

The graphs of linear regression analyses showed strong correlations between emotional and multimodal ratings in both the synaesthete and non-synaesthete groups, and illustrated that emotional responses fed into synaesthetic responses as predicted in H4. However, a Pearson's partial correlation analysis revealed that the strong correlation between emotional and synaesthetic responses became insignificant in all but two conditions after controlling for multimodal ratings. This was not observed for the relationship between multimodal responses and synaesthetic responses after controlling for emotional responses.

The strength of the relationship remained significant for 6 out of 7 conditions (Dance 2, $p <$ .052). As predicted in H5, continuity between multimodal and synaesthetic responses predicts a stronger relationship between these two factors irrespective of emotion, reinforcing the argument that the strength of synaesthetic responses has a grounding in action.

However, the results of the study were subject to some limitations. The identification of genuine synaesthetes remains difficult and is well documented in synaesthesia research as being complex (Eagleman et al., 2007; Rothen et al., 2013). For the purpose of this study, music-colour synaesthesia was described to participants as “spontaneously seeing colours and shapes on hearing music”. All synaesthetes were self-identifying via an online survey and no formal verification methods were used. However, all potential synaesthetes were asked to provide an example of a piece of music that elicits a very strong synaesthetic experience and one that does not, and a brief description of why (see Appendix D). Part 2 of the survey also invited synaesthetes to describe their experience as well as to rate it, and most offered rich and detailed explanations to support their synaesthesia.

A further limitation is the relatively small sample size. Typically occurring in only 4% of the general population (Cytowic, 2018; Simner et al., 2006) its rarity in occurrence and variability from person to person, challenges the recruitment of a large number of synaesthetes. This meant that it was not possible to carry out a Principal Component Analysis on the synaesthete group alone to observe clustering across emotional, multimodal and synaesthetic responses, as KMO measures for adequate sampling could not be met. However, a sample size of 29 is a comparatively large number in synaesthesia research (e.g., Itoh et al., 2017, 2019; Mattingley et al., 2001; Ward, Tsakanikos & Bray, 2006).

Also, it was not possible to fully control the variety of instrument pairings selected by participants (see Appendix B). Although 14 of the 29 synaesthetes and 7 of the 33 controls chose a pairing between violin and guitar, it is possible that differences in timbre may have had an effect on emotional, multimodal and synaesthetic ratings. This might also have been true with regard to variations in performance by the different artists. However, an attempt was made to mitigate these differences by using a Bach Cello Suite, as each dance shares the same key and has a characteristic sound, tempo and time signature of its own.

Despite these limitations, the importance of this study is that it provides empirical evidence of the role of multimodal/sensorimotor features in music-colour synaesthesia, including in comparison to emotional features, the relationship between action and synaesthesia, and continuations with typical music perception as an embodied phenomenon. The results show that the most influential effect on the intensity of listeners' multimodal, emotional or synaesthetic responses was not whether the music was performed on an instrument the listener was familiar with, but whether the music was generated electronically or performed by a human. This suggests that the lack of expression in a deadpan electronic production fails to communicate both emotional characterisations in the music (see Timmers, 2007) and the multimodal/sensorimotor cues that would point to a grounding in action. Synaesthetes and non-synaesthetes were also shown to share a relationship between the intensity of emotional and multimodal responses suggesting the existence of common mental processes in music-colour synaesthesia and typical music cognition. However, it was found that although action and emotion both mediated the intensity of synaesthetic responses, it was multimodal/sensorimotor intensity that was shown to be fundamentally associated with the intensity of the synaesthetic response and not emotion as previously argued (Isbilen & Krumhansl, 2016; Krumhansl, 2002; Palmer, 2013; 2016). The outcome of the study is that it highlights the commonalities between general music cognition and the possible mechanisms that underlie music-colour synaesthesia, and demonstrates that certain forms of music-colour synaesthesia may be grounded in expressive action.

Finally, although the present study examines the intensity of emotional, multimodal and synaesthetic responses, it could be extended in a number of ways. Further investigations might look at a group of synaesthetes who experience performance specific synaesthesia (e.g., violinists, for whom there is a strong coupling between the actions of the performer and the musical outcome). After controlling for different levels of expertise and familiarity with the instrument, comparisons could be made of how well each of the multimodal dimensions correlate with synaesthetic dimensions on average. Additionally qualitative analyses might be carried out to support the quantitative findings. A selection of participants might be invited to a short post-test interview and a general inductive approach might be used to uncover main themes and categories emerging from the interviews, and from synaesthetes' descriptions of music eliciting strong or no synaesthetic experience. It is argued that this research further encourages us to place synaesthesia in response to music on a continuum with from "synaesthesia" to "typical music cognition" not just in perceptual terms as previously argued (Eitan; 2007; Marks, 1975; 1987) but also in sense of music cognition as an embodied phenomenon.

CHAPTER SIX – SUMMARY, DISCUSSION AND CONCLUSION

"I believe they have got a mauve Hungarian band that plays mauve Hungarian music. See you soon. Goodbye."

O. Wilde (1899) — *An Ideal Husband*

The main focus of this thesis was to develop and test the hypothesis that higher forms of music-colour synaesthesia are mediated by concept and context, but grounded in action. The research aims and objectives were achieved by focussing on three key questions that were investigated through a series of papers: i) is music-colour synaesthesia purely based on sound, or can it also be induced from a musical concept; ii) do certain forms of music-colour synaesthesia have a grounding in sensorimotor action; iii) can music-colour synaesthesia be explained as a continuation of typical perception and cognition and, in particular, of general music cognition?

I have challenged the traditional explanation of a single purely sensory to sensory mechanism underlying music-colour synaesthesia and have argued for a rejection of a distinct set of rules (Simner, 2012; Cohen Kadosh & Terhune, 2012), and a "one for all" explanation for its cause (Auvray & Deroy, 2015). The inconclusive results of the eight colour-hearing neuroimaging studies evaluated in Chapter Two indicated that a purely perceptual explanation may not be directly translatable to all forms of music-colour synaesthesia, nor that it is able to satisfactorily explain the phenomenon. Yet I do not propose an alternative explanation for all forms of synaesthesia nor do I dismiss the existence of synaesthetic experiences arising from purely perceptual stimuli. Instead, I have argued that a single mechanism is not sufficient to explain the synaesthetic experiences that arise on hearing music either from a sensory musical stimulus or from a non-sensory musical concept (Auvray & Deroy, 2015).

Evidence that a synaesthetic response may be induced by a musical concept was provided in Chapter Three. Synaesthesia was elicited from reading written musical key signatures showing that synaesthetic experiences associated with music are not confined to a response on hearing an individual tone or chord (Mills et al., 2003; Ward, Tsakanikos & Bray, 2006). Also evidenced was the possibility that synaesthesia associated with music may be mediated by concept but grounded in sensorimotor action. In Experiment 2 synaesthetes demonstrated interference when naming synaesthetic colours in the Treble and Bass conditions, but not in the Word condition, suggesting that conceptual information carried by the "idea" (Nikolić, 2009) of a musical key notated on the stave rather than written in words might also include sensorimotor information i.e., thoughts about production or hand shape (Curwen, 2020a). Stemming from this, a theoretical framework for a sensorimotor explanation of music-colour synaesthesia was set out in Chapter Four detailing an active role for the body and its situated power of action. The similarities between recent embodied and enactive accounts of typical music cognition and perception and synaesthesia research were highlighted, and it was argued that music-colour synaesthesia might be reconciled with a sensorimotor account and viewed as a "normal variant of human perception" (Sollberger, 2013, p. 171). The colours, shapes, textures and moving landscapes experienced by the synaesthete are phenomenally different to typical music cognition, but the lived-experience of synaesthesia on hearing music is integral to the synaesthete's perception, experience, knowledge, and musical understanding.

Chapter Five aimed to investigate the relationships between emotion, action, and synaesthesia and continuations with non-synaesthetic perception. Synaesthetes and non-synaesthetes were shown to share a relationship between the intensity of emotional and multimodal responses and these intensities were shown to relate to the synaesthetic experience of synaesthetes, supporting the existence of common mental processes in music-colour synaesthesia and typical music cognition. While both emotion and action correlated with the strength of the synaesthetic experience multimodal responses had a significantly stronger influence than emotional ratings aligning to the hypothesis that the intensity of synaesthetic responses are grounded in multimodal experiences. A difference in the intensity of responses was expected to be observed between performances on a familiar instrument and on an unfamiliar instrument. Yet the most influential effect on listeners' multimodal, emotional or synaesthetic responses was not whether the music was performed on an instrument the listener was familiar with, but whether the music was generated electronically or performed by a human. This implied that the electronic performance failed to communicate emotional nuances or multimodal/sensorimotor cues implicating a lack of grounding in action.

Challenges in Synaesthesia Research

Consistency

The challenges facing synaesthesia research were discussed in Chapter Two and highlighted in Chapters Three and Five. Consistency over time remains the primary measure for synaesthesia and difficulties in verifying the condition are well documented (Eagleman et al., 2007; Rothen et al., 2013). The studies in Chapter Two required a specific form of synaesthesia elicited from the concept of a written musical key signature, and the presence of synaesthesia was tested independently. Experiment 1 in Chapter Two illustrated how the identification of true synaesthetes from amongst the 12 self-reporting participants was not clear-cut, and that an indication of high consistency in colour selection was not an absolute means of verification (Cohen Kadosh & Terhune, 2012; Simner, 2012). Synaesthetes were not always able to consistently match a single colour to their synaesthetic experience, particularly if that experience could only be described using a unique combination of colours, shapes and textures. As a result, some of the consistency scores were lower than expected and the colour description open to experimenter interpretation. Further complications arose from the not entirely random colour selections made by controls. Although scores were lower and not as precise as in the synaesthete group, non-synaesthetes demonstrated a "higher than chance" level of consistency in colour choices. The blurring of the distinction between synaesthetes and non-synaesthetic people highlights shared mental processes when making associations between colours and music. Notwithstanding that I have argued that music-colour synaesthesia might be better understood as a continuation of typical music cognition, this evidence shows that consistency should be better considered as an "associated characteristic" of synaesthesia rather than as a definitive measure (Ward & Mattingley, 2006). Although the colour choices made by controls were generally more consistent than expected they did not match the very precise selections made by the synaesthete group. Such variability in colour choices meant that the Stroop tests in Chapter Two were not suitable for the control group, and testing for a comparative strength of synaesthetic response in the group of non-synaesthetes in Chapter Five was also not feasible. There was also a certain level of variability within the synaesthete group as synaesthesia is a complex and highly individual response. For example – and setting the distinction between associators and projectors aside – not all the synaesthetes in Chapter Two experienced synaesthesia for all nine keys, and some experienced colours they were unable to describe. Such differences challenge the ability to capture the authenticity of the synaesthetic experience through purely empirical experimentation. An alternative or complementary method to consistency testing for verifying the existence of synaesthesia might be that used in Chapter Five. The study was carried out online and synaesthetes were identified by only self-report from written descriptions of their experience. However, this was only feasible as the type of synaesthetic response was not specific to the study. We did not recruit synaesthetes whose responses related specifically to playing their own instrument as we were interested in investigating this as a general feature of music-colour synaesthesia. Nevertheless, it will be of interest for future research to examine performance-related synaesthesia as a potential specific form of music synaesthesia. The reliance on consistency as the primary measure for the verification of the presence of synaesthesia means that some cases of synaesthesia are overlooked and others misdiagnosed. There is certainly scope for a broader spectrum of characteristics to be taken into consideration in future diagnostics.

Sample Size

Chapters Three and Five also highlighted the difficulties in recruiting a sufficient number of synaesthetic participants. Synaesthesia in its various forms is thought to occur in only 4% of the population (Cytowic, 2018; Simner et al., 2006). Testing synaesthetes whose specific experience is elicited from the concept of a written musical key signature narrows the sample population size further. Consequently, sample sizes in synaesthesia research are typically low. Nevertheless, the results from the sample of nine synaesthetes in Chapter Three were significant and effect sizes were large, and the pool of 29 synaesthetes in Chapter 5 was greater than average (e.g., Itoh et al., 2017, 2019; Mattingley et al., 2001; Ward, Tsakanikos & Bray, 2006).

Novelty

The current research project aimed to address several limitations in the literature associated with synaesthesia and music including whether a musical concept could elicit a synaesthetic response; whether the strength of a synaesthetic response could be influenced by multimodal (sensorimotor) or emotional factors; and whether music-colour synaesthesia could be viewed as a continuation of typical music cognition rather than as a separate and distinct condition. Historically the focus of research in music-colour synaesthesia has rested with tone-colour synaesthesia and other forms have received comparatively little attention, particularly the understanding of synaesthesia that is elicited from a conceptual or performative inducer rather than from a purely perceptual stimulus. The project provided the first empirical evidence for the existence of a form of synaesthesia that arises from the concept of written musical key signatures, for the role of multimodal/sensorimotor features in music-colour synaesthesia and the relationship between action and synaesthesia, and for continuations with typical music cognition with a particular focus on its embodied and enactive nature.

Conclusion

The similarities with cross-modal correspondences in non-synaesthetes and music-colour synaesthesia offer an opportunity to gain a better understanding of the processes of general cognition and consciousness from person to person. It is hoped that this research may promote investigations in various forms of synaesthesia that will include the role of our sensorimotor system and actual as well as imagined interactions with the environment. Future researchers may be encouraged to place synaesthesia in response to music on a continuum from "synaesthesia" to "typical music cognition", rather than assuming it to be special, separate and unconnected. Synaesthesia relates to individual ways of understanding music that is not necessarily more radically different than other variations between individuals. Individual engagement with music in specific contexts shapes the way music is perceived and known, of which synaesthesia is a part.

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APPENDICES

Appendix A – List of Performances Used to Create Stimuli

Instrument	Artist	Link to Source
Vc	Mischa Maisky	https://tinyurl.com/2mc8epxy
Vl	Rachel Podger	https://tinyurl.com/3nz3sych
Sax	Andrew Richard Dahlke	https://tinyurl.com/2p9frwkh
Va	Lillian Fuchs	https://tinyurl.com/2p87pbjb
Db	Jeff Bradetich	https://www.youtube.com/channel/UCdFEFZ6HZ5ZD_SibGDAJlGg
Cl	Daniel Silver	https://www.youtube.com/watch?v=3DIIlr19VMw&t=11s
Cl	Peter Koetsveld	https://tinyurl.com/24nvud82
Cl	Wilfried Berk	https://youtu.be/CVkKiJ_D8LQ
Pn	Eleanor Bindman	https://tinyurl.com/3stpyf8h
Ob	Gonzalo X Ruiz	https://tinyurl.com/bp9eekz6
Bcl	James T Shields	https://youtu.be/nmA1biVyow4 https://youtu.be/dSI9xmR2gOY
Fl	Sabine Kittle	https://tinyurl.com/3d6npeha
Mar	Jean Geoffrey	https://tinyurl.com/ycknj43j
Bn	William Ludwig	https://tinyurl.com/2p93wrmr
Trpt	David Cooper	https://tinyurl.com/bdh7szm4
Hn	Jacek Muzyk	https://tinyurl.com/2p888brt
Gui	Jeffrey McFadden	https://tinyurl.com/4wt5hbhh
Tbn	Denson Paul Pollard	https://tinyurl.com/3vrzamhu
Hp	Victoria Drake	https://tinyurl.com/yyy22sue
Rec	Bolette Roed	https://tinyurl.com/mur2pha8
Bgtr	Ariane Cap	https://tinyurl.com/mr4636vu

Note. Pn = Piano, Gui = Guitar, Mar = Marimba, Sax = Saxophone, Vc = Cello, Bn = Bassoon, Cl = Clarinet, Vn = Violin, Fl = Flute, Bcl = Bass Clarinet, Va = Viola, Hn = French Horn, Hp = Harp, Tpt = Trumpet, Bgtr = Bass Guitar, Tbn = Trombone, Rec = Recorder, Db = Double Bass, Ob = Oboe

Appendix B – Instrumental Pairings Selected by Participants

Instrumental Pairing	Synaesthetes	Controls
Guitar & Piano	14	7
Violin & Flute	1	4
Oboe & Trombone	-	2
Cello & Bass Clarinet	2	1
Sax & Marimba	1	2
Trumpet & Double Bass	-	3
Viola & Bassoon	1	1
Clarinet & Piano	2	-
Bassoon & Piano	1	1
Sax & Piano	2	-
Bass Guitar & Clarinet	-	1
Bassoon & Guitar	1	-
Clarinet & French Horn	1	-
Flute & Viola	-	1
Guitar & Trumpet	-	1
Guitar & Clarinet	-	1
Guitar & Flute	-	1
Guitar & Trombone	-	1
Guitar & Violin	1	1
Harp & Clarinet	-	1
Harp & Trumpet	-	1
Harp & Bassoon	-	1
Piano & Viola	1	-
Piano & Cello	1	-
Recorder & Oboe	-	1

Appendix C – Participant Information and Consent Form in the SmartSurvey Form

Participant Information

You are being invited to take part in the above research project. Before you decide whether, or not, you wish to participate in this project, it is important for you to understand why the research is being carried out, and what it will involve. Please read the following information carefully and ask me if there is anything that you would like me to clarify or explain.

This research project is designed to explore how music-colour synaesthesia is mediated by concept and context but is grounded in action, and to test the commonalities between the mechanisms that underlie music-colour synaesthesia and general music cognition

Participation is entirely voluntary, and you are not obliged to be involved. If you do participate, you can withdraw at any time without giving a reason. If you do choose to withdraw, any information that you have supplied will remain confidential, and responses from partial completion of the study will not be included in the data pool.

The results from your participation will contribute towards a longer-term study.

All the information collected from you, and about you during this research, will be strictly confidential. This data shall not be processed by anyone but the experimenter and the supervisor. The results of this research may be used for subsequent research and research outputs from this project may be made available to audiences outside the University, for example, via websites, conference presentations, journal articles. However, all data collected will be anonymised using a coding system so that you will not be identifiable in any reports or publications.

Information Related to Ethics and Data Management:

According to data protection legislation, we are required to inform you that the legal basis we are applying in order to process your personal data is that 'processing is necessary for the performance of a task carried out in the public interest' (Article 6(1)(e)). Further information can be found in the University's Privacy Notice https://www.sheffield.ac.uk/govern/data-protection/privacy/general

The University of Sheffield will act as the Data Controller for this study. This means that the University is responsible for looking after your information and using it properly. This study has received ethical approval from the Department of Music, and is conducted in accordance with the research ethics guidelines of The University of Sheffield.

The final research project will be available to view, once it has been submitted and reviewed, in the office of the University of Sheffield Music Department, which can be found at Jessop Building, 34 Leavygreave Road, Sheffield, S3 7RD.

If you have a complaint about any part of the experiment, please notify either of the supervisors.

Complaints will be recorded and addressed immediately.

Caroline Curwen (Lead researcher) - ccurwen1@sheffield.ac.uk
Dr Renee Timmers (Supervisor) - r.timmers@sheffield.ac.uk
Dr Andrea Schiavio (Supervisor) – andrea.schiavio@gmail.com

Part One

Part One of the experiment comprises the collection of some general demographics via this form. You will also be asked about your musical ability, and whether you experience any form of music-colour synaesthesia. Those who do experience synaesthesia for music will be asked to provide an example of a piece of music that elicits a very strong synaesthetic experience and one that does not, and a brief description of why. This part of the study should take approximately 10 mins.

Part Two

Part Two is an online experiment. You may be invited to participate following the completion of Part One.

You will be invited to use headphones to listen to twelve short musical excerpts. Each excerpt will be followed by a list of sensorimotor and emotional dimensions and you will be asked to select and rate the most applicable poles via a radial button, and to rate your liking of the excerpt. Those who experience synaesthesia for music will also be asked to rate the intensity of their synaesthetic experience. Excerpts can be played as many times as necessary. There will be no time limit and you will also have the option to save your progress and continue later. The online experiment should take approximately 30 minutes. Following the experiment, you may be invited to participate in a short post-test interview.

Participant Consent

If you do decide to take part in this research, please give your consent by acknowledging that:

I have read and understood the project information sheet or the project has been fully explained to me (if you feel that it has not been fully explained to you, please email Caroline Curwen at ccurwen1@sheffield.ac.uk who will go through anything that is unclear)

- I have been given the opportunity to ask questions about the project.
- I agree to take part in the short post-test interview, which will be audio-recorded
- I understand that my taking part is voluntary and that I can withdraw from the study at any time.
- I do not have to give any reasons for why I no longer want to take part and there will be no adverse consequences if I choose to withdraw.

How my information will be used during and after the project:

- I understand my personal details such as name, phone number, and email address etc. are used for contact and scheduling purposes only, and will not be revealed to people outside the project.
- I agree for audio recordings to be made of the interview.
- I understand that these recordings will not be revealed to people outside the project.
- I understand and agree that authorised researchers will have access to the data I provide.
- I understand and agree that quotes from my anonymised transcriptions of the interviews may be used in publications, reports, web pages, and other research outputs
- So that the information you provide can be used legally by the researchers I agree to assign the copyright I hold in any materials generated as part of this project to The University of Sheffield.

I consent to participate in this online study of Music-Colour Synaesthesia and Sensorimotor Features:

I Consent: Yes/No

Appendix D – Questions in Part One of the SmartSurvey Form

All data will be anonymised, but so that an identification number can be assigned to your responses please provide the following:

Last 2 letters of your surname
Month of you birth, i.e., 05
First letter of the town where you were born
Please provide your email address.
What is your age?
What is your nationality?
What is your gender?

Please rate the level of expertise you have acquired on your principal instrument.

Beginner Intermediate Grade 8 or equivalent Very high level amateur Professional

Do you have perfect pitch?

Yes
No
Don't know

Please choose your principal instrument

Cello	Bassoon	Other (please specify):
Violin	Oboe	
Double Bass	Piano	
Guitar	Marimba	
Clarinet	Trumpet	
Bass Clarinet	Trombone	
Flute	French horn	
Saxophone	Viola	

Do you enjoy listening to electronic music?

I have no experience with electronic music
No
Some types
Yes

Please play this excerpt and select one of the following options that best describes your response to it:

I love this performance on the Marimba
I am OK with listening to Bach being performed on the Marimba
I cannot stand listening to Bach being performed on the Marimba or any instrument other than the one it was originally written for

Do you ever experience colours on hearing music?

Yes
No

Please indicate all the stimuli that might lead you to experience colours on hearing music:

Musical keys - sounded
Musical keys - association with (not necessarily sounded)
Musical tones
Different instruments/timbre
Compositional style
Different composers
Musical notation
Other (please specify):

How would you describe your experience of synaesthetic colour?

Being in my mind's eye, or of 'knowing' the colour
Projected outside the body into external space

Please provide an example of a piece of music that elicits a very strong synaesthetic experience and one that does not, and a brief description of why.

Do you experience any other form of synaesthesia?
Yes
No

Select any of the following that are experiences you are familiar with:

Colours for letters and/or numbers
Colours for days of the week or months
Auditory-tactile synaesthesia - certain sounds induce sensations in parts of the body
Spatial sequence synaesthesia - numerical sequences seen as points in space
Mirror-touch synaesthesia - feeling same sensation as other persons feels
Lexical-Gustatory Synaesthesia - different kinds of tastes when hear certain words or phonemes
Other (please specify):

So that you can be correctly directed to Part Two of the study, please select the pairing of instruments that includes your principal instrument. If you have played the second instrument before, please enter an alternative instrument from the list that you have never played in the 'Other' box.

Cello and Bass clarinet
Violin and Flute
Viola and Bassoon
Double Bass and Trumpet
French Horn and Clarinet
Oboe and Trombone
Saxophone and Marimba
Piano and Guitar
Other (please specify)

Appendix E – Questions in Part Two of the SmartSurvey Form

Please play the above excerpt and answer the following questions:

Please indicate the strength of your motivation to move and vocalise to the music.

	Not at all	Weakly	Moderately	Strongly	Very Strongly
Imagined sing/hum along?					
Imagined move/dance along?					
Actually move/dance along?					
Actually sing/hum along?					

Please rate the applicability and intensity of the following terms (Left column A and Right column B) that best describe your listening experience.

	Very Strong A	Strong A	Moderate A	Weak A	N/A	Weak B	Moderate B	Strong B	Very Strong B	
Spiky										Round
Happy										Sad
Positive										Negative
Pleasant										Unpleasant
Spatially High										Spatially Low
Rough										Smooth
Thick										Thin
Excited										Calm
Bright										Dark
Dynamic										Static
Light										Heavy
Tense										Relaxed
Weak										Strong
Angry										Tender
Warm										Cold

Please rate the extent and the intensity of your synaesthetic experience:

	Not at all	Weakly	Moderately	Strongly	Very Strongly
Dark/light shades					
Movement					
Shapes					
Colours					
Textures					

Please detail any other experience: