Hearing the York Mystery Plays:

Acoustics, Staging and Performance

2 Volumes

Volume 1: Thesis

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Abstract

The study of medieval acoustics has been centred on places of worship, leaving aside sites used for secular drama. This thesis explores the importance of integrating medieval drama into the historiography of the acoustics of performances spaces through the study of the *York Mystery Plays*.

The *York Mystery Plays* were performed regularly from the late fourteenth century up to 1569 and have been the subject of numerous research studies. However, the consideration of the acoustics of the performance spaces as an essential means of gaining a further understanding of the staging and performance of the plays has, for the most part, been absent from previous studies.

This thesis uses virtual acoustics to study Stonegate, one of the performance sites used in medieval times. To apply virtual acoustics to the study of the plays acoustic measurements of Stonegate are conducted and analysed through room acoustic parameters. A virtual model of the same space is then simulated and calibrated using the on-site measurements as a reference and its accuracy is also checked through listening tests. The virtual model of modern Stonegate is then modified in order to create different simulations of the site in the sixteenth century, which are then used to test different staging hypotheses developed by early drama scholars.

The acoustics of Stonegate are shown to have been suitable for the spoken extracts of the plays, due to its low reverberation time and high clarity. However, these characteristics are more challenging for the performance of music. Nevertheless, research has shown that the resulting spatial impression is comparable to that associated with music performances in concert halls. Furthermore, future research of the acoustics of other medieval sites in York may help to further the understanding of how the performances spaces and the plays were experienced.

Contents

List of Tables

List of Figures

List of Maps

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Declaration

I declare that this thesis is my own work and that all source material has been referenced.

I also declare that parts of this research have formed part of conference presentations, proceedings, journal papers and public engagement talks. Although some of these publications have second or third authors this thesis only uses those sections that are my own. A full list is included below:

- López, M., 'The Use of Virtual Acoustics for the study of the York Mystery Plays' in the *2nd Annual Postgraduate Symposium*, Department of Theatre, Film and Television, University of York, York, UK, 27 May 2011 [Presentation].

- López, M., Pauletto, S. and Kearney, G., 'The application of virtual acoustics in the reconstruction of medieval Stonegate' (Poster) in *ISPRS Working Group V/2 Conference, Cultural Heritage data acquisition and processing*, York , UK, 17-19 August 2011.

- López, M., Pauletto, S. and Kearney, G., 'Virtual Acoustics and the study of music in the York Cycle' in *Conference of Interdisciplinary Musicology*, Glasgow, UK, 30 August-3 September 2011.

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- 'Virtual Acoustics and the York Mystery Plays' in *York 10x10x10: The History and Future of the City*, York, UK, 1 November 2011 [Presentation].

- López, M. 'The Application of Virtual Acoustics to the reconstruction of Medieval Theatre Performance Spaces' in *Sensed*, *The Remote Sensing and Photogrammetry Society Newsletter*, No. 43, January 2012, pp. 19-21.

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- López, M., Pauletto, S. and Kearney, G. 'The Application of Impulse Response Measurement Techniques to the Study of the Acoustics of *Stonegate*, a Performance Space Used in Medieval English Drama' in *Acta Acustica united with Acustica*, Vol. 99, No. 1, January/February 2013, pp. 98-109.

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- López, M. and Pauletto, S., 'The *York Mystery Plays*: Acoustics and Staging in *Stonegate*' in the *14th Triennial Colloquium of the Société Internationale pour l'étude du Théâtre Médiéval*, Poznan, Poland, 22-27 July 2013.

Chapter 1: Introduction

1.1 Introduction

The present chapter introduces the theoretical framework of this research project by exploring the importance of establishing links between drama and music and their performance spaces throughout history. The omission of medieval drama from studies on acoustics is discussed and the importance of such a study is further determined by exploring medieval notions of sound and hearing. The research questions are presented and related to the thesis structure. The contributions to knowledge as well as terminology are also discussed.

1.2 Hearing, Listening and the Acoustics of Performance Spaces

Central to this thesis is the idea that the study of the acoustics of historical performance spaces, used either for drama, music or a combination of both, should not be isolated from considerations on the historical and cultural context that gave rise to the items performed as well as the performance spaces themselves. An understanding of historical and cultural aspects allows the acoustical data collected and analysed by engineers to acquire a deeper meaning and can open up new avenues for the interpretation of results by reflecting on what the acoustic characteristics of the performance spaces in question might have meant to contemporary performers and audiences.

Such a historical and cultural approach can focus on two main aspects. Firstly, it should consider the relationship between the performance space and the dramatic or musical items that were performed in it. An analysis with this focus should contemplate how the space affected the performance and reception of the dramatic and musical items and how these items might have been tailored to suit the characteristics of the spaces that were used for their performance. Secondly, broader considerations on the importance of the sense of hearing and of listening within the culture studied are also essential, this might entail not only the consideration of sound in the context of a performance but also its role in every day life. The following subsections explore these two aspects as well as their relevance to this research project.

1.2.1 The Acoustics of Performance Spaces for Music and Drama

The spaces used for drama and music performances in Western culture have changed throughout history; however, certain acoustical effects seem to have remained consistently desirable. Speech intelligibility has been considered the primary function for spaces devoted to drama, whereas musical performances have favoured different features depending on the characteristics of the music being performed.

The development of theatre acoustics can be seen as a the result of a process of trial-and-error and not so much as a result of the understanding of physical aspects (Barron 1993). In Ancient Greece the construction of outdoor theatres reflected both the need to accommodate large audiences (14000 people in the case of Epidaurus), which was a consequence of a democratic society, and to ensure speech intelligibility (Blesser and Salter 2007). Shankland (1973) explains that those ancient Greek theatres that have been praised for their acoustics, for example Epidaurus, have outstanding characteristics for both speech, by ensuring good speech intelligibility, and for music, which could be in the form of vocal items sung by a soloist or a chorus, as well as pieces played with musical instruments. The acoustics of these theatres is a result of the arrangements of seats in relation to the performance areas where the actors were located, an arrangement that allowed for a greater amount of early reflections arriving at the listener, and which was also affected by the position of the performer within the staging area (Shankland 1973). Moreover, the use of masks in Greek drama aided sound propagation by acting as a megaphone (Barron 1993).

More recent research on the acoustics of ancient theatres was conducted as part of the ERATO project (Identification, **E**valuation and

Revival of the **A**coustical Heritage of Ancient **T**heatre and **O**dea). Although the ERATO project included the study of the acoustics of Greek theatres the main focus was on ancient Roman theatres and odea, concentrating on the identification of their acoustic characteristics, their virtual restoration and their revival. The study of the acoustic features of both theatres and odea, through acoustic measurements and computer simulations, made it possible to establish that the differences in their acoustic characteristics were related to their use (Rindel 2013). Roman theatres were used for drama performances and were semi-closed open-air structures, which often included a *velum*, which was a textile that was used as a sunshield (Rindel 2013). Odea were roofed theatres with a semi-circular seating arrangement for the audience and they were used both for the performance of music and plays (Rindel 2013).

Elizabethan theatre also employed semi-closed structures; actors and directors thought of these structures, in particular the wooden frame, as an essential part of a company's tools, which influenced the production of sound and its propagation (Smith 1999). The Globe (1599-*c.*1650) in London is possibly the most famous example of an Elizabethan playhouse; it has an open roof and an auditorium with a polygonal shape. Its modern reconstruction, called Shakespeare's Globe, has allowed the study of its characteristics through acoustic measurements, which demonstrated that the large number of early reflections arriving at most of the audience positions resulted in good intelligibility (Richardson and Shield 1999). Smith explains that experiments in Shakespeare's Globe furthered the understanding on the use of the performance space for delivering soliloquies by indicating that "An actor may occupy the position of greatest *visual* presence at the geometric center of the playhouse, but he commands the greatest *acoustical* power near the geometric center of the space beneath the canopy." (Smith 1999: 213-214)

The 1988-90 excavations of the remains of the Rose (1587-1606) and Globe playhouses contributed to the scholarly discussions on the characteristics of the playhouses and how they were used (Bowsher and Miller 2009). The excavations provided tangible evidence to the discussions that had hitherto been mainly based on written records, while demonstrating that caution should be exercised when using evidence from one playhouse to arrive at general conclusions about all playhouses of the period. Among the main findings is the fact that the alterations made to the Rose in 1592 consisted in changes to the northern half of the playhouse. Furthermore, the Rose was shown to have been polygonal, with fourteen sides and a diameter of approximately 22m; previously scholars had suggested that playhouses had a diameter of about 30m and the number of sides would have been four, eight, twelve, sixteen or twenty-four.

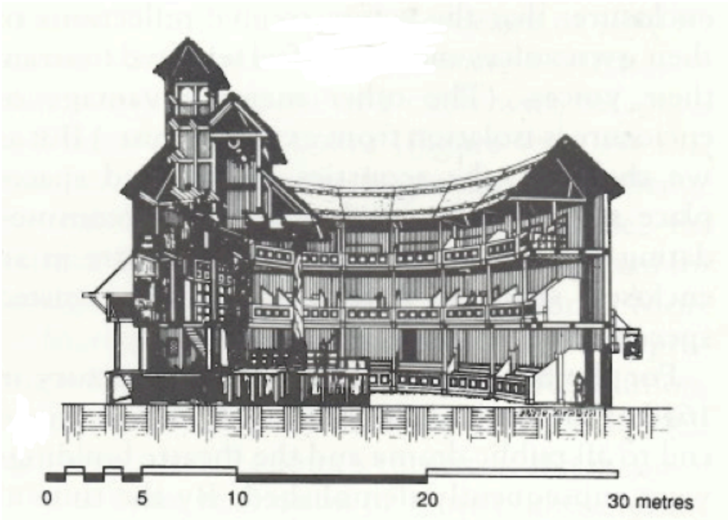


Figure 1.1 – Longitudinal perspective section of an Elizabethan theatre (Barron 1993: 247).

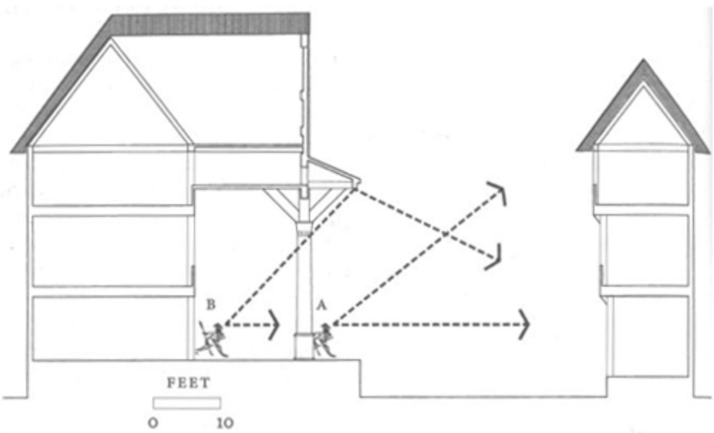


Figure 1.2 – Side view of the 1599 Globe theatre, the dashed arrows indicate the propagation of sound depending on the position of the performer (Smith 1999: 212).

The seventeenth century saw the development of the proscenium theatre, and much experimentation was undertaken to find the 'ideal' plan design for an auditorium (Barron 1993). Eventually it was the Baroque theatre, whose auditorium follows a horseshoe plan, which was the one to gain the most popularity in Europe. Such popularity is related to the fact that all members of the audience receive reflections that enhance speech intelligibility (Barron 1993).

Although acoustic considerations are essential to the process of theatre design, other factors also have a great influence. Choices are often affected by the aesthetic preferences of those involved, the tension between the desire to follow traditional designs and the readiness to innovate and the need to increase seating capacity while including types of seating which often reflect the social standing of the audience members (Barron 1993; Blesser and Salter 2007).

The study of the acoustics of performance spaces for music requires the consideration of the different musical styles developed throughout the centuries since these were influenced by the acoustic characteristics of the performance spaces they were composed for. Dart explains that composers from past centuries were aware of the effect the acoustics of spaces had on their music and different compositional styles were partly a response to a desire to suit the spaces in question (Dart 1954). Furthermore, the study of the acoustics of music performance spaces from the 11th to the 18th century demonstrated, through the analysis of acoustical data and sound samples, that musical pieces are particularly suited to the acoustic characteristics of the spaces they were composed for, resulting in a more moving and engaging experience (Bassuet 2004).

In the Middle Ages the development of plainchant, which is characterised by its monophonic texture and slow melodic lines, seems to be perfectly suited to the long reverberation time of the churches where it was performed (Barron 1993). The longer reverberation time of the spaces meant that sound took longer to decay and become inaudible. As a result, notes from a plainchant item were sung at the same time than the sound of previous notes, which were lingering in the space, transforming a monophonic composition into a piece that included a harmonic element, which was the result of the interaction between the composition and the acoustics of the space (Forsyth 1985).

The relationship between musical compositions and acoustics can also be traced to Renaissance Venice, in particular to St Mark's, and its role in the development of the *cori spezzati* performance style. The use of this style in sixteenth-century Venice was evident in the work of Adrian Willaert; his compositions used two choirs, each of them comprised of four voices, they interacted with each other by either singing alternately or simultaneously and the choirs needed to be physically separated (Moretti 2004). The development of this performance style through Willaert's compositions was accompanied by changes in the architecture of the space, which were supervised by Jacopo Sansovino and involved alterations to the chancel; these changes were related to the desire of providing better acoustics for the newer compositional and performance styles (Howard and Moretti 2009; Moretti 2004).

Howard and Moretti (2009) point out, referring to Renaissance Venice, that the close connection between musical compositions and the acoustics of the spaces was weakened by the increase in the availability of printed music, which meant that pieces could be performed in other spaces than those they were composed for and it would be the task of local musicians to adapt the performance of the pieces to suit the characteristics of the new performance spaces.

The Reformation and its emphasis on the intelligibility of the sermon resulted in alterations to the characteristics of worship spaces, which involved, for example, including drapes to increase sound absorption and reduce the reverberation time as well as the addition of galleries to ensure a larger number of people were close to the pulpit (Forsyth 1985). Although these alterations are related to the change in religious practices they had an impact on musical compositions from the Baroque period. Bach composed pieces, such as *St Matthew's Passion*, for the Thomaskirche in Leipzig, which had been altered as a result of the Reformation; the change in the acoustics of the space allowed the use of a faster tempo as well as rapid harmonic changes, which would have not been possible with the long reverberation times that characterised medieval churches (Forsyth 1985).

The compositions of the Classical period with their emphasis on structure, their use of ornamentation and the inclusion of fast passages, benefitted from the acoustics of the small concert halls where they were originally performed, which were characterised by a short reverberation time and acoustical intimacy (Beranek 1962, Forsyth 1985). Acoustical intimacy is the effect by which a piece is perceived as being performed in a small space even though it is being performed in a large room (Beranek 1962) (see Chapter 3.3.1).

The generation of romantic musicians was more invested in providing an aural experience, presenting clear melodic lines was not a concern and the emphasis was placed on appealing to the sense and emotions of the listeners (Rosen 1995). Therefore, this music benefits from longer reverberation times which result in lower definition of the musical notes and rhythms; these qualities are evident in the halls built in the second half of the nineteenth century (Beranek 1962).

1.2.2 Medieval Drama and Acoustics

The outline provided in section 1.2.1 on the relationship between acoustics and drama and music performances throughout history demonstrated that research on this subject has been extensive. However, it is also possible to observe that research on pre-seventeenth century theatre acoustics has focussed either on Greek and Roman or Elizabethan theatre. The study of medieval acoustics has been mainly centred on churches as worship spaces and as sites for the performance of liturgical music. The only study on medieval drama and acoustics known to the author focusses on the liturgical drama *El Misteri d'Elx* dating from *c.*1450, which was performed in the Basilica of Santa Maria in Elche, Spain (Pereal, Campillo and Cervero 2011). Although it studies a piece of medieval drama it focusses once more on the effects of the acoustics of a church on the performance of sung items.

An examination of the historiography of the acoustics of performance spaces shows that there has been a deliberate omission of those spaces used for the performance of religious vernacular drama, that is, a group of plays in the vernacular and with a religious subject matter that, in the case of England, were first performed in the fourteenth century (Rastall 1996). As it will be seen when exploring the York Mystery Plays, this form of medieval drama did not only include spoken word but also incorporated musical items. Different staging methods were employed, including the use of a booth stage, *locus*-and-*platea* staging, theatre in the round, processional staging and performances in great halls. The scarcity of acoustic studies on this subject could be attributed to two characteristics of the performance spaces: they were mainly performed outdoors and no theatres were built, instead temporarily assembled stages were used (Tydeman 1986).

The fact that these plays were performed outdoors and in temporarily assembled stages should not be interpreted as an indication that acoustics were not a key consideration for organisers and performers. The space available for the performance could have been modified to improve acoustic conditions, in particular to ensure speech intelligibility and audience engagement. Furthermore, the inclusion of plainchant items in most medieval plays also poses some relevant questions. Performers and audiences would have normally sung or listened to these pieces within the acoustic settings of churches but within the performance of the plays the pieces would have been transformed by the contrasting outdoor acoustics. This change might have posed challenges to singers who might have had to modify their performance to suit the acoustics of the space but it would have also affected the perception of the pieces by the audience; although audiences might not have known exactly why the pieces sounded differently in a church space than outdoors they would have certainly noticed a difference and might have reacted differently as a consequence.

To further the understanding on the reasons why examining acoustics in connection to medieval dramatic performances is relevant it is necessary to explore the significance of sound and hearing in the period in question.

1.2.3 Sound and Hearing in the Middle Ages

Implied in the study of medieval drama and acoustics is the need to explore ideas on sound and the sense of hearing in the period in question, which would have influenced the performance and reception of the plays. A key point to consider is the sonic environment, meaning the soundscape contemporary performers and audiences inhabited. Schafer (1994), who coined the term soundscape, suggests that soundscapes include three main types of sound. Keynote sounds are those sounds that form part of the natural environment, such as the wind, rain and thunder. The second type of sounds are signals, they are consciously listened to and are used to communicate meaning, such as the use of bells. Finally, soundmarks are equivalent to landmarks; they have features that make them recognisable to members of a particular community.

When considering keynote sounds in the medieval soundscape it is possible to reflect on their levels as well as their impact on everyday life. Overall sound levels would have been lower than in modern cities, which would have affected sound perception. Sounds that we would nowadays consider quiet would have been clearly audible and more easily identifiable (Woolgar 2006). The sound of storms, thunders, and animal cries, such as dogs barking, would have had a greater impact than they do today.

Sound signals that were of particular relevance in the medieval period were those produced by bells. The sound of church bells served to regulate life within monasteries as well as the activities of lay communities. Within religious institutions different bells were used to communicate different meanings, such as the times for prayer, calls for assemblies and meals announcements, among others (Hendy 2013). Church bells were also a key aspect of the soundscape of towns since the bells of parish churches functioned not only as an indication of the passage of time but also as a means to express the power of a church over an area of the town; a parish church has been understood as “an acoustic space, circumscribed by the range of the church bell.” (Schafer 1994: 54). Bells were also used by civic authorities to announce battles, public ceremonies and indicate curfew

(Blesser and Salter 2007; Woolgar 2006). The fact that bells were used for such specific functions meant that the unexpected ringing could be used to indicate danger, death or a miracle (Hendy 2013).

Sound could also be associated with good or evil, heaven and hell. On the one hand sounds such as loud laughter, sneering, shouting, hissing and nonsensical expressions, among others, were associated with demonic possessions (Hendy 2013; Woolgar 2006). On the other hand, words and music were a means through which to communicate with God and the divine message. Christianity considers the spoken word and, as a result, hearing of the utmost importance (Ong 2000). In the Scriptures, God communicates with the faithful by speaking to them and it is believed that "faith comes from what is heard, and what is heard comes through the word of Christ." (Romans 10: 17). In the Middle Ages religion was mainly transmitted through the sense of hearing, in the form of the sermons given by preachers (Ong 2000) and hearing these sermons constituted a means for Salvation (Hendy 2013; Woolgar 2006).

In the sixth century, Boethius, through his work *De Institutione Musica*, transmitted to the Middle Ages notions of music derived from the Antiquity, which referred to three types of music. *Musica mundana* referred to the omnipresent sound that was a result of the rotation of the celestial spheres and which resulted in harmonious music, which was inaudible to humans due to their sinful nature (Rastall 1996). *Musica humana* was the relationship between body and soul, harmony could be achieved within individuals and achieving this harmony was linked to the idea of healing through music. *Musica instrumentalis* corresponds to what is considered as music in modern times, both vocal and instrumental. Evidence has shown that Boethius' theories were still being studied at the University of Oxford in the fourteenth century (Dyer 2009).

It was also believed that music could encourage religious devotion. In the fourth century St Augustine in *Confessions* refers to music and "the pleasures of the ear", pointing out that he feels his mind "is kindled more religiously and fervently to a flame of piety" when the holy words are sung than when they are not, and he concludes that music can be used to stimulate devotion in the listeners (St Augustine: Book X: XXXIII). Similarly, in the thirteenth century Pope Innocent III believed that harmonious singing helped kindle religious devotion (Woolgar 2006: 81).

1.3 Acoustics and the York Mystery Plays

This research project explores the relationship between medieval drama and the acoustics of its performance spaces by focussing on the study of the York Mystery Plays, which were a series of plays with a religious theme that were performed in the streets of York from the fourteenth to the sixteenth century. These plays followed a processional form of staging, which used wagons that were manhandled through the streets following a predetermined route. This thesis proposes the employment of virtual acoustic models to study the acoustics of one of the performance spaces, Stonegate, a street in central York.

The York Mystery Plays have been the subject of extensive research with points of interest including the staging of the plays, their performance and the role of audiences. Such studies are faced with the challenge of working with information that is often scarce and open to several interpretations; the plays themselves offer few stage directions and the documentation regarding staging is almost non-existent. These circumstances have made it necessary for scholars to draw information and techniques from different fields of study, including Archaeology, History, History of Art, Music and Theatre, in order to attempt to arrive at a better understanding of the plays, their staging, performance and reception. Moreover, existing theories have used as sources the surviving documents, the archaeological findings regarding the streets used for the performances, research into similar events in continental Europe, as well as the experience gained in modern productions.

Although scholars have acknowledged that acoustic considerations might have been an important factor in performance and staging decisions, this has only received limited attention and has not been the focus of any known studies related to the plays. The present project incorporates the theories developed by scholars from different disciplines in relation to performance practices and uses them as points of departure to design different virtual models with the objective of analysing their effects on the acoustics of the performance space.

The exploration of the importance of sound and hearing in medieval times evidences the importance of considering acoustics in relation to the performance of the plays, by studying both speech and music, two elements that were considered essential to Christianity. Central to the performance of the York Mystery Plays was the desire to reverence Christ. Forms of art in the Middle Ages had a didactic purpose and there was no differentiation between "beauty (*pulchrum*, *decorum*) and utility or goodness (*aptum*, *honestum*)." (Eco 1986: 15) On this note, Tydeman emphasises the importance of the oral nature of the plays in connection to didacticism by explaining that medieval drama was "…brought into being to render the salient truths of the Christian faith graphic and compelling for those unable to read the scriptures for themselves, even if the better-educated were not excluded from attending." (Tydeman 1994: 17-18).

The importance of the reverence of Christ coupled with the desire to communicate religious doctrine to the audience indicates that the lines delivered and the music performed would have needed to be as intelligible and engaging as possible so that the Christian message could be transmitted to the audience. Therefore, it is difficult to conceive staging and performance decisions that did not consider aural aspects to be crucial for the performance of the plays.

1.4 The Understanding and Conservation of Acoustical Heritage

The present thesis can be considered within the context of digital heritage, that is, the use of digital means to further the understanding, aid the conservation and facilitate the dissemination of elements of importance to cultural heritage. When studying spaces with importance for cultural heritage, traditionally, the main focus has been placed on the 'visual' aspects, disregarding the importance of their acoustics. However, in the last decade researchers have developed an increasing interest in the study, conservation and reconstruction of the acoustics of past environments, highlighting that this knowledge would contribute to the better understanding of past cultures, and how spaces were utilised and experienced.

Two major projects in this field were the ERATO project (see section 1.2.1) and the CAHRISMA project (**C**onservation of the **A**coustical **H**eritage by the **R**evival and **I**dentification of the **S**inan's **M**osque **A**coustics). The ERATO project was conducted from 2003 to 2006 and had the objective of studying the acoustic characteristics of Greek and Roman theatres, focusing on their identification, restoration and revival. Similarly, the CAHRISMA project concentrated on the idea of hybrid architectural heritage, that is, the belief that when dealing with the preservation and restoration of spaces of acoustic importance, both visual and aural aspects should be taken into account (Yüksel, Binan and Ümver 2003).

A more recent project, which commenced in 2008, is the *Chavín de Huántar Archaeological Acoustics Project*, run by the Centre for Computer Research in Music and Acoustics (CCRMA) and the Centre for Archaeology/Anthropology of the University of Stanford. This project studies the Chavín de Huántar, which is a pre-Inca ceremonial centre found in Peru. It utilises acoustic measurements and computer models to archive the acoustics of the space, as well as reconstruct the parts that cannot be accessed or that are not well preserved. Simulations of the space studied are also being prepared in order to communicate the findings to the wider public.

It is thanks to advancements in acoustic measurement equipment and specialised software for virtual acoustics studies that it is possible to study acoustics in connection to the York Mystery Plays, which in turn provides a starting point for research into acoustic considerations of medieval drama.

It is necessary for scholars working on acoustics and those working on medieval theatre to attempt to bridge this gap in knowledge, which would deepen our understanding of the staging techniques of that period.

Furthermore, the study of acoustics in the York Mystery Plays allows future creations of immersive simulations that combine visual and auditory stimuli, which in turn could widen the interest of the public in the plays, which are still performed regularly in modern day York.

This project, in keeping with the ones briefly described above, is based on the premise that acoustic considerations are essential in the understanding of spaces, their utilisation and how they were experienced. Nevertheless, it is paramount to bear in mind that even if it is possible to recreate the acoustics of past environments through the application of technological advances to further the knowledge on the subject, it is never possible to reconstruct the experience of the listeners.

> We will still hear acoustic environments, however accurately simulated or reconstructed by engineers to replicate what the ancients heard, from the perspective of modern listeners. The spatial experience of our ancestors is forever buried with them. Nevertheless, we can at least partially reconstruct their cultural frameworks to show the degree to which aural architecture and the experience of sound depend on culture. (Blesser and Salter 2007: 68)

1.5 Research Questions

The present thesis uses the theoretical framework presented in the previous sections to explore two main research questions:

1. What were the effects of the acoustics of the street spaces used for the performance of the York Mystery Plays on both the spoken and musical parts of the plays?

2. What were the effects of the application of different staging techniques on the acoustics of the performance space?

The research questions are investigated in the following ways:

a. A performance space used for the York Mystery Plays is selected in relation to the amount of extant information and its state of conservation; acoustic measurements are conducted on site and the results are analysed.
b. A virtual model of the same space, in its modern state, is modelled using specialised software and its accuracy is determined through objective and subjective analyses.
c. Research into the characteristics of the street in question in the period of the performances of the plays is conducted and eight virtual models are simulated as a response to the findings, allowing the analysis of the different acoustical characteristics and their impact on the plays.
d. Different wagon structures are modelled and incorporated into the simulations of the street space. The models designed are selected due to the differences in their structure and orientation. Different possible positions of performances and audiences are also studied.

1.6 Thesis Structure

The remaining parts of this thesis explore in detail the scholarly research that has been utilised as a starting point for this project as well as the steps that have been taken to answer the research questions. The way in which chapters are organised as well as an outline of their content is presented below.

Chapter 2 introduces the main aspects of the performance of the York Mystery Plays. It includes a brief history of their development throughout the centuries, discusses theories related to acting and singing, explores the evidence on the staging and performance of the plays and considers the role of audiences. It also explores the importance of the soundscape and introduces the relevance of the study of acoustics to further our understanding on the plays.

Chapter 3 explains the concept of virtual acoustics and the steps involved in its application to the study of the York Mystery Plays. It explores the interaction among spaces, performers and audiences by covering concepts related to sound propagation, the human voice as a sound source and auditory perception. The room acoustical parameters used as a basis for the analyses included in this project are introduced and the acoustic modelling techniques are explained.

Chapter 4 presents the research carried out to answer the first research question. The rationale behind the selection of Stonegate as the performance space to be studied is explained. A brief history of York, which is focussed on the changes in the topography from the Roman to the Tudor era, is presented and particular attention is paid to the characteristics of streets and buildings in the period of the performances of the plays and specifically the evidence regarding buildings in Stonegate. The investigation on the acoustics of Stonegate starts by considering its characteristics as it stands today through acoustic measurements on site. These measurements are then used to calibrate a virtual model of the same space and determine its accuracy through objective and subjective evaluations. The validated model is then used as the basis for generating eight computer models with the aim of representing different possible characteristics of the street in the sixteenth century. The virtual models are analysed through the study of different room acoustical parameters.

Chapter 5 explores the second research question. It presents the reasoning behind the incorporation of different wagon structures, orientations as well as performers and audience positions within the virtual street spaces. The results of the analyses are presented and explored in connection to their relevance to the performance of the York Mystery Plays.

Chapter 6 provides a summary of the work carried out and draws conclusions in relation to the research questions presented in the introduction. It reflects on the possibilities of future work.

1.7 Contribution to Knowledge

The contribution of the present research project to knowledge is two-fold. Firstly, it establishes the importance of the study of the acoustics of performance spaces used for medieval drama. By doing this it takes the first step in the integration of these sites to the historiography of the acoustics of performance spaces. Secondly, it contributes to the field of early drama by analysing the ways in which acoustics might have been an influencing factor in staging and performance decisions as well as indicating the effects of acoustics on the performance of the spoken and sung parts of the plays. Moreover, both contributions are achieved through the use of a truly interdisciplinary approach, which demonstrates the importance of combining research from the humanities with research in acoustics to provide a deeper understanding of the York Mystery Plays.

1.8 On Terminology

The interdisciplinary nature of this project requires the use of terminology that pertains to different research fields and cannot be considered as common knowledge across disciplinary boundaries. The thesis in question has been written by bearing in mind its potential appeal to experts in different disciplines. Therefore, although some of the concepts introduced are well known among specialists in acoustics, these have been explained in the body of text and every effort has been made to ensure explanations are as accessible as possible to scholars within different areas of expertise. To further clarify concepts a glossary has also been included at the end of the thesis.

Although the present project has used the terminology "York Mystery Plays" in its title, it is of importance to point out that the plays are often referred to as the "York Cycle" or the "York Corpus Christi Play". The nomenclature "York Mystery Plays" makes reference to the fact that the staging of the plays was the responsibility of the different craft-guilds of the city, which were also referred to as 'mysteries' (Beadle and King 1995: xv-xvi). The use of this term has proven popular within the contemporary drama scene and as a result it is more often recognised by lay audiences. Referring to the plays as the "York Cycle" has the advantage of emphasising the importance of considering them not as independent pieces but as parts of a whole, which are connected in the context of the performance. The connection between the York Mystery Plays and the Corpus Christi feast has led to the plays being referred to as the "Corpus Christi Play", with the word 'play' in singular also being used as a reminder that the plays should be considered as a unified piece and not as a series of separate units (Beadle and King 1995: x). These three terms will be used interchangeably through the thesis.

The history of the York Mystery Plays spans from the fourteenth to the sixteenth centuries, this means that its performance lived through what can be considered as different historical periods, such as the Late Middle Ages and the Early Modern Period, in particular the Tudor Era. Despite this difference in historical periods the present thesis shows predilection for the use of the general terms "medieval period" or "Middle Ages". This choice is due to the fact that it is of importance to point out that the plays originated in the pre-Reformation period and survived, albeit with consequences, throughout political and religious changes as an expression of medieval drama and the 'old order'.

1.9 Conclusions

The present chapter explored the relationship between drama and music and their performance spaces throughout history and discussed the exclusion of medieval drama from the historiography of the subject; with the study of medieval acoustics having focussed on the characteristics of religious institutions. Notions of sound and hearing in the medieval period were introduced in order to further our understanding of the importance of sound and acoustics for the period in question. The relevance of the study of acoustics in connection to the York Mystery Plays was presented as a first step towards an integration of medieval drama to the history of acoustics as well as contributing to the discussion on staging, performance and reception of the plays, while at the same time highlighting the role of virtual acoustics within digital heritage studies.

The research questions that this project will be exploring were presented together with an outline of the methodology used and the organisation of the thesis. Finally, questions on terminology that are key for the interpretation of the written work were discussed.

Chapter 2: The York Mystery Plays

2.1 Introduction

The present chapter includes a brief history of the York Mystery Plays from the earliest surviving record up to the final performance in the sixteenth-century, with references to the broader historical, political and cultural context surrounding their performance. Key components of the performance of the plays are analysed by referring to the acting style, the use of the voice and its connection to the text as well as the use of music as an essential element of the Cycle. Different theories on the staging of the plays are considered by taking into account the use of wagons, the playing stations and the positions and role of audiences. The information presented throughout the chapter is then linked to an exploration of the soundscape of the city of York in the period of the performance of the plays, indicating the need for an acoustical analysis of the performance spaces to further our understanding on the staging, performance and reception of the plays.

2.2 A Brief History

The York Mystery Plays are a series of plays or pageants in Middle English that narrate events of relevance to the Christian faith, starting with *The Fall of the Angels* and ending with *The Last Judgement* (Appendix - Table 2.1). The staging of the pageants was the responsibility of the different craft-guilds of the city. The plays were performed outdoors in a processional manner using wagons specifically constructed for the occasion and manhandled through the streets of York. The cycle of plays had three main aims: to honour and reverence Jesus, to manifest the wealth of the city and to elicit the devotion of the audiences while eliminating vices (REED 1979: 11, 37, 697, 722).

The York Mystery Plays are thought to have originated late in the fourteenth century; the earliest evidence of their existence is from 1376, it is found in the *A/Y Memorandum Book* and refers to expenses "For one building in which three Corpus Christi pageants are housed per annum." (REED 1979: 3, 689). Another key document included in the *A/Y Memorandum Book* is the *Ordo Paginarum* (The Order of the Pageants), which dates from 1415. This document lists fifty-two pageants by including the characters and, in most of them, a reference to the actions performed (REED 1979: 16-24, 702-709). However, the scarcity of the information contained in the *Ordo* has led to the belief that it is possible that by this date the descriptions do not refer to full plays but to *tableaux* or possibly, due to the verbs of speaking that are included in the descriptions, a midpoint between *tableaux* and plays (Twycross 2007).

The text of the York Mystery Plays has survived in the form of *The Register* (British Library, Additional MS 35290), which was the official record of the plays and was compiled between 1463-1477 from the individual copies of the plays used by the craft-guilds for rehearsals and performances (Beadle 1982; Beadle and King 1995). Only one of the individual copies held by the guilds survives, it is The Scriveners' play *The Incredulity of Thomas* dating from the sixteenth century (Sykes MS, York City Archives) (Beadle and King 1995; Davidson 2013). From the sixteenth century *The Register* was used by the Common Clerk at Holy Trinity Priory Gates (Micklegate) to monitor the performance and subsequent annotations on the manuscript, related to revised or rewritten plays, are thought to have derived from this monitoring activity (Beadle 1982; Beadle and King 1995).

The York Mystery Plays were connected to the Corpus Christi feast, which was proclaimed in York in 1325 and honoured the presence of the body of Christ in the Host. This feast was celebrated on the first Thursday after Trinity Sunday, which could be between the 23rd of May and the 24th of June. Originally, the plays were performed on Corpus Christi, and on that same day there were three processions taking place in York. There was a procession within St Mary's Abbey, another around the precincts of the Minster, and finally a civic procession in which the consecrated Host was carried through the streets of York (King 2003). While the civic procession was organised by the Corpus Christi Guild, the plays were the responsibility of the City Council who would issue billets authorising the craft-guilds to prepare their pageants for the performance (White 1984). After 1426, procession and plays seem to have been moved to separate days when Brother William Melton suggested that citizens and visitors were being distracted from the religious ceremonies due to the festive climate generated by the plays (REED 1979: 43, 728). The cycle was changed to "the Wednesday which is the eve of the same feast" and "the procession should always be made solemnly on the day of the feast itself" (REED 1979: 43-44, 729). White (1984) questions whether this arrangement was ever put into practice and explains that after 1468 the cycle was being performed on the original day and the civic procession had been moved to the Friday. An additional change was observed in 1569 when the plays were performed on the Tuesday in Whitsun week (the Tuesday after the Pentecost feast) (REED 1979: 355).

Despite the relationship between the annual Corpus Christi feast and the York Mystery Plays, the assumption that the plays were meant to be performed every year cannot be corroborated since not all the civic records from 1376 have survived (Rogerson 2011). Furthermore, plague outbreaks are known to have resulted in the cancellation of the plays, as in 1550 when the city council cancelled the performance by withdrawing the billets that had been given to the craft-guilds (REED 1979: 295). There were two other plays that could be used as alternatives to the York Mystery Plays: the Creed Play and the Pater Noster Play. They were didactic plays with a religious theme and a processional mode of staging; in their origins the Creed Play was the responsibility of the Corpus Christi guild, while the Pater Noster and St. Anthony's guilds were in charge of the Pater Noster Play (Johnston 1975). The earliest references to these plays date from 1378 and 1446 for the Pater Noster and Creed Play respectively and throughout the fifteenth and sixteenth centuries the city council became increasingly involved in their production (Johnston 1975). The Creed Play replaced the York Mystery Plays in 1535, whereas in 1536 and 1558 it was the Pater Noster Play that was performed instead of the York Cycle (Johnston 1975).

The Reformation also affected the performance of the York Mystery Plays. In 1548 the Corpus Christi feast was abolished and although the cycle of plays was performed, it excluded the three Marian pageants of *The Death of the Virgin*, *The Assumption of the Virgin* and *The Coronation of the Virgin* (REED 1979: 291-292). The accession of Mary Tudor to the throne in 1553 and, as a result, the reinstitution of Catholicism, was supported by the city of York (Cross 2007). York's population had remained mainly Catholic throughout the 1530s and 1550s and had seen the 1548 Act that authorised the seizure of the chantries by the crown as an attack to one of their most valued doctrines, the purgatory (Cross 2007). As a result of such a political and religious climate the Marian pageants were willingly reintroduced to the 1554 performance (Cross 2002; REED 1979: 310). However, such reincorporation was short-lived as the succession of Elizabeth to the throne and the reintroduction of Protestantism led to a renewed prohibition of the Marian plays in 1561 (Beadle 1982; Cross 2007; REED: 331-332).

Further challenges were faced in 1567/1568 when the city council, wishing to perform the Creed Play but anxious about its appropriateness, sent a copy of the same to the Dean of York Matthew Hutton for perusal (Johnston 1975; REED 1979: 352-354; White 1984). The Dean suggested abandoning the performance of the Creed Play as it did not adhere to the current doctrine and advised that only rewriting it could make it appropriate (Johnston 1975; REED 1979: 352-354; White 1984). The plan to perform the Creed Play was then abandoned and although the council wanted to have a performance of the York Mystery Plays it became uneasy regarding its suitability and considered sending it for scrutiny; eventually, no performance took place in 1568 (Johnston 1975; REED 1979: 354; White 1984)

A performance of the York Mystery Plays took place in 1569 and there are no extant records on any hesitation by the city council regarding their appropriateness (White 1984). White (1984) argues that such lack of anxiety may have been due to alterations having been made to the play, the time that had elapsed from the receipt of Dean Hutton's advice on the Creed Play or the fact that the performance had been moved to the Tuesday of Whitsun (REED 1979: 355), disassociating it from what used to be the Corpus Christi day and as a result, detaching it from Catholic traditions.

After the unsuccessful attempt to reinstitute the Catholic faith in 1569 in what is known as the Revolt of the Earls or the Rising of the North, the authorities became more reluctant to tolerate reminders of the old faith (Cross 2007; White 1984). Endeavours by the city council to reintroduce the Cycle by requesting permission from civic and ecclesiastical authorities in 1579 and 1580 were unsuccessful (REED 1979: 390, 392-3) and the 1569 performance of the York Mystery Plays would be the last until its revival in 1951 (Rogerson 2011).

The Pater Noster Play was performed in 1572 after being examined by the Lord Mayor and the performance took place on the former Corpus Christi day (REED 1979: 365), which might have been an intentional reminder of previous traditions (White 1984). That same year, after the performance had taken place, the Archbishop of York requested to be sent the copies of the Pater Noster Play, an episode marking the end of the performance of religious drama by the city of York (White 1984).

2.3 Performing the York Mystery Plays

A. Acting

Extant records of the York Mystery Plays provide little information on the actors involved and their training or performance style. A pivotal document is the 1476 ordinance that introduces a process of quality control whereby four skilful actors from the city would be in charge, in the period of Lent, of scrutinising the actors of the Corpus Christi Play (REED 1979: 109). Moreover, it indicates that actors involved in the performance should possess “connyng”, “voice” and “personne” (REED 1979: 109). Rogerson (2011b) explains that “connyng” refers to the capacity to learn their lines whereas ‘voice’ relates to the ability to project their voices in outdoor spaces. The latter ability is also mentioned in the proclamation of the Corpus Christi Play dating from 1415, which refers to the necessity for “good players well arayed & openly spekyng” (REED 1979: 25). The word “personne” is a more ambiguous term since it could have been making reference to the physical appearance of the actors or it could have been referring to the capacity to impersonate a character (Rogerson 2011b).

Gurr (2009) argues that the concept of actors impersonating their characters did not originate until the beginning of the seventeenth century; it was then that the term "personation" began to be used to praise actors that possessed this skill, while exaggerated acting was condemned. Rogerson (2011b) questions this argument and believes that it might have also been a skill of importance for performances in the late Middle Ages.

It is also possible to consider actors' approach to the plays in connection to devotional practices (Rogerson 2011b). Actors would have been familiar with affective piety, which was the medieval practice of attempting to understand Christ's humanity and arrive at feelings, emotions and imaginations equivalent to those which would have been felt if the events of Christ's life were happening in the present (Rogerson 2011b). Such practices were invoked in Good Friday sermons in late medieval England (Johnson 2004) and it is possible that such experiences were evoked when performing the plays and applied to either a "naturalistic" or a "stylised" performance style (Rogerson 2011b). Regarding the performance style, Twycross (1994) explains that the use of elements such as masks to represent devils or heavenly characters, and the gilding of God in the performances, seem to indicate a stylised performance, although a mixture of both styles could have been possible.

As noted above, audibility was of great importance for the performance of the York Mystery Plays and the lack of skill regarding voice projection could result in actors not being authorised to take part in the plays (REED 1979: 109). The notion of audibility as a main concern in the performance of the Cycle is strengthened by considerations on the significance of speech. King (2000) points out that in some plays the relationship between words and actions is such that action seems to follow the word, arguing that this coincides with the connection, at the core of Christianity, between words and the fulfilment of actions, which is evident in the initial words of John's Gospel: "In the beginning was the Word, and the Word was with God, and the Word was God". (John 1: 1-2).

King (2000) introduces her theory on the preponderance of words over actions by analysing three situations: voices off, the direction of the audience's attention and the constraint of actions. She believes that some plays might have included lines that were delivered by a character that was out of the audience's sight (voice off) generating suspense by delaying the action and making the actor invisible to the audience. This might have been the case in *The Fall of the Angels* when Lucifer falls into hell and is transformed into a diabolic character. Lucifer might have delivered some of his lines out of sight and would have returned to the sight of the audience once he had been transformed (King 2000). This example indicates not only the prevalence of telling over showing, but it also demonstrates that such prevalence could have been employed as a theatrical effect (King 2000).

Spoken lines were also used to manipulate the audience's attention. In *The Crucifixion* Jesus directs the audience's attention to his wounds by saying:

Behold mine head, mine hands, and my feet

(*The Crucifixion* l. 255)
(Beadle and King 1995: 220)

The aural reference to the wounds could have also served the function of overcoming any limitations in the visual representation while at the same time reminding the audience of the five wounds of Christ (King 2013).

Calls for attention can be found at the openings of several of the pageants and in many cases they are requests to the audience to listen instead of requests for silence (King 2013). In *The Entry of Jerusalem* Jesus says:

To me take tent and give good heed

(*The Entry into Jerusalem* l. 1)
(Beadle and King 1995: 107)

Another call for attention can be found in Pilate's opening lines in *The Death of Christ*. In this case he is exhorting the audience to be quiet and simultaneously redirecting the audience's attention from the Calvary scene from the previous pageant to himself (King 2000).

PILATE: Cease, seigniors, and see what I say,
Take tent to my talking entire.

(*The Death of Christ* ll. 1-2)
(Beadle and King 1995: 223)

Words can also provide restrictions to the actions: "Mary does not weep, separately as it were, at the base of the cross; her *planctus* lyrics, spoken in a weeping voice, *are* the expression of her grief." (King 2000: 162)

Although the consideration of the primacy of words is essential in the understanding of the plays, it is important to remember that voice and language are distinct media and the voice is capable of going beyond what can be expressed by the words being pronounced (Lagaay 2011). Consequently, studies on the cycle should consider not only the words said but also "how" they were said:

> After years of study of the largely silent embodied gestural histories of medieval drama it is past time for the talkies to arrive, to look not at the morally inflected meaning of spoken text, but how it sounded, and what connotations that may have been designed to provoke. (King 2013: 4)

Questions of volume and pitch might have been essential to the performance of different characters; tyrannical characters open eleven of the pageants and the intention to convey a sense of bullying would have resulted in exceptionally loud voices (King 2013). Voice projection can also be related to the content of the plays. Training in such skill was common to many occupations, including preachers; therefore the fact that twenty-two pageants have openings that resemble the act of preaching might be an indication of the mode of delivery (King 2013). The use of masks for supernatural characters would have also had an impact on the voices, since depending on the mask used they could have muffled their voices or have acted as amplifiers (King 2013).

B. Singing

Music was an important part of life in the Middle Ages and York was no exception. Music was performed within religious institutions such as parish churches, monasteries and the Minster, as well as in secular contexts where it was performed by minstrels, such as the city waits (Davidson 2013). Religious music could have the form of monophonic plainchant or polyphonic items, and the former was the musical form most commonly used for worship (Rastall 1996). Although plainchant was the predominant musical style, the tradition of polyphonic music in late medieval York should not be underestimated. The main surviving source of medieval polyphonic music in York is the York Masses (c.1490-1520); it includes polyphonic settings in three and four parts as well as pieces in which there is an alternation between a monophonic and a polyphonic style, which was a result of the need to condense the longer liturgical items such as the Creed (Colton 2005). However, it is worth noting that the use of polyphonic music in parish churches might have been reserved to Sunday Masses, while being infrequent in weekday ceremonies, which were often of a simpler nature (Duffy 1992).

Singers were trained in cathedrals and monastic schools and their training would include learning the Psalter (The Book of Psalms) and the plainchant repertory by heart, as well as reading Latin and plainchant notation; a select group of singers was also trained in polyphonic singing and the reading of mensural notation (Rastall 1996). The majority of the members of the clergy would have been able to perform plainchant items as part of the daily worship but would have lacked training in polyphony (Rastall 1996). Laity might have joined in the singing of the least complex monophonic items (Hiley 1993) although their participation was most probably based on listening (Crocker 2000).

References to singing in the York Mystery Plays can be associated with two types of characters: angels and good, non-divine characters (Rastall 1996). Angelic singing is used in the plays to benefit worthy listeners, such as the Virgin Mary in *The Annunciation and the Visitation* where musical settings of the *Ave Maria* and *Ne timeas Maria* would have been sung (Rastall 1996, 2001). Angels also sing to provide a glimpse of Heaven, as in *The Resurrection* where an item called *Christus Resurgens* is performed (Rastall 2001). Non-divine characters that do God's will, can also sing to praise God as in *Moses and Pharaoh* where a setting of *Cantemus Domino* would have been sung and in *The Annunciation and Visitation* when Mary sings *Magnificat* (Rastall 2001). Although the devil and his acolytes are known to have sung in other medieval plays, no examples can be found in the York Cycle (Rastall 1996, 2001).

The identification of the use of musical items, such as the ones mentioned above, is not due to the inclusion of notated music in the manuscript but to the analysis of different elements associated with the plays. Such elements include dramatic directions, text references, the use of Latin and the extant records on the plays (Rastall 1996, 2001). Dramatic directions found in *The Register*, which were either copied at the time of its compilation or as a result of the monitoring of the plays by the Common Clerk, provide references to the inclusion of vocal music and in some cases the piece to be performed is specified by the inclusion of an *incipit* (Rastall 2001). Textual references to music within the plays can also further the understanding on musical performances; for example, in *The Shepherds* play the shepherds comment on the *Gloria* sung by the angel, their own imitation of this piece and the song they sing on their way to Bethlehem (Rastall 1996, 2001). The use of Latin passages sourced from the liturgy, in some cases, can be an indication of a sung piece (Rastall 1996). However, the identification of the *incipit* is not sufficient to determine the piece to be performed, the full text needs to be studied as different texts might share the same *incipit*; once the text has been identified, appropriate musical settings can be analysed (Rastall 1996).

Records of the York Cycle provide little information on the use of music. In the *Ordo Paginarum* only the description of three plays include allusions to music and these are *The Entry into Jerusalem*, *The Coronation of the Virgin* and *The Last Judgement* (Rastall 2001; REED 1979: 16-24, 702-709). A lack of references to music in the descriptions should not necessarily be interpreted as proof that no music was used since the descriptions were not employed to entice audiences to attend the performances (Rastall 2001). The records of payments in relation to musical activities are also imprecise and no clear conclusions on the use of singers and minstrels can be derived from them (Rastall 2001).

The preponderance of musical examples that have not been notated in the manuscript is related to the fact that the medieval music tradition was mainly aural, music was often sourced from the liturgy and such items were often memorised by singers, which eliminated the need to include them in the copies of the plays; if singers needed to consult the pieces they could use their own service-books by referring to the verbal *incipits* included in the text (Rastall 1996). Therefore, the inclusion of *incipits* in the play texts indicates that they were sung in their customary musical setting (Rastall 1996).

The lack of notated music could indicate that the pieces were sung monophonically, to improvised polyphony or that there was a polyphonic version of the piece that was known to the performers; while the addition of a musical *incipit* might indicate that a particular version of a piece was used (Rastall 1996). Furthermore, the non-inclusion of notated music could indicate that the music was pre-existent while its inclusion would indicate that it was a newly composed piece included as a reference (Rastall 1996).

The only surviving notated music from the York cycle is found in the play *The Assumption of the Virgin*. The composition dates from 1430-1440 (Rastall 1984) and consists of three polyphonic pieces with the incipits *Surge, proxima mea*, *Veni de Libano, sponsa* and *Veni, electa mea*. The manuscript includes two polyphonic versions of each text and all pieces were composed in the same period, in two parts and in the mezzo-soprano range; the versions referred to as "A versions" are included in the body of the text at the appropriate points of the play whereas the “B versions” are copied at the end of the play (Rastall 1984, 1996). Regarding their musical characteristics, the “A versions” are homorhythmic, they present short and clear musical phrases and simultaneous cadences, whereas the ‘B Versions’ are longer, present free counterpoint and include overlaps at cadences (Rastall 1996).

The Assumption of the Virgin includes twelve angels that deliver one line of speech each with the exception of Angel VIII who delivers two lines. Choirboys of the York Minster could have played the roles of the angels, and all, most or some of them would have also sung the polyphonic pieces (Rastall 1984, 1994, 1996). Although the number of singers that performed the pieces is not known, the “B version” of *Veni de Libano, sponsa* has a four-part chord, which indicates four as the minimum number of singers required (Rastall 1984). Furthermore, pictorial evidence suggests that the use of four singers for two-part polyphony might have been a practice of the period as indicated in the painting *Mary, Queen of Heaven* by Master of the St. Lucy Legend (*c*.1485)(see Figure 2.1); this painting shows four angels, two at each side of Mary, singing a two-part polyphonic setting of *Ave Regina Caelorum* (Rastall 1994).

Trained singers from the York Minster and parish churches might have performed the most complex vocal pieces with the Cycle, such as those included in *The Assumption of the Virgin*, and they might have even participated in more than one play (Rastall 1996). It is also possible that the actors themselves performed the simpler, congregational chants since they would have been familiar with the musical items from their use in liturgical services (Rastall 1996).

Furthermore, the York Mystery Plays are thought to have been performed by all-male casts. Young female roles would have been played by males who had still not reached puberty (which was reached later in the Middle Ages than in modern times), these males would have not only had the size, shape and skin-texture that allowed them to perform the roles but also a concordant voice; the roles of older females, on the other hand, would have been played by older men (Rastall 1996).

Figure 2.1 - *Mary, Queen of Heaven* by Master of the Saint Lucy Legend, c.1485 (The National Gallery of Art of Washington). The red ovals indicate the positions of the angels that are singing the polyphonic piece.

Information regarding the participation of minstrels in medieval drama in general and the York Mystery Plays in particular is scarce; the most relevant sources are Fouquet's miniature *The Martyrdom of St Apollonia* (1452-1460) and the records from both Chester and Chelmsford (Rastall 1996). Fouquet's painting dates from the mid-fifteenth century and represents the staging of a dramatic piece. Depicted on the left of the painting are a positive organ as well as minstrels playing shawms and folded trumpets (Rastall 1996) (see Figure 2.2). It is possible that the minstrels are accompanying the execution, a common practice in the Middle Ages; or maybe the miniature compresses two separate events: the execution of Apollonia and a performance by a "loud" band (Rastall 1996). The records of the Painters' guild in Chester suggest that minstrels did not perform during the play but they accompanied the wagons as they were moved from one station to the other whereas the Chelmsford records include payments towards minstrelsy for the dramatic festival that took place in 1562 (Rastall 1996).

2.4 Staging the York Mystery Plays

One of the most challenging aspects of research into the York Mystery Plays is the lack of information regarding the appearance of the wagons, and their use during the performances. Throughout the years scholars have developed different theories based on the text, inventories, the characteristics of the streets, other religious processional events, as well as experience drawn from modern productions. The present chapter will consider three main aspects of staging: how the wagons were built, their orientation and the use of the performance space. Although these aspects will be presented separately to ensure clarity, it is necessary to bear in mind that they are interconnected and, as will be seen, cannot be considered in isolation.

Any study of the staging of the York Mystery Plays must avoid the dangers of applying modern conceptions of theatre performances that might not have existed during the Middle Ages. On this note McKinnell argues that

> 'Success' and its opposite cannot be completely assessed by modern standards of visibility, audibility, or audience comfort. However, it makes obvious sense to assume that productions which could be clearly seen and heard were always preferred (and especially that people who paid for special seats or saw the Play from privileged positions because of their rank expected a good view). (McKinnell 2000: 80)

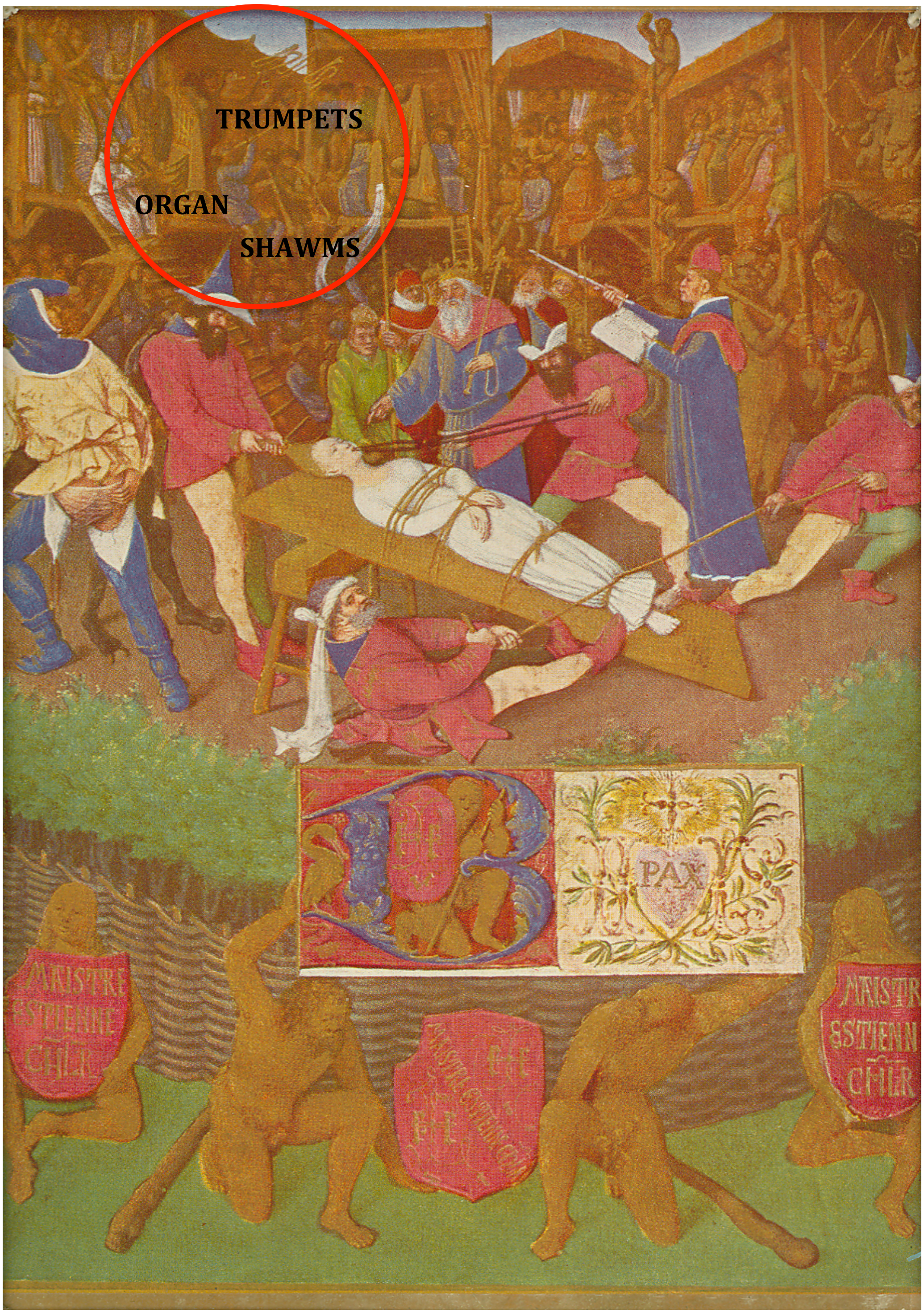


Figure 2.2 – *The Martyrdom of St Apollonia* by Fouquet, 1452-1460 (The University of Maryland Digital Archive). The red oval indicates the musicians' scaffold.

In the present project it will be assumed, as McKinnell does, that "good" seeing and hearing were desired during the performances of the plays. It might be possible to go even further and argue, based on the considerations on speech, singing and voice presented in section 2.3, that the importance of the verbal and musical content as well as the religious message might indicate that audibility was more desirable than visibility. Moreover, ensuring good audibility for the majority of the audience would have meant that even those that could not see the performance clearly, due to their distance from the wagon, could still follow the play.

A. How were the wagons built?

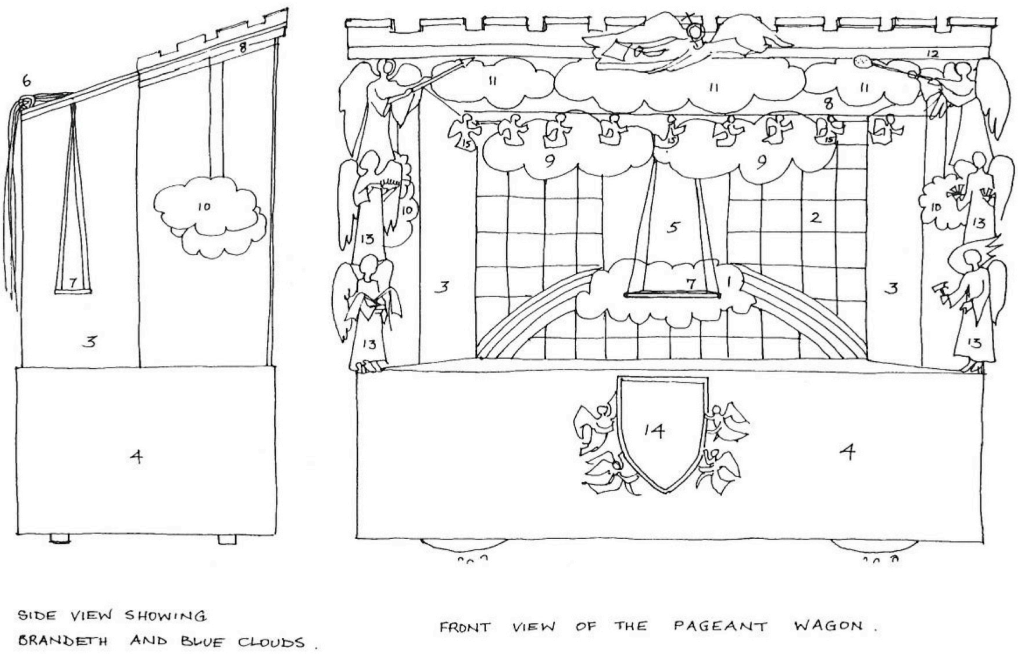
The only surviving documentation on how the York wagons were constructed refers to the Mercers' guild and their pageant of *The Last Judgement*. The most relevant document is a 1433 indenture containing a description of the Mercers' pageant (REED 1979: 55-56). Johnston and Dorrell (1973) explain that the wagon description indicates a complex structure, consisting of a pageant with wheels that has four iron poles and a heaven of iron. The indenture also lists clouds, a rainbow made of timber, cloths for the back and the sides of the wagon, a 'seat' of iron that would allow God to go to Heaven and descend, and twenty artificial angels (Johnston and Dorrell 1973) (see Figure 2.3). Johnston and Dorrell (1971) also mention that a Hell mouth appears listed separately and they believe that it was not attached to the wagon, but it might have been located in the street in front of the main pageant (see Figure 2.4).

In 1463, the guild added a completely new and separate pageant used as an additional space for the souls in *The Last Judgment* to rise from (Johnston and Dorrell 1973; REED 1979: 95-96). Meredith (1979) points out that although there is information regarding the materials used for its construction, there are no details on what it looked like or how it was connected to the great pageant. Johnston and Dorrell (1979) highlight the fact that there is no mention of wheels in relation to the souls' waggon, which might indicate that it was transported from one station to another by placing it on top of the main pageant. However, Meredith (1979) mentions that there is evidence of the Mercers buying two wheels the previous year and that their low cost seems to indicate that they could not have been used for the great pageant.

In 1501 the Mercers commissioned to Thomas Drawswerd the construction of a new wagon, which would replace the 1433 wagon (Johnston and Dorrell 1979). The most substantial evidence regarding this new wagon comes from a 1526 inventory (REED 1979: 241-242). Johnston and Dorrell (1973) underline that the omission of references to curtains, hanging clouds or borders could indicate that since Drawswerd was a carver he might have "provided a solid wooden structure with the details of heaven carved into or painted on the fabric." (1973: 19) The roof might have been gabled due to the use of a windlass as a mechanism to allow the ascent and descent to and from heaven (Johnston and Dorrell 1973). There is a mention of windows, which might indicate that the wagon was closed on three sides and they might have been a means to provide lighting; they "were probably ornately carved alabaster or wood frames set into the walls of the wagon" (Johnston and Dorrell 1973: 19). Two doors are also listed: "pagand dure" and "hell dure" (Johnston and Dorrell 1973; REED 1979: 241-242).

Although the study of the Mercers' wagons can serve as a starting point for the study of the ones belonging to other guilds, it is important to remember that the Mercers were a very wealthy guild and that other wagons might have been much less elaborate (Beadle and King 1995).

The information drawn from the Mercers' documentation provides an incomplete picture on what the wagons looked like. It does not present a detailed description on how the elements in the inventories are positioned in the overall structure nor does it make reference to dimensions. As a consequence, it is of importance to resort to other sources to gain a better understanding of the appearance of the wagons. With this aim in mind it is necessary to study religious processional events that took place in continental Europe and were contemporary to the York Mystery Plays.



1. A cloud and ij peces of Rainbow of tymber.
2. A grete coster of rede damaske payntid for the bakke syde of þe pagent.
3. ij other lesse costers for ij sydes of þe Pagent.
4. iij other costers of lewent brede for þe sides of þe Pagent
5. A litel coster iiij squared to hang at þe bakke of god.
6. A Iren pynne
7. A brandreth of Iren þat god sall sitte vppon when he sall fly vppe to heuen with iiij rapes at iiij corners
8. A heuen of Iren with a naffe of tre
9. ij peces a rede cloudes and sternes of gold langing to heuen
10. ij peces of blu cloudes payntid on both sydes
11. iij peces of rede cloudes with sunne bemes of gold and sternes for þe heist of heuen
12. A lang small border of þe same wurke
13. vij grete Aungels halding þe passion of god Ane of þame has a fane of laton and a crosse of Iren in his hede gilted
14. iiij smaler Aungels gilted holding þe passion
15. ix smaler Aungels payntid rede to renne aboute in þe heuen. A lang small corde to gerre þe Aungels renne aboute

Figure 2.3 - Diagram of York Mercers' Pageant Wagon 1433 and corresponding key as included in Johnston and Dorrell (1973: 10, 15).

Twycross (1980) studied the Flemish *ommegangen*, which were religious processions on pageant cars that followed a predetermined route through a town, carrying relics or revered images to be venerated by the public (see Figure 2.5). The examination of written records of the processions as well as paintings by artists such as Boonan and van Alsloot resulted in the uncovering of evidence of their existence from the fourteenth century when floats with religious *tableaux* started being included, but the processions existed before this date when costumed figures representing religious characters walked in the processions (Twycross 1980).

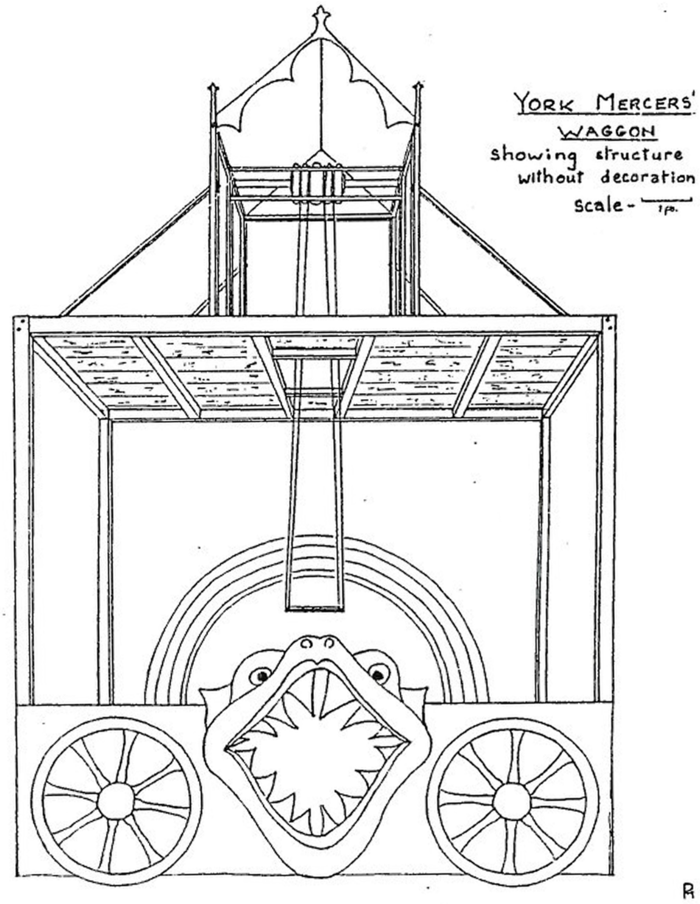


Figure 2.4 - The Mercers' Wagon according to Peter Meredith (1979: 14).

Figure 2.5 - *The Triumph of Archduchess Isabella* by Denys van Alsloot, 1615 – *Ommegang* in Brussels (Victoria & Albert Museum).

Twycross (1980) explains that although the wagons she analyses are from the Renaissance period she believes that the pageant cars used to represent biblical episodes remained mostly unchanged throughout the years and therefore would have been very similar to the medieval ones. The merchants of York who travelled to the Netherlands in the Middle Ages would have seen the *ommegangen* and could have returned to England with a description of the wagons, which in turn could have influenced the structures built by the craft-guilds in York (Twycross 1980).

Brussels and Louvain wagons analysed by Twycross (1980) consist in a base shaped as a cube, columns holding a roof and are open on all sides (see Figures 2.6-2.8) with the exception of some that include walls or balustrades built up to approximately knee-height (see Figures 2.9-2.12). Roof structures for Brussels and Louvain are shown as flat and heavily ornamented (see Figures 2.6, 2.9) or pitched (see Figure 2.7, 2.8, 2.11) whereas only two of the Antwerp wagons have roofs, *The Nativity* and *The Epiphany*, these roofs are pitched and in the case of *The Epiphany* it resembles a canopy (see Figure 2.13) (Twycross 1980).

Although the representations of the pageant carts used in the Netherlands provide a useful insight on the types of wagons used in other religious processional events, caution needs to be exercised when using pictorial representations since it is not possible to be certain of the accuracy of the depictions (Twycross 1980).

Figure 2.6 – *The Triumph of Archduchess Isabella* by Denys van Alsloot, 1615 – The detail shows the *Annunciation* wagon (Victoria & Albert Museum).

Figure 2.7 – *The Triumph of Archduchess Isabella* by Denys van Alsloot, 1615 – The detail shows the *Nativity* wagon (Victoria & Albert Museum).

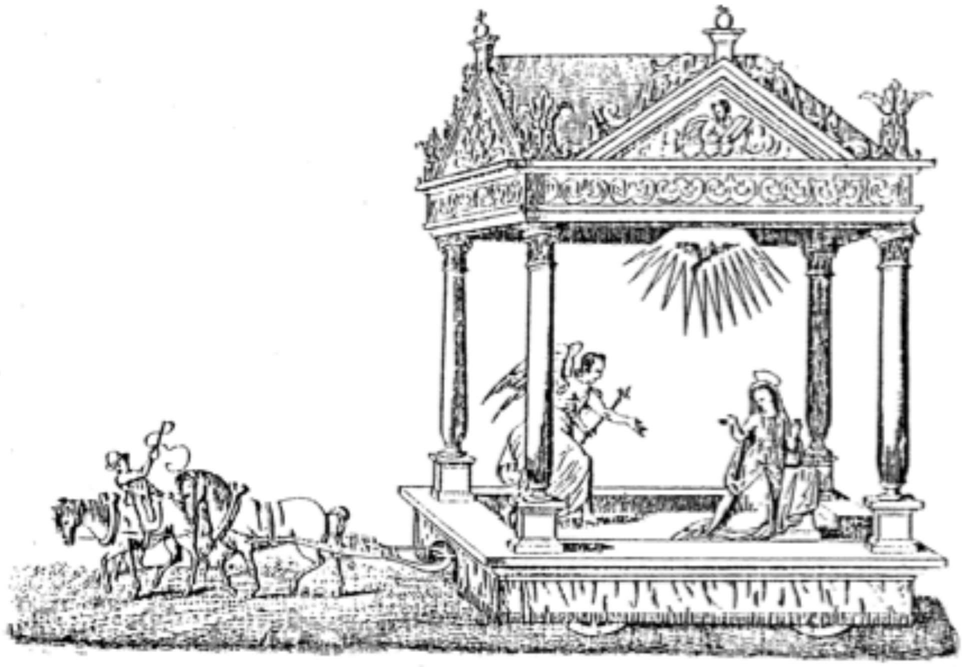


Figure 2.8 - Louvain – *Annunciation* wagon (Twycross 1980: 22).

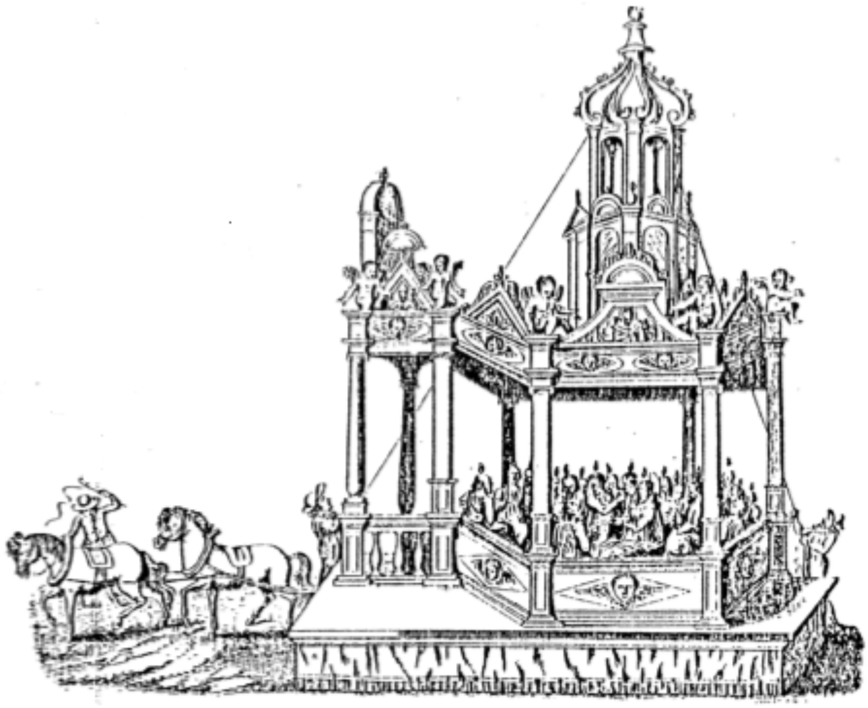


Figure 2.9 - Louvain – *Pentecost* wagon (Twycross 1980: 29).

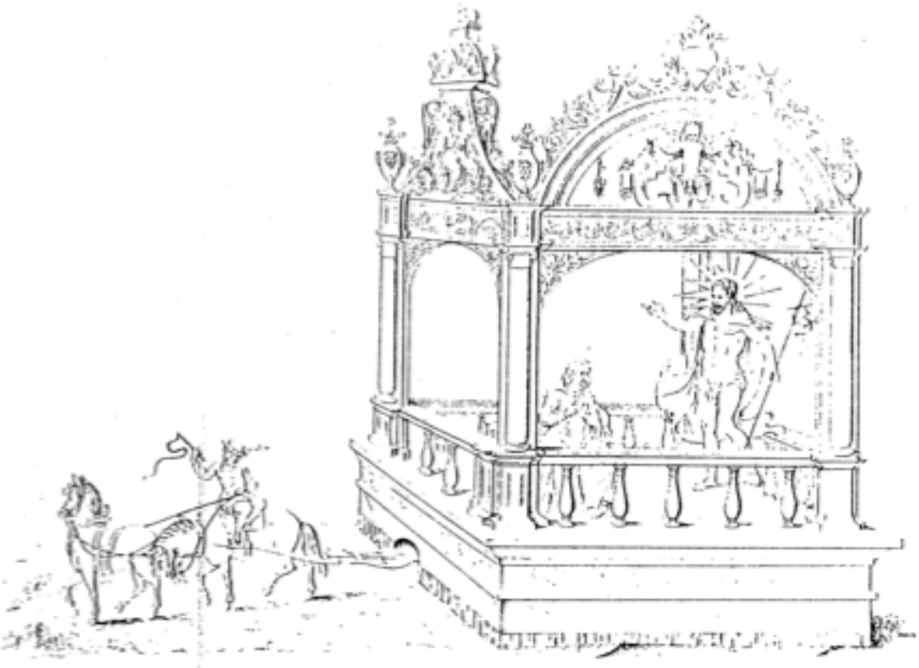


Figure 2.10 - Louvain- *Resurrection* wagon (Twycross 1980: 23).

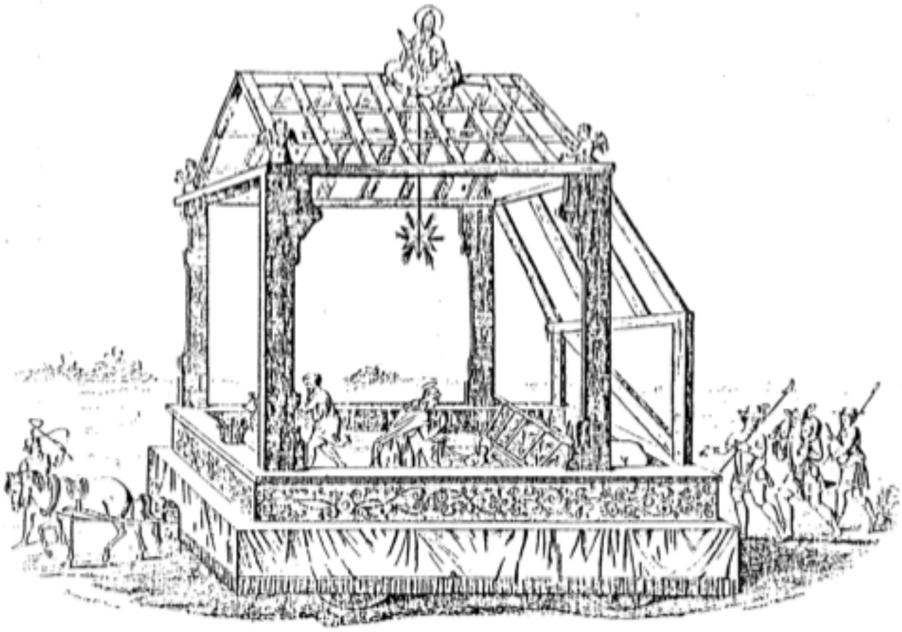


Figure 2.11 - Louvain – *Nativity* wagon (Twycross 1980: 24).

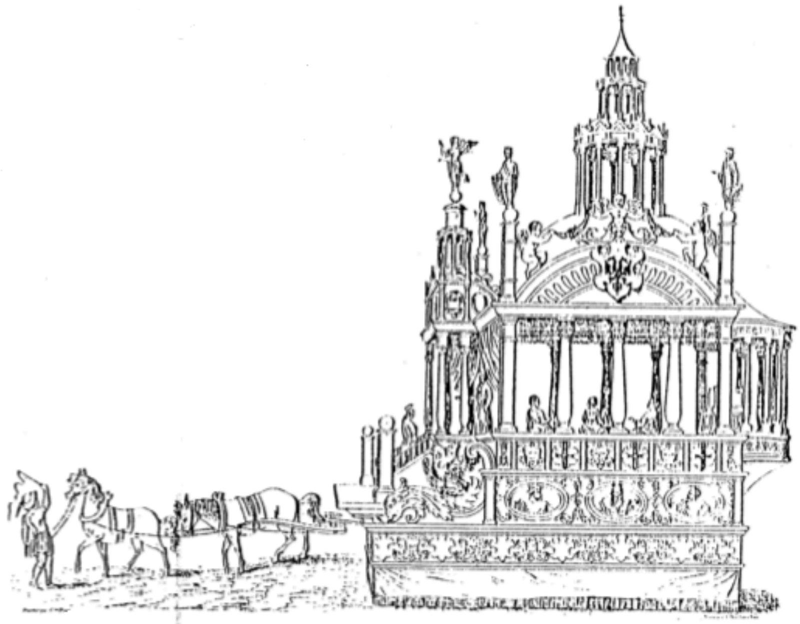


Figure 2.12- Louvain - *Presentation of the Virgin* wagon (Twycross 1980: 29).

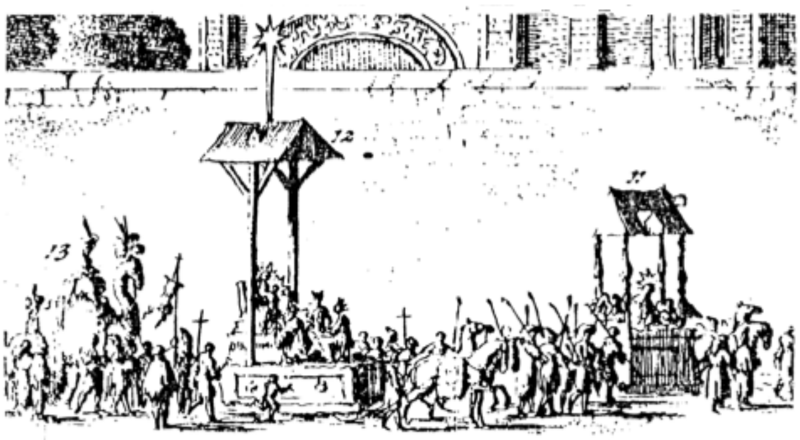


Figure 2.13 - Antwerp Ommegang (detail) by Jan Luyken (Twycross 1980: 24).

Nelson (1979) studied processional events in Spain by focussing on the Good Friday procession in Valladolid and the Holy Thursday procession in Medina del Campo. The Valladolid procession dates from the XVIth century and consists of twenty-four wagons that carry sculpted figures representing scenes from the Passion; the wagons used are four-wheeled, steerable, present mechanisms to raise the platform and to provide more floor space and have curtains covering the wheels (Nelson 1979). The procession in Medina del Campo includes eight scenes that are represented with sculpted figures on top of platforms and carried through the streets on the shoulders of guildsmen (Nelson 1979). None of the wagons in either of these processions have roofs or canopies, which Nelson (1979) believes would obscure visibility for audiences.

The study of the streets of York themselves can further our understanding on the wagons used for the plays by indicating their possible dimensions. McKinnell (2000) points out that the streets of York became narrower with height due to the presence of overhanging jetties; therefore, multi-level wagons would have had to be lower than the overhanging jetties or narrow enough to be able to go through the space between them. Since the pageant route, as will be seen in section 2.5, was within the city walls, the city gates did not present limitations to the wagon height (McKinnell 2000). The wagon decks might have been approximately 1.83 meters high and it is possible that multi-level wagons such as the one belonging to the Mercers had a height of around 7 meters (McKinnell 2000).

B. Wagon Orientation

Two main alternatives for the orientation of the wagons during the performances have been studied: the side-on and the front-on orientations. Side-on orientation refers to the use of the longer side of the wagon as the front of the performance space, with the actors performing towards the side of the street (see Figure 2.14a). Front-on orientation indicates the use of the front of the wagon as the front of the stage, and in this case the performers are playing towards one end of the street (see Figure 2.14b).

Considering the side-on orientation introduces the question of whether the orientation was towards the left- or the right-hand side of the pageant route. In 1978 Twycross argued in favour of the left-hand side theory after noting that most stations were defined by places on the left-hand side. In 1992 she modified her theory and suggested that the wagons were used with a front-on orientation, stating that her support to the side-on theory had been mainly influenced by the consideration of the wagon as a proscenium stage and by the frontispiece by David Jee that is featured in Sharp's *Dissertation on the Pageants or Dramatic Mysteries anciently performed at Coventry* (see Figure 2.15).

Twycross (1992) explains that the modification of her initial theory was triggered by Eileen White's work (1984, 1987), which questioned the left-hand side theory, research on Alan Nelson's (1979) work on Holy Week processions in Valladolid and Medina del Campo and her own work on the Flemish *Ommegangen* (1980). Twycross clarifies, "I merely present it as an interesting non-culture specific solution to a common situation. These pageants are drawn/carried processionally through the streets, and oriented so as to make the maximum visual impact as they approach." (1992: 80).

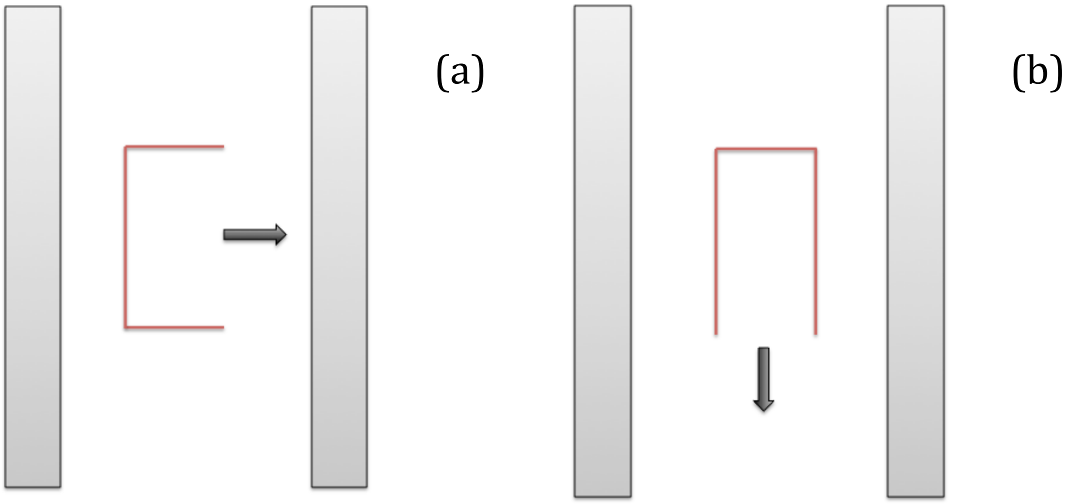


Figure 2.14 – Representation of wagon orientation, the arrows show the orientation of the performance. **(a)** Side-on orientation, **(b)** Front-on orientation.
The wagons were represented as semi-enclosed structures to facilitate the interpretation of the figure.

McKinnell (1990) also supports the theory of front-on orientation; as arguments for this theory he mentions the impact the wagon produces when approaching down the street, the similarity of this type of staging with other contemporary forms of visual arts, the lifting gear not overbalancing the wagon, and less manoeuvring required than with a side-on wagon, as turning the wagon to face the corresponding side of the street would not be an issue. Moreover, he considers that side-on wagons would have been too wide for the streets, and in some stations where the streets were narrow the audience would have been too close to see properly, a front-on wagon, on the other hand, can use as much of the length of the street as necessary (McKinnell 1990)

Nelson (1979) highlights that the wagons used in Valladolid and Medina del Campo follow a front-on orientation, and he states that

> Reconstructions of English pageants with orientation to the side should be considered problematic, as a) virtually with no precedent in illustrations of medieval or Renaissance processions, and b) limiting visibility to one side of the pageant or the other, unless the pageant is turned around in its course. (Nelson 1979: 69)

Figure 2.15 - David Jee's frontispiece in Sharp's *Dissertation on the Pageants or Dramatic Mysteries anciently performed at Coventry,* 1825 (British Library Images Online).

McKinnell (1990) mentions as a downside of the front-on orientation that it would have been difficult to use the front of the wagons as an entrance for actors because of the space taken up by the steering circle and undercarriage; a problem that could have been solved by the use of detachable steering bars.

White (1987) points out that if scaffolds were placed on the sides of the street for paying audiences (see section 2.6) then the use of front-on wagons would have resulted in a restricted view of the plays, that would have been the same or worse than that of the standing audience that was watching the play without charge. Twycross (1992) suggests that the scaffolds might have been placed across the mouth of the streets eliminating the problem of limited visibility, adding that

> This seems to hinge on the nature and amount of visibility expected by a medieval audience. It may be that this was not the same as ours. In fact, the concept of equally good sightlines for every member of the audience is a relatively new one, even in purpose-built theatres: and we could not expect it when watching a procession. (Twycross 1992: 88)

Nevertheless, Twycross (1992) suggests that if enclosed wagons were used then they are less likely to have had a front-on orientation since an enclosed front-on wagon would have resulted in the view being most likely completely blocked for those members of the audience watching the plays from windows.

A further drawback of the front-on orientation is that the actors would have strained their voices in order to reach a greater number of people and ensure their involvement in the plays (White 1987, 2000). Moreover, differences in wagon orientation would have resulted in different actor-audience dynamics. Side-on performances in the narrow streets of York would have been more intimate, whereas, performing longitudinally would have enabled a greater number of people to see the play (White 2000).

White (1984) suggests that playing stations located at street junctions (see section 2.5) might have presented the opportunity for an alternative orientation; they could have been positioned against one of the street corners, with actors performing towards the property/properties listed as part of the station, while also allowing greater room for audiences (see Figure 2.16).

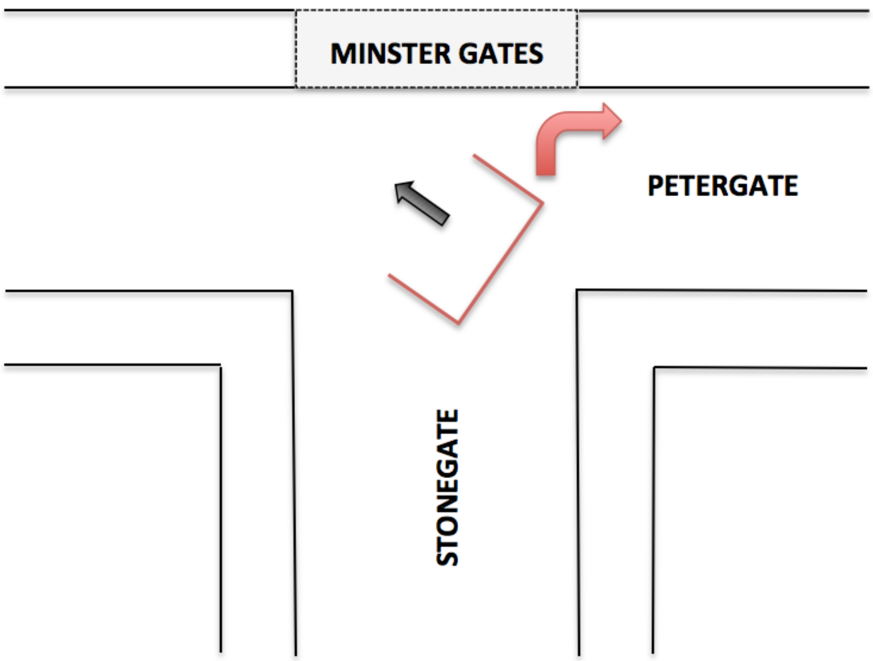


Figure 2.16 – Possible wagon orientation at Minster Gates. The black arrow indicates the orientation of the wagon and the red arrow indicates the direction of the pageant route. Adapted from White (1984: 462).

C. Wagon Space vs. Street Space

The only surviving evidence of the use of the street level in medieval processional drama comes from the Coventry Cycle in which the following stage direction is found: "Here Herod rages in the pageant and in the street also" (Beadle and King 1995: xxiii). This direction has often been taken as proof of the use of the street space in other cycles (Beadle and King 1995), although it has also been argued that the necessity of including this direction may be an indication of an atypical situation (Rogerson 2000).

Beadle and King (1995) consider that the wagon space would have been insufficient to perform the longer plays, whereas Blasting (2000) argues that the use of street space was not related to space limitations, but to the representation of the journeys taken by the characters. Such would be the case in *The Entry into Jerusalem*, where the street would have been used to represent Jesus' journey on the donkey (Blasting 2000). Additionally, the limited space would have forced the performers to be positioned in a 'flat manner' (standing next to each other) making the staging technique analogous to representations in the medieval visual arts (Blasting 2000). Blasting (2000) also questions Kolve's (1966) argument that the street was used for actions that were not geographically localised. He believes that Kolve's theory is influenced by modern conceptions in which the stage can only represent one space at a certain time, but this was not an existing conception in the Middle Ages, as it can be seen in medieval paintings representing more than one event simultaneously (Blasting 2000). The use of the street space might have also been impractical because of time limitations, the narrow width of the streets of York and because it would have resulted in a greater number of people having difficulty in seeing the plays (Blasting 2000).

Walsh (2000) argues that the relationship between street space and wagon space was particularly important in those plays that included "travelling scenes" and "high places"; the street space was utilised to represent the journey of the characters and the wagon represented high places that could also have symbolic significance. This could have been the case in *Abraham and Isaac*, where Mount Moriah could have been represented by the wagon, emphasising its importance and highlighting the connection between Isaac carrying the firewood as an antitype of Jesus carrying the cross (Walsh 2000). Walsh (2000) considers the problems of visibility derived from playing at street level only relevant when considering non-paying audiences, since paying audiences would have watched from scaffolds or the windows of nearby buildings. Furthermore, the audience at street level may have been accustomed to being in close proximity to the actors, and acquainted enough with the theatre codes of the time to make space for the actors in the travelling scenes (Walsh 2000).

Rogerson (2000) defends the theory of on-wagon performances stating that modern directors often interpret parts of the York text as indicators of the use of street-level but they might not have had this meaning in early theatre. The stage directions implicit in the dialogues are interpreted through a modern conception of theatre in which words that refer to an action or movement will necessarily have to be accompanied by the corresponding action, but limited movements on the wagon could have been just as effective in creating the illusion of travelling (Rogerson 2000). Rogerson (2000) also suggests that staging techniques might have been different among the guilds and that the same play may have varied in its performance according to the station.

McKinnell (2000) takes an aural approach to the consideration of street-level performances by suggesting that the street-level might have been reserved for those scenes that were loud enough for the audience not to mind whether the action could be seen.

2.5 The Stations

The York Mystery Plays were performed processionally, which meant that the wagons followed a predetermined route through the city (see Map 2.1) and they stopped at different stations (street spaces) where an audience would have gathered to see the plays. The pageant route remained the same throughout the history of the Cycle but the number of stations used as well as the stations themselves varied (Twycross 1978; White 1988). Both the Cycle and the Corpus Christi civic procession followed the same route up to Minster Gates (Cowling 1976). At Minster Gates the wagons would turn right into Petergate and their final stop would be on Pavement, whereas the civic procession would enter the Minster precincts and exit them through the southeast to reach St. Leonard's Hospital through Lop Lane (now Little Blake Street) (Cowling 1976).

The York city records indicate that the council was particularly interested in regulating the playing places. In 1394 it ordered that the plays should be played in the "places appointed from ancient times and not elsewhere" (REED 1979: 8, 694) and that a failure to do so would result in fines for the members of the craft-guild at fault. A record from 1399 (REED 1979: 10-12, 697-698) indicates that illegitimate playing places are being added, resulting in the impossibility of performing all the pageants on the same day. Such a situation is noted as an inconvenience both for the commons of the city and any members of the audience who have travelled to watch the plays. It is requested that from then on the plays only be performed in the twelve stations (see Appendix - Table 2.2) that had previously been approved by the Mayor and the Council and that fines for the addition of spaces and for any craft-guild members holding up the performance be imposed; moreover, banners would be used to indicate the playing stations (REED 1979: 10-12, 697-698).

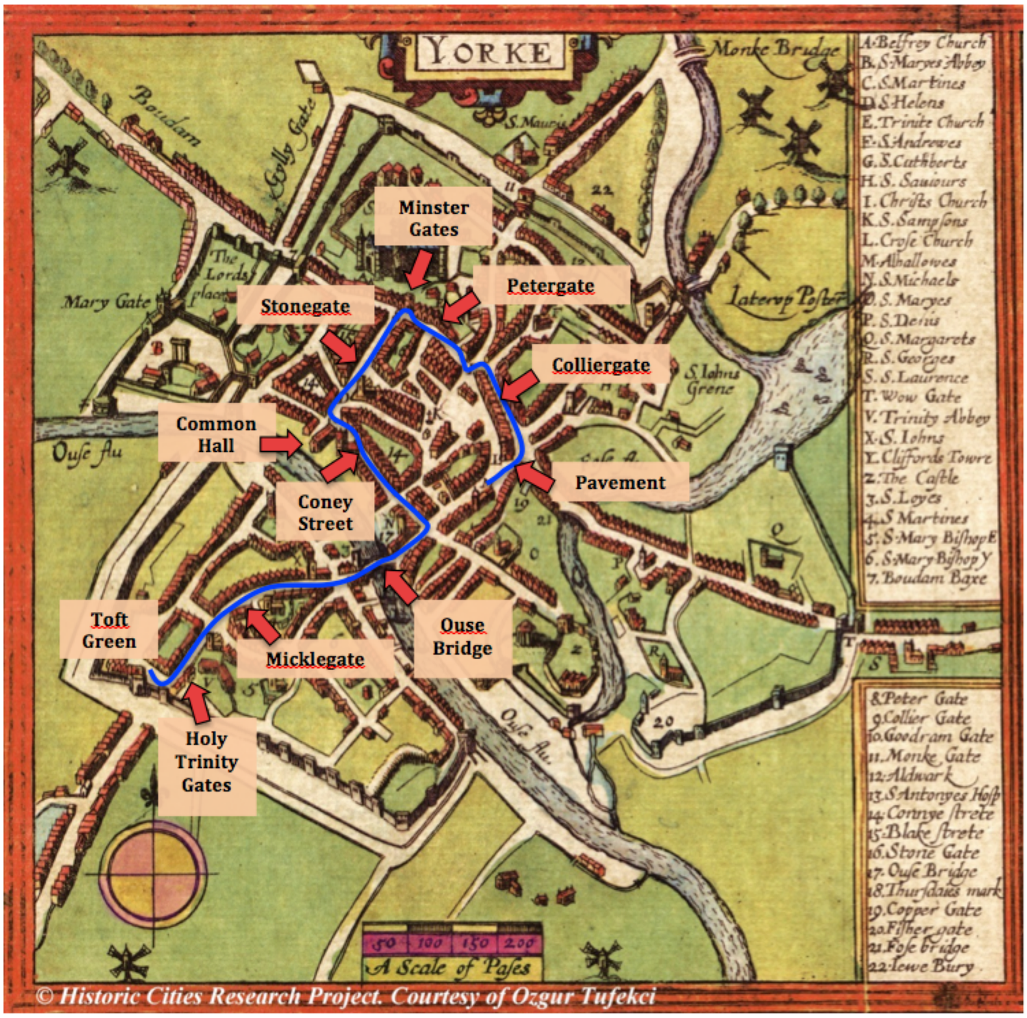
Crouch (1991) believes that the desire to keep to the prescribed stations was influenced by the fact that the "stationholders", which were the people that paid the city to have the plays performed at their door, would lose part of the profit they earned from letting house rooms to groups as well as places at scaffolds erected outside their property, if the performances were delayed due to additional playing places being used.

The 1417 proclamation requires the pageants to be ready by 04.30 and the wagons to be moved along the route as fast as possible (Dorrell 1972; REED 1979: 25). According to Dorrell's (1972) calculations, which are based on the stations used in 1399, the pageant of *The Last Judgement* would finish playing at the last station at 00.29. Due to the length of the performance any delays would have been considered serious. In 1554 the Girdlers were fined for delaying the performance by not being ready at the proper time (REED 1979: 314) and playing at unauthorised places (Dorrell 1972).

On the 7th of June 1417, the council decided that the people who built scaffolds outside their houses and rented places to an audience "shall pay the third penny of the money so received to the chamberlains of the city to be applied to the use of the same commons." (REED 1979: 28-29, 713-714) However, due to the closeness of the Corpus Christi celebration this measure could not be enforced (REED 1979: 29, 714). The 12th of June 1417 saw the genesis of what Crouch (1991) denominates the "auction system", when it was decided that the pageants

> must be played before the doors and holdings of those who have paid better and more generously to the Chamber and who have been willing to do more for the benefit of the whole commons for having this play there, not giving favour to anyone for his individual benefit, but rather that the public utility of the whole

of the commons of York ought to be considered. (REED 1979: 29, 714)



Map 2.1 – West Riding of Yorkshire (detail) by John Speed, 1610 (Historic Cities Research Project). The pageant route is indicated in blue.

The comparison of the playing stations of 1399 and 1569 demonstrates that many of the playing places were the same but in 1569 instead of twelve stations, seventeen were appointed on the 26 and 27th May (REED 1979: 356-357; White 1984, 1987) (see Appendix - Table 2.2). However, since the Chamberlains' records for this year have not survived it is not possible to corroborate whether payments were received for all stations and it is possible that some of the appointed places were not actually used for the performance (White 1984).

On the morning of the performance craft-guilds had to assemble in Toft Green, also known as Pageant Green, to get their pageants ready (White

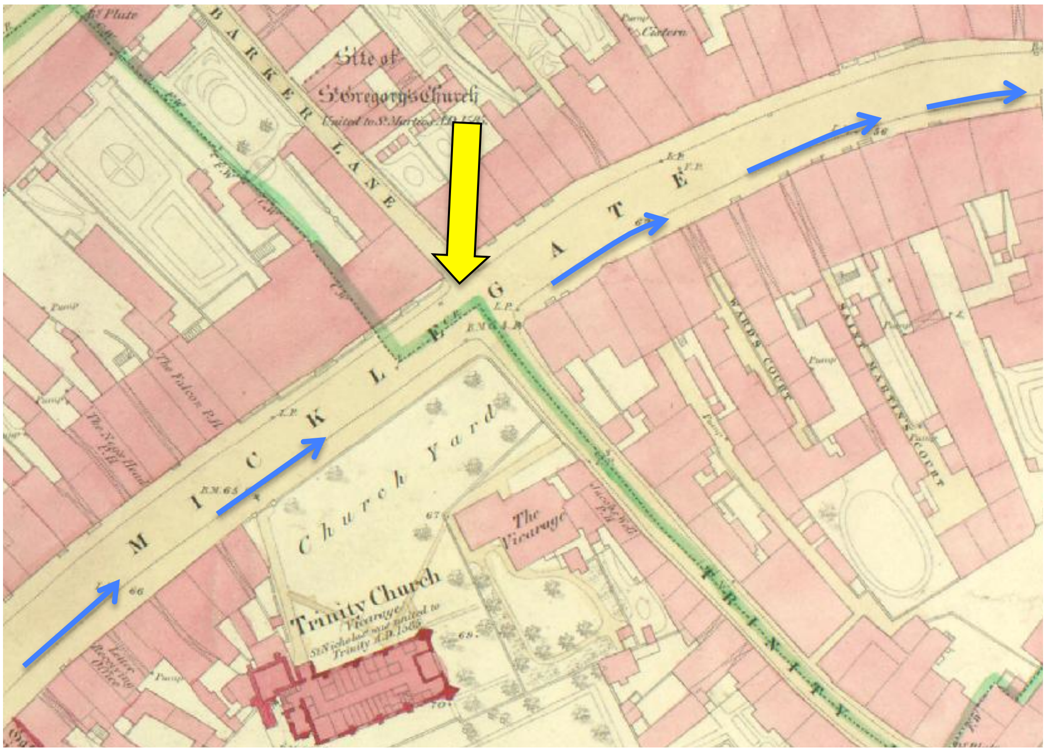
1984). Toft Green was within the city walls and when considering the pageant route it was to the left of Micklegate Bar. It was one of the largest open spaces in York and was used by several craft-guilds for the storage of the wagons in buildings called “pageant houses” (Davidson 2013; REED 1979: xxii; White 1984).

The first playing station was the Holy Trinity Priory Gates on Micklegate. The gate was demolished in 1854 and it can be seen in John Speed’s map (see Map 2.1); it is at this station that from 1520 the Common Clerk used *The Register* to monitor the performances (White 1984).

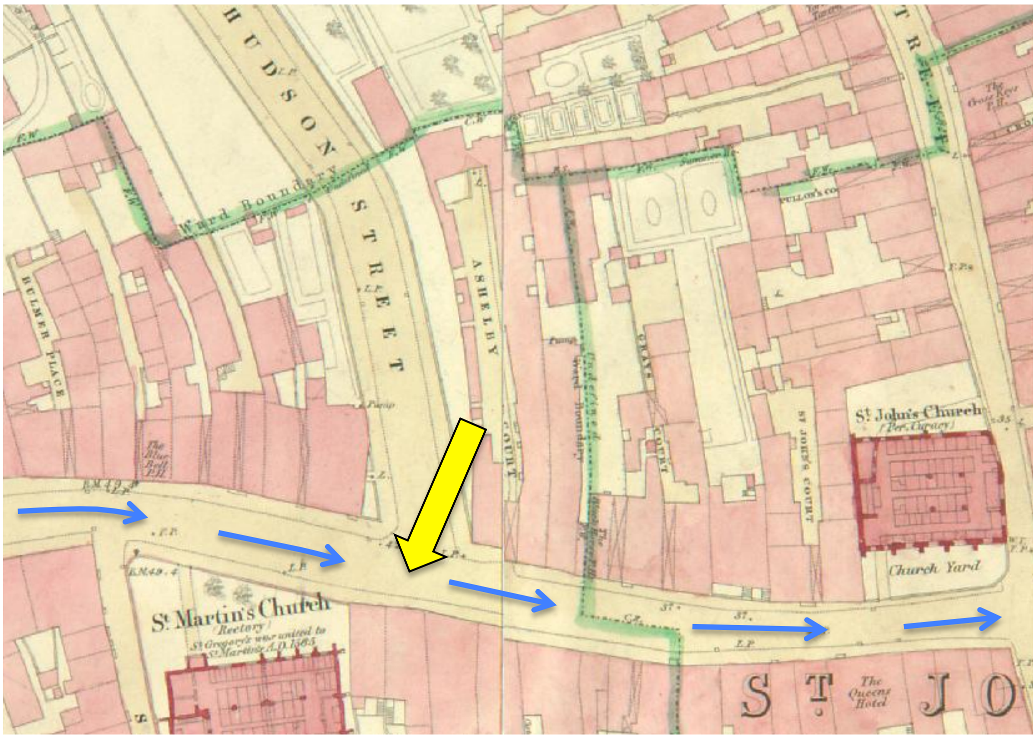
The next three stations in both 1399 and 1569 were also located on Micklegate, which together with Pavement were the broadest streets within the pageant route (White 1984, 1987). Micklegate was also of great relevance to the city as it was part of the route from London to Scotland (RCHM, III, 1962-81). Judging by the amount of money stationholders were willing to bid for the stations, Micklegate can be considered a popular area; such popularity could have been the result of audiences’ desire to see the plays when the actors were still energetic (Twycross 1978). It might have also been related to audiences wanting to finish watching the plays as early as possible so as to have more free time at the end of the day to pursue other holiday activities (Twycross 1978); audiences on Micklegate would have finished watching the whole cycle between 17.48-18.59 (Dorrell 1972). Moreover, the greater width at these stations would have allowed the congregation of larger audiences (White 1984), which would have been a more attractive prospect for stationholders. In 1399 the second and third stations were at Robert Harpman’s and at John de Gysenburn’s doors, whereas in 1569 they were appointed to Mr Harrison and The Cowper (REED 1979: 11, 698, 356-357; White 1984).

Mr Henrison/Harrison’s station has been located at the top of St. Martin’s parish, at Gregory Lane (now Barker Lane) on the left-hand side of the pageant route (White 1984) (see Map 2.2). The station assigned to The Cowper, identified as William Cowper, was located in the vicinity of the Three Kings Inn, which had been listed as a station in 1551 and 1554; the Three Kings Inn and Cowper’s property are thought to have been located at the lower end of St. Martin's parish, near Hudson Street and on the left-hand side of the route (White 1984) (Map 2.3). Such location for the third station would result in a distance of 162m in relation to the second station, the largest gap observed within the pageant route and justified by the presence of a hill between the stations (White 1984). The fourth station, also in Micklegate, is identified as being in the vicinity of St. John's church, located at the Micklegate, North Street and Skeldergate junction on the left-hand side of the pageant route (White 1984) (see Map 2.4).

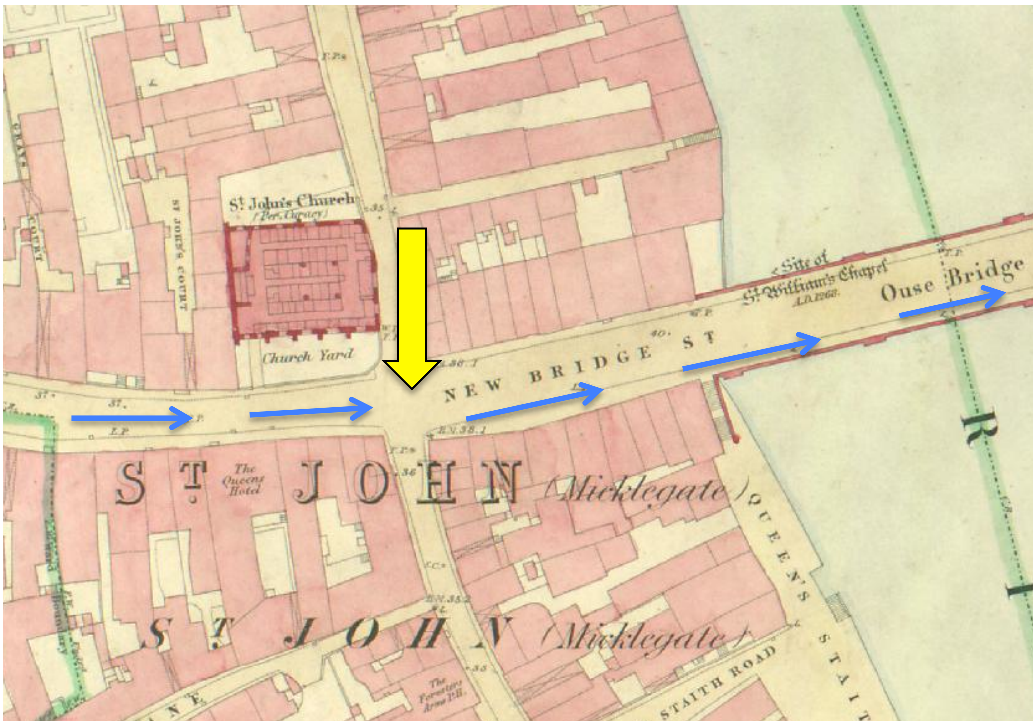
The 1569 list includes a station at Gregory Paycock's door, which is not present in the 1399 list. It can be located within St. Michael's parish, close to Ouse Bridge and on the left-hand side of the pageant route (White 1984, 2000) (see Map 2.5). The appearance of Ouse Bridge and Ousegate has changed significantly since the sixteenth century, when shops and houses were located on the bridge (White 1984) (see Figures 2.17-2.18). Moreover, the bridge used for the 1569 performance had been rebuilt in *c.*1567 when the previous bridge, which was made of stone and dated from the twelfth century, collapsed in the winter of 1564-5 together with twelve of the houses built on it as a consequence of flooding (RCHM, III, 1962-81; White 2000). No performances took place while the bridge was being rebuilt (White 2000). Both bridges had a width of approximately 5.64m and in the nineteenth century the sixteenth-century bridge was demolished in order to build a new wider one (White 2000). The next station, in both 1399 and 1569, is located at the crossroads joining Coney Street (now Spurriergate), Nessgate and Ousegate (White 2000) (see Map 2.5).



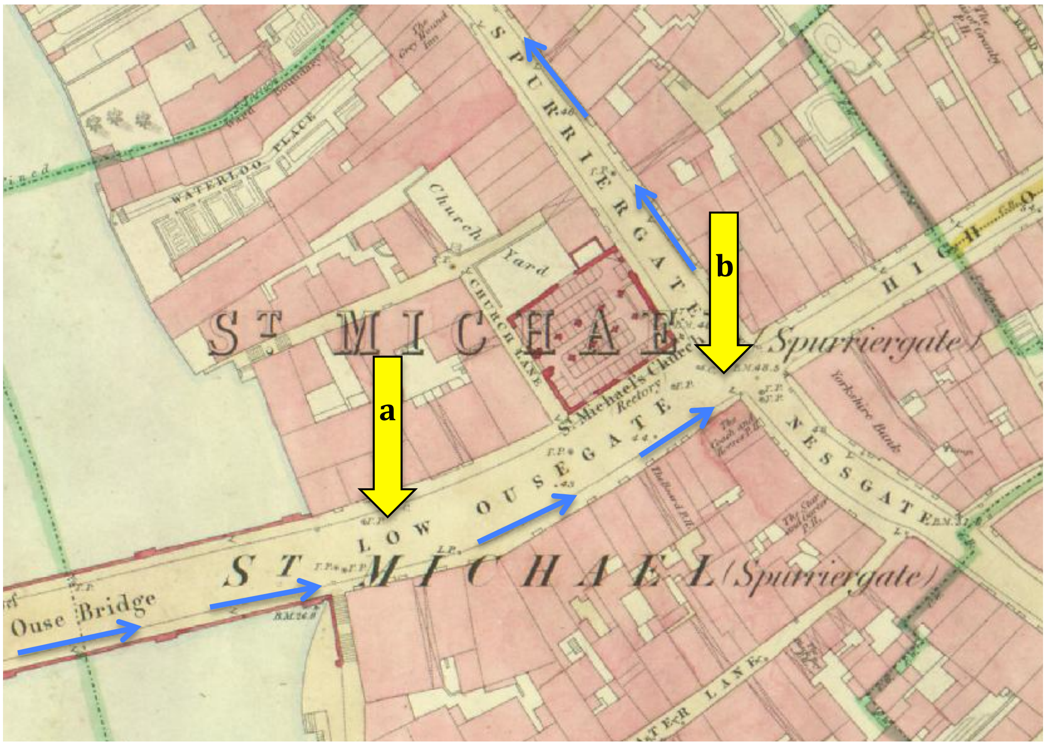
Map 2.2 – The yellow arrow indicates the approximate location of Mr Harrison's house in 1569. The boundary between Trinity Micklegate and St. Martin's parishes is marked in green (Ordnance Map Office 1852). The blue arrows indicate the pageant route.



Map 2.3 – The yellow arrow indicates the approximate location of William Cowper's station in 1569. The boundary between St. Martin's and St. John's parishes is marked by the green vertical line (Ordnance Map Office 1852). The blue arrows indicate the pageant route.



Map 2.4 – The yellow arrow indicates the approximate location of the fourth station at the junction of Micklegate, North Street and Skeldergate (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

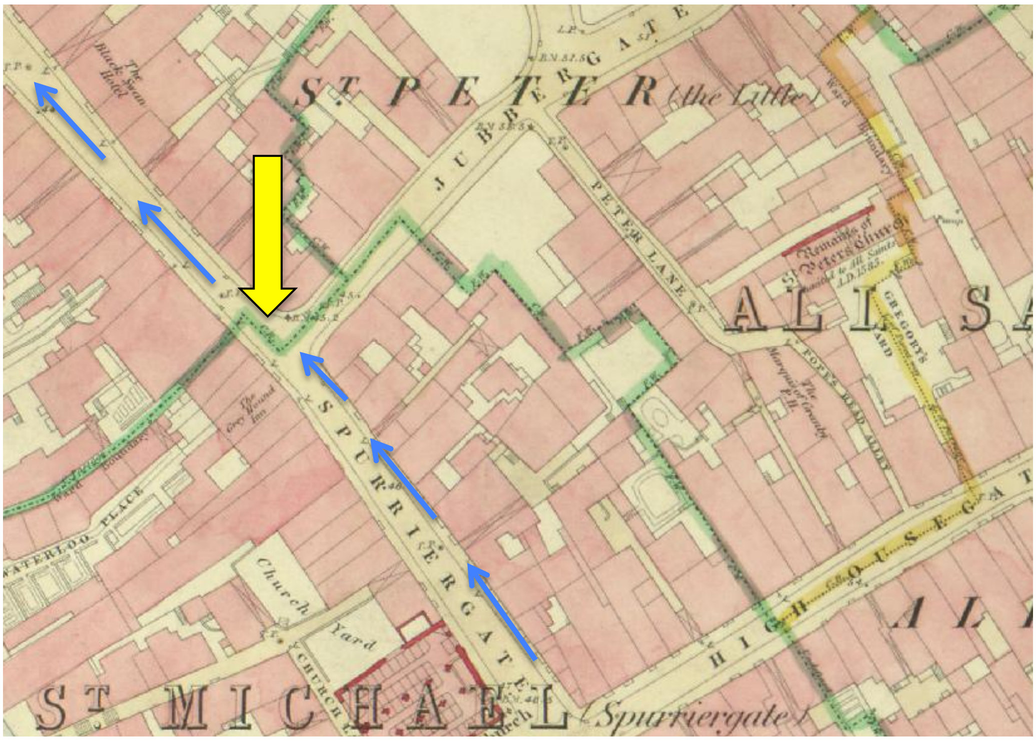


Map 2.5 – The yellow arrow labelled "a" indicates the approximate location of Gregory Paycock's house, and the arrow labelled "b" indicates the junction of Ousegate, Spurriergate and Nessgate (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

Figure 2.17 – *Low and High Ousegate* (Cave 1813).

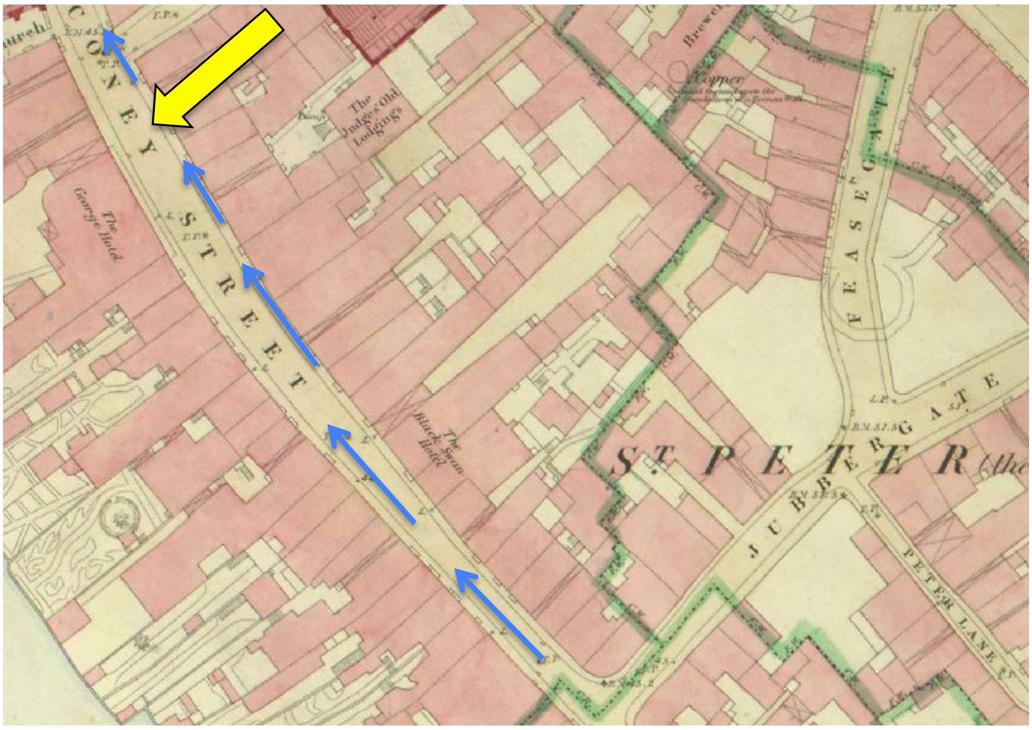
Figure 2.18 – *Ouse Bridge, York* by Francis Place, 1703 (Brown 2012: 73).

The next three stations are in Coney Street, which was much narrower at the time of the performances (around 7.01-10.06m); it was widened in 1770 and 1841 (White 1984). The first of these stations is located at the end of Jubbergate (now Market Street), where the road widens; in 1569 it was allocated to Mr. Appleyard, who was on the left-hand side of the pageant route (White 1984, 2000) (see Map 2.6). The next playing station cannot be precisely located but it is thought to have been midway between Jubbergate and the Common Hall (Guildhall) (White 2000). In 1569 it was allocated to Reginald Fawkes whose property was on the right-hand side of the pageant route (White 1984) (see Map 2.7).



Map 2.6 – The yellow arrow indicates the approximate location of Mr Appleyard's house in 1569 (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

The last station in Coney Street is referred to as Common Hall and Common Hall Gates in 1399 and 1569 respectively. The Common Hall (Guildhall) was built *c.*1449-59 by the city and the St. Christopher and St. George Guild (RCHM, V, 1962-81). It is located beside the River Ouse and separated from Coney Street by the Mansion House, which was built in 1725 as the residence of the Lord Mayor, with a courtyard in between the Common Hall and the Mansion house (White 1982). Before the construction of the Mansion House there were two tenements alongside Coney Street, which were separated by the Common Hall Gates and access to the Common Hall was through the gates and a 2.44m wide passage (White 1984). The tenements on Coney Street belonged to the St. Christopher and St. George Guild until 1549 when the dissolution of the religious guilds resulted in the reacquisition of the properties by the city (White 1984). If the indication of playing at the Common Hall is taken literally then the wagons would have had to turn left, go through the gates and the narrow passage to arrive at the courtyard outside the Common Hall (White 1984). Such manoeuvres would have not been possible with wagons of the size described in section 2.4 and it can be assumed that in all performances where the station was marked at Common Hall it referred to Common Hall Gates (White 1984) (see Map 2.8).

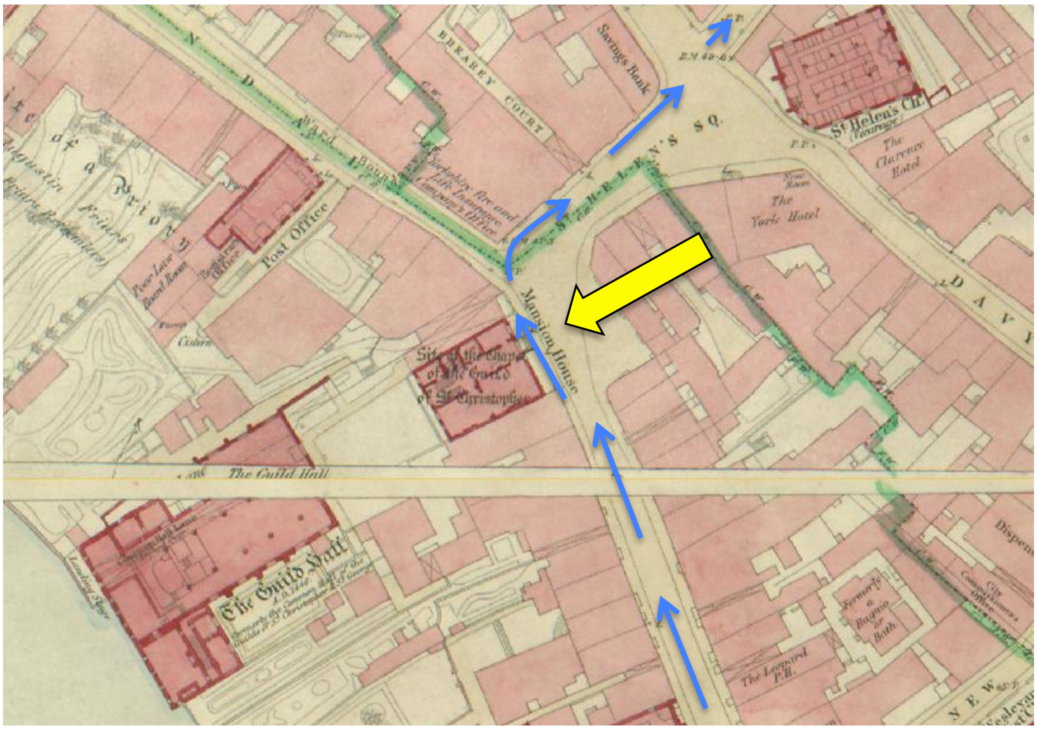


Map 2.7 – The yellow arrow indicates the approximate location of Reginald Fawkes' property (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

On Corpus Christi the Mayor and aldermen would gather to hear the play at a room along the pageant route and such gathering was recorded as taking place at Common Hall in 1538 (White 1982, 1984). The station was referred to as Common Hall Gates for the first time in 1551, after the tenements alongside Coney Street were reacquired by the city; therefore, the new name used for the station might be an indication that the Mayor could now use the tenements on Coney Street without restrictions and it is possible then that the Mayor and aldermen's party did not become fixed at this station until 1549 (White 1984).

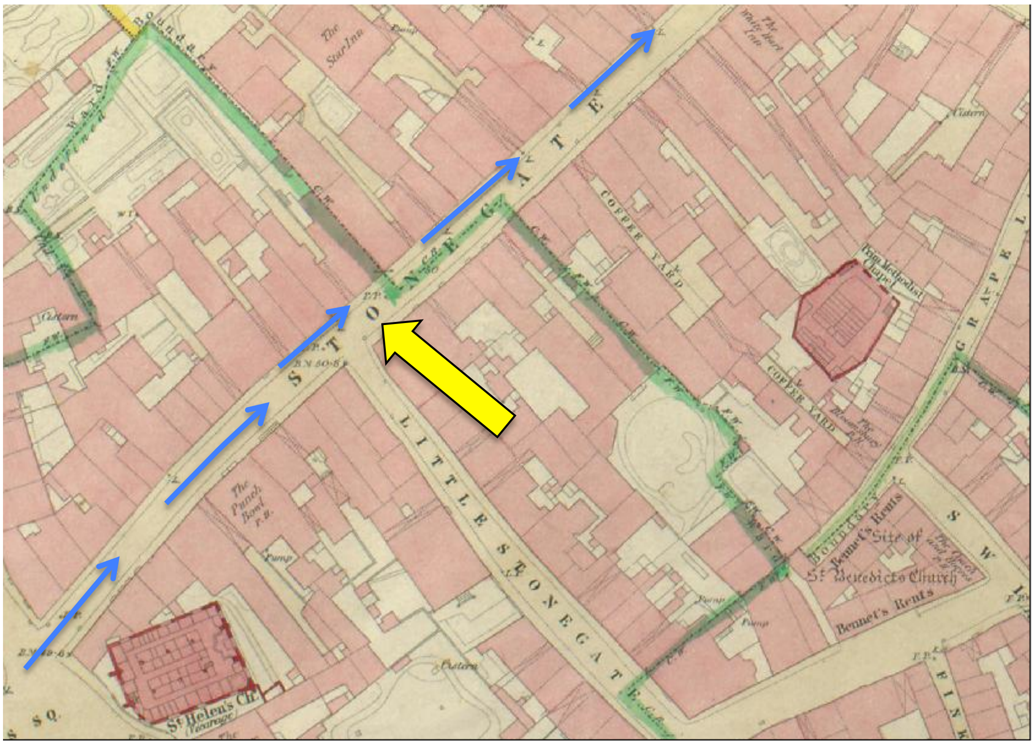
Figure 2.19 – *Coney Street* (Cave 1813).
The George Inn and the other buildings shown were midway between Jubbergate and Common Hall.

After playing at Common Hall Gates the wagons would turn into Stonegate, which at the time of the performances and until the eighteenth century reached Coney Street instead of St. Helen's Square (Raine 1955). There are two stations in 1399 and 1569 associated with Stonegate. The first one is indicated in 1399 as being at Adam del Brigg's door whereas in 1569 it is about Christopher Willoughby's house. Evidence indicates that Willoughby's house was half way down Stonegate on the boundary between St Michael le Belfray and St Helen's parishes, which was opposite Swinegate (now Little Stonegate) (White 1984). On the right hand side of the pageant route there were about six houses from Little Stonegate towards York Minster that were in St Helen's parish, where Christopher Willoughby lived (White 1984). His house could then be located on the right-hand side of the pageant route approximately where Mulberry Hall stands today (White 1984, 2000) (see Map 2.9 and Figure 2.19).



Map 2.8 – The yellow arrow indicates the location of the Common Hall Gates station (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

The second station listed in connection to Stonegate was located at Minster Gates. Minster Gates, nowadays the name of a street extending from Stonegate and leading to the Minster, was in medieval times the location of one of the gates into the Minster precincts, which was demolished sometime between 1736-1800 (RCHM, V, 1962-81). Although the name might lead us to believe that the play was performed exactly at that site, it is just an indication of the area in which the stationholder should be located (White 1984) (see Map 2.10). In 1569 no stationholders appear as having been allocated to this playing place and therefore the site cannot be precisely located (White 1984). In the 1554 record the site was identified in connection to Anthony Dycconson and Robert Staynburn and located in the corner of Stonegate, opposite the Minster Gates and on the left-hand side of the pageant route (White 1984).



Map 2.9 – The yellow arrow indicates the approximate location of Christopher Willoughby's house in 1569. The boundary between St. Michael le Belfray and St. Helen's parishes is marked in green (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

Figure 2.20 – *Stonegate* (Mulberry Hall) (Cave 1813).

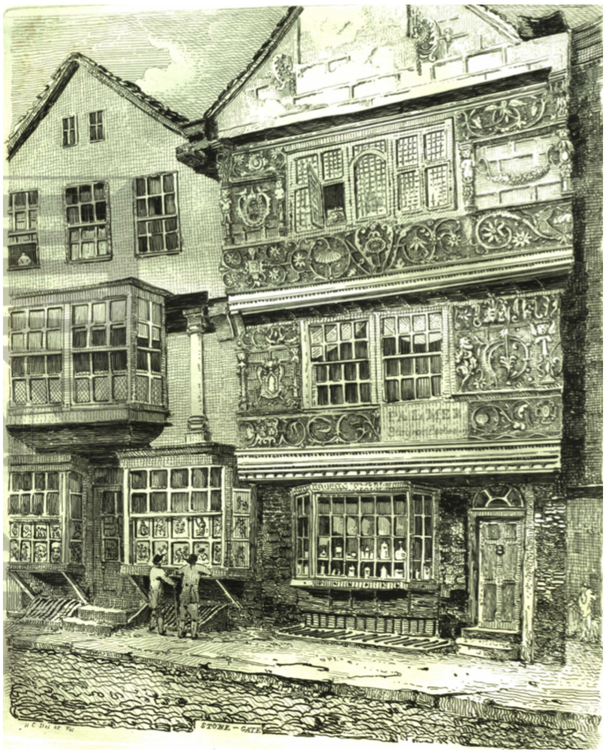


Figure 2.21 – *Stonegate* (Nos. 33 and 35) (Cave 1813).

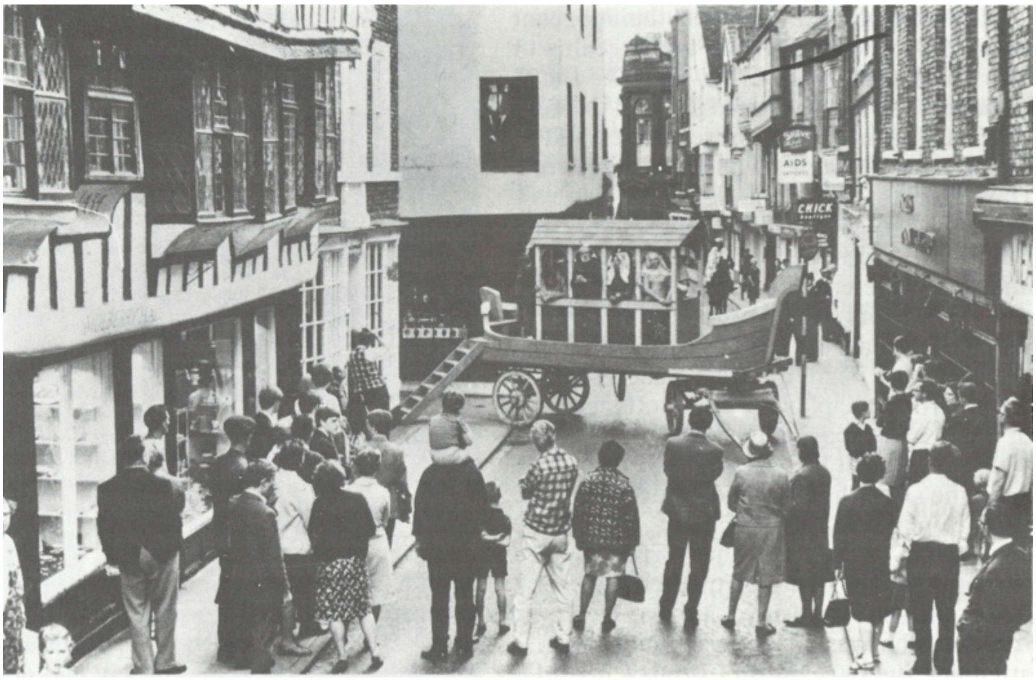
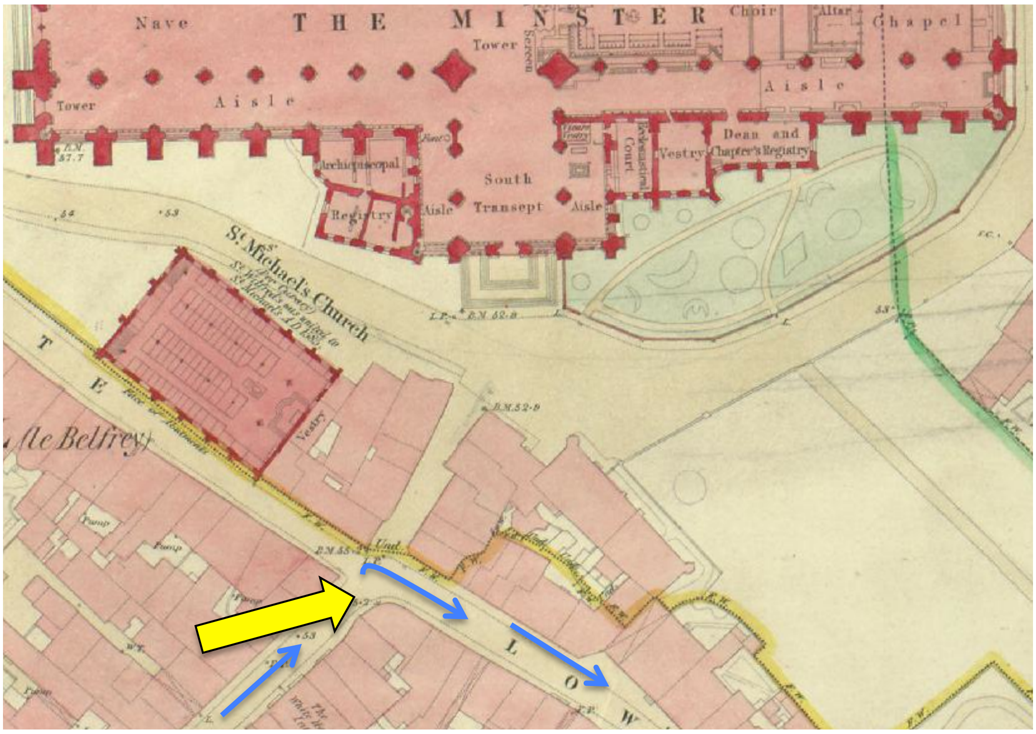


Figure 2.22 – *The Flood* in Stonegate in 1966 (White 1984b: 24).



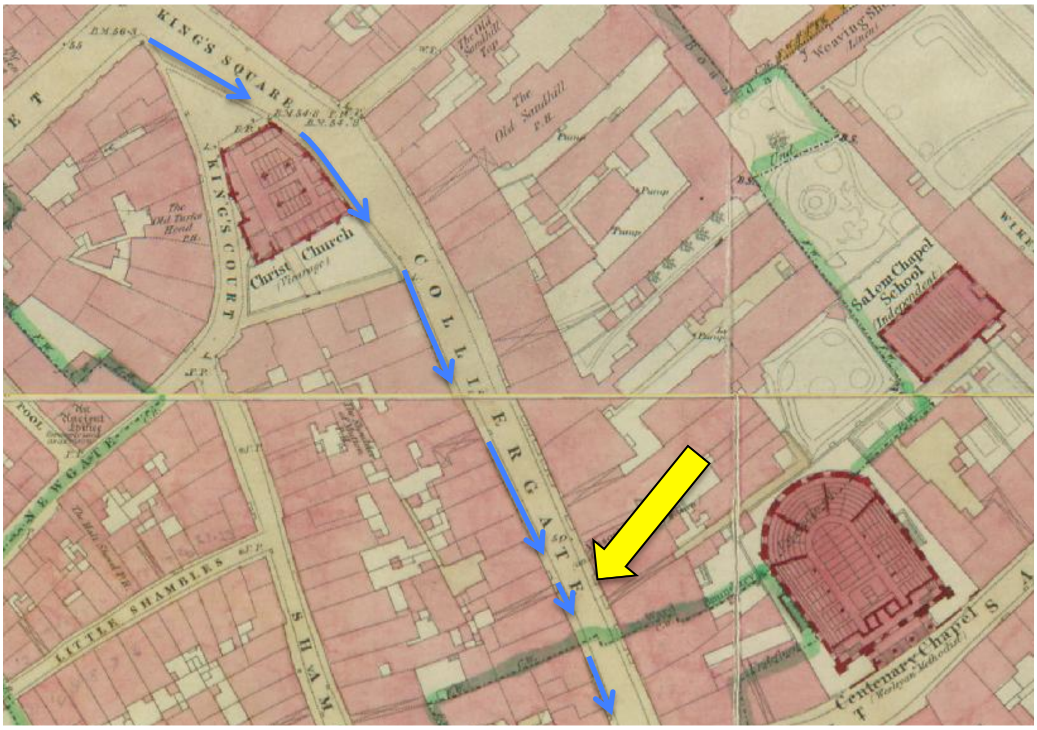
Map 2.10 – The yellow arrow indicates the approximate location of the Minster Gates station (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

In 1569 a station was added in Petergate and situated at Mr Birnard's house in Trinity Parish Goodramgate, only eight houses in Petergate, all on the left-hand side of the pageant route, belonged to this parish (White 1984). Four houses were located at each side of Hornpot Lane, which led to Trinity Church, and it is at Hornpot Lane where the station might have been located (White 1984) (see Map 2.11). Another station in Petergate, located at the end of Girdlegate (now Church Street), can be found in the 1399 and 1569 lists and in the latter it is appointed to Mr Hutton (White 1984) (see Map 2.11).

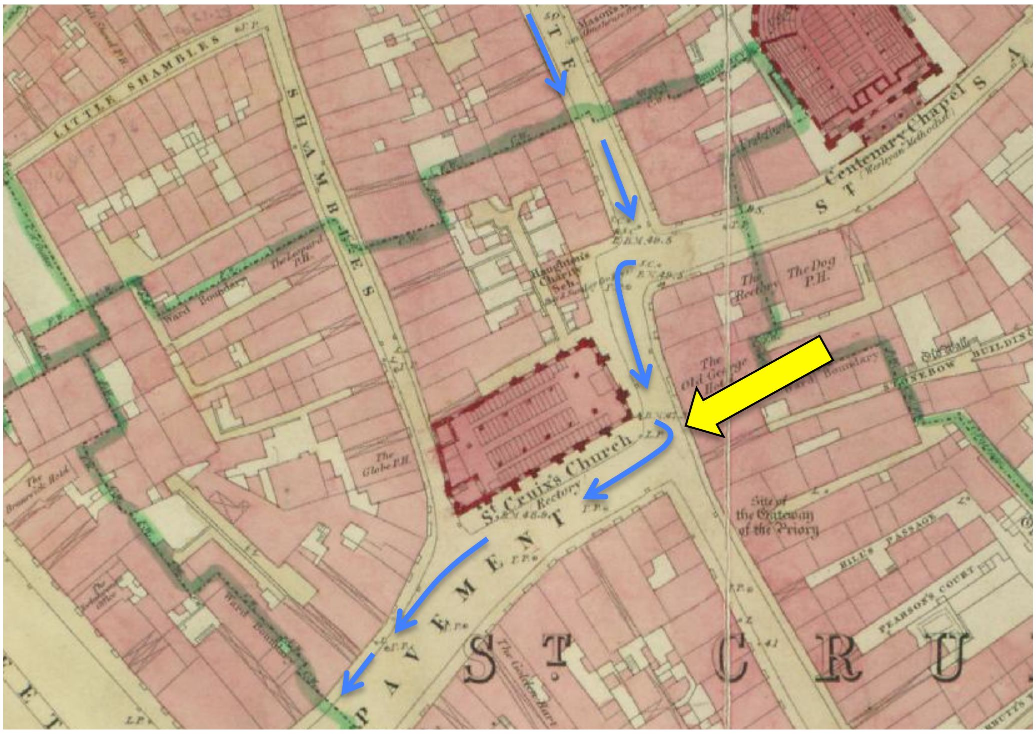
The 1569 list includes two additional stopping places between Girdlegate and Pavement. The first is a station appointed to John Chamber and located in Colliergate. Since John Chamber lived in Christ's parish the station could have been located towards the end of the street, providing as much distance as possible from the previous stopping place (White 1984) (see Map 2.12). The second was a station taken by William Beckwith, which may have been located at the end of Hosier Lane (now Pavement), near the gate of the Carmelite Friary, where Colliergate turns into Fossgate (White 1984, 2000) (see Map 2.13).

Map 2.11 – The yellow arrow labeled "a" indicates the approximate location of Mr Birnard's house, and the arrow labeled "b" indicates the station on Petergate at the end of Girdlegate. The green line on the upper section of the map indicates the St Trinity Goodramgate parish (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

The final section of the route was in Pavement and it is the section that has changed the most since the sixteenth century, with major alterations taking place between the seventeenth and the twentieth centuries. In the sixteenth century Pavement included two churches located at opposite ends of the street: St. Crux, situated in Hosier Lane (now Pavement) and All Saints, located in the direction of Coppergate and High Ousegate. In 1671 the demolition of a row of fourteenth century houses located in the All Saints area took place and a Market Cross replaced the buildings; the churchyard was also reduced in size in order to widen the street (RCHM, V, 1962-81). Further demolitions occurred in 1769 when a second row of medieval houses, this time located in Hosier Lane, was pulled down (RCHM, V, 1962-81) (see Figure 2.22). The nineteenth and early twentieth century saw the removal of the Market Cross in 1813, the creation of Parliament Street in 1836, the demolition of St. Crux in 1887 and the creation of Piccadilly in 1912 (RCHM, V, 1962-81).



Map 2.12 – The yellow arrow indicates the approximate location of John Chamber's house in 1569 (Ordnance Map Office 1852). The blue arrows indicate the pageant route.



Map 2.13 – The yellow arrow indicates the approximate location of William Beckwith's station (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

Figure 2.23 – *Pavement with the Church of St. Crux and All Saints* (Cave 1813).

Pavement is, along with Micklegate, the widest portion of the route and would have been able to accommodate larger audiences and therefore should have been a highly coveted space. However, the opposite was true and records suggest that the city struggled to find bidders and when it did find stationholders willing to pay for having the play at their doors the amounts paid were usually less than those recorded for other stations (Twycross 1978). The unpopularity of Pavement might have been due to the fact that plays performed there would have finished very late in the day (Twycross 1978); the first play would have been performed at about 06.58 and the last at 00.29 (Dorrell 1972).

In 1569, despite its unpopularity, two stations are listed in Pavement. They provide unprecedented examples in the life of the Cycle, as each of them is listed as being located between the houses of two different stationholders which lived on opposite sides of the street (White 1984, 2000). One of the stations is located between Mr Herbert's and the Sheriff's house and the other between Mr Paycock's and Mr Allen's properties.

Christopher Herbert lived in the site now known as Herbert House on the left-hand side of the pageant route midway between the station that was suggested for Mr Beckwith and the old Market Cross, whereas the sheriff mentioned in the list is William Robinson from St. Crux parish, who can be located opposite Mr Herbert's house near the Shambles (White 1984, 1987, 2000) (see Map 2.14). Robert Paycock's house can be located in All Saints parish at the end of Coppergate and it was on the left-hand side of the pageant route opposite the church (White 1984). William Allyn's house was located opposite Paycock's property, near High Ousegate, on the right-hand side of the pageant route (White 1984, 2000) (see Map 2.14).

As the plays finished at the last station the wagons would have been moved down Coppergate or High Ousegate, over Ouse Bridge and down Micklegate and back to Toft Green, where the craft-guilds that had pageant houses could dismantle their wagons and store them (White 1984, 2000).

Map 2.14 – The yellow arrow labeled "a" indicates the approximate location of Christian Herbert's and William Robinson's houses and the arrow labeled "b" indicates the station between Robert Paycock's and William Allyn's houses. The green line indicates the boundary between the St. Crux and All Saints parishes (Ordnance Map Office 1852). The blue arrows indicate the pageant route.

Stationholders seem to have been, in most cases, interested in the professional gain associated with having the plays performed at their doors and although stationholders could have different occupations, there seems to have been a great number of innholders and owners of alehouses (White 1984). Several aldermen had stations along the route, which seems unusual as they would have been able to join the Mayor at the Common Hall Gates, but it is possible that they had their own guests to entertain (White 1984).

2.6 Audiences

Although not much information survives as to how audiences watched the plays or what their reactions were to them, (Meredith 1996) it is possible to think about three main audience positions. The first one is the group of eminent individuals such as the Lord Mayor, the Lady Mayoress and the aldermen who could watch the performance from the windows of buildings, such as the tenements at Common Hall Gates, along the pageant route; a better view is thought to have been achieved by removing the glass from the windows (White 1984).

A different audience position might have been the result of people hiring a place at a scaffold set up at a playing station. Evidence for the use of scaffolds dates from 1417 and is recorded in the *A/Y Memorandum Book* where it is stated that the people who receive money from the scaffolds set up before their doors in public property should pay a third of their earnings to the chamberlains (REED 1979: 29, 713-714). This reference is the only extant record of the use of scaffolds; there is no documentation indicating how they were constructed or if they were used after this year (Meredith 1996).

The record also states "No one spoke against this kind of ordinance except only a few holders of scaffolds in Micklegate." (REED 1979: 29, 714). Meredith (1996) suggests that this statement could indicate that scaffolds were only constructed in Micklegate and complaints were arising due to the fact that a small group of people were making a profit out of using the public space. Furthermore, the closeness of the meeting (7th June) when the scaffolds where discussed to the date of the performance seems to indicate that it was a matter of urgency, suggesting that this might have been a new occurrence and the city was only now realising the possible repercussions (Meredith 1996). Meredith (1996) believes that the existing evidence suggests that scaffolds were only used in 1417 and only ever in Micklegate and, possibly, in the Pavement, which were the widest sections of the pageant route.

Although no information has survived regarding the characteristics of the scaffolds it is possible to gain an insight through the observation of Fouquet's *The Martyrdom of St Apollonia* (Crouch 1991) (see Figure 2.24). Southern (1975) provides a detailed analysis of the scaffolds shown in Fouquet's miniature and although this might indicate possible ways in which the audience's scaffolds of the York Cycle were constructed, it is necessary to bear in mind that the miniature depicts a different mode of staging, that of medieval theatre in the round and scaffolds are shown to be used both by actors and audience members. Fouquet's depiction shows a kneeling and standing audience at ground level, quite close to the action, while the different scaffolds, both for actors and audience, have floors raised by supporting posts at about 2.44m above the ground level (Southern 1975). An upper storey in each structure is formed by the inclusion of frames or rods that support the curtains that enclose the structure at the top, sides and back (see Figure 2.25); the ground level seems to include curtains at the back but it is unclear whether there are any at the sides (Southern 1975). The scaffolds have a width of approximately 2.44m, access to the actors' scaffolds is through a ladder or a ramp but no form of access is shown for the audience's scaffolds, suggesting that it might have been placed at the back (Southern 1975).

Audiences of the York Mystery Plays could have also watched the performance by standing at the playing stations. It has been suggested that standing audiences would have had a restricted view of the plays, with the best spots being reserved for the scaffolds, and the crowded streets would have limited their mobility (Crouch 1991). However, if scaffolds were only used for Micklegate and the Pavement, the widest streets within the route, then the narrower streets would not have been as cramped and more space would have been available for standing audiences and there would have been fewer mobility restrictions (Meredith 1996). Furthermore, Meredith (1996) argues that the standing audience would have been essentially mobile, reorganising the narrative presented in the Cycle by viewing the plays, either by chance or by choice, in a different order, some pageants more than once and others not at all. Additionally, evidence for the width of the streets as a way of limiting audience numbers can be found in 1551 (REED 1979: 298). In this year, due to a plague, the city council decided to reduce the number of playing places to ten and to remove Trinity Gates, one of the widest portions of the route, from the list (REED 1979: 298; White 1984). Such a measure seems to indicate that they were not expecting the lower number of stations to result in greater numbers of people congregating in the remaining sites (White 1984).

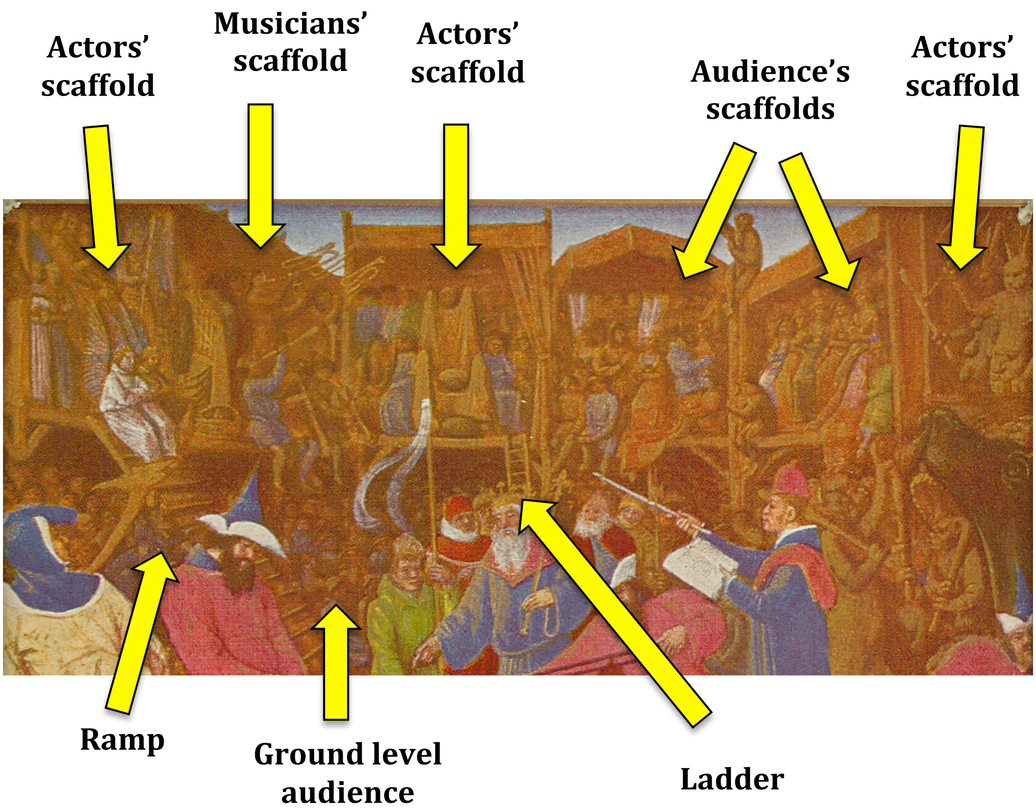


Figure 2.24 – *The Martyrdom of St Apollonia* by Fouquet, 1452-1460 (The University of Maryland – Digital Archive).

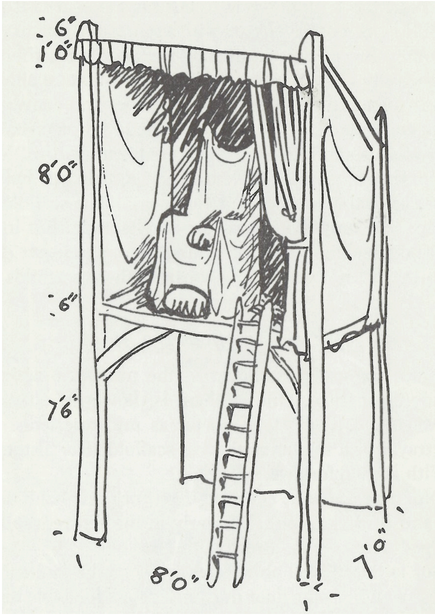


Figure 2.25 - Reconstruction of the actors' scaffold at the centre of Fouquet's miniature (Southern 1975: 96).

Rastall (1996) argues that standing audiences, due to their proximity to the actors, would have had a greater involvement in the actions portrayed than those located on scaffolds or at windows. In *The Crucifixion*, the standing audience would have been transformed into part of the cast by playing the part of the crowd surrounding the actual Crucifixion, without the presence of the crowd the play would lose its sense as only Jesus and the soldiers are scripted (Rastall 1996). Furthermore, audience members could have participated by responding 'Amen' to blessings and by singing some of the plainchant items (Rastall 1996).

2.7 The Soundscape: Acoustic Considerations

The rich soundscape of the city during the performance of the York Cycle would have been an essential part of the actors' and audiences' experiences. The soundscape would have included sounds that were intentionally produced during the performance, those that were a result of the performance but were not part of the narrative and those sounds that were independent from the performance.

The first category of sounds, those that were included intentionally as part of the performance, would include the actors' voices as well as the music sung and played as part of the Cycle (Davidson 2013). As it was observed in section 2.3 an essential characteristic for the actors involved was the ability to project their voices and to make themselves audible (King 2013; REED 1979: 25, 102, 109; Rogerson 2011b). Furthermore, the preponderance of the word over the action described by King (2000) seems to indicate that it must have been absolutely necessary for most of the audience to be able to hear the words as clearly as possible. Restricted audibility would have rendered effects such as voices off, the direction of audience's attention through the voice and the constraint of actions, ineffective and audiences might have felt detached from the plays. Although voice projection and volume would have been essential in achieving audibility (King 2013) it is also necessary to consider the role of the acoustics of the performances spaces in enhancing or compromising intelligibility. Consequently, it is of importance to study the acoustics of the playing stations, which would have been, in most of the cases (see section 2.5), narrower than today at ground level and further enclosed due to the presence of timber framed houses with prominent jetties (Davidson 2013, White 1987,).

Acoustic considerations in relation to the music of the plays are also essential. It is of relevance to study how the performance of plainchant items was affected by their rendition and reception in outdoor spaces, considering that these items were composed to suit the very different acoustic characteristics of religious spaces (Barron 1993) and it was in such spaces that they would have been regularly heard by churchgoers. Furthermore, the understanding of the acoustics of the spaces might help gain an insight on its effects on the different polyphonic settings included in *The Assumption of the Virgin* and their suitability for outdoor performances.

Although the research into the acoustic characteristics of the playing stations can further our understanding on their effects on speech and music, it is also necessary to consider the use of wagons and their impact on the acoustics. As outlined in section 2.4, there has been an abundance of research studies that have focussed on the use of the pageant wagons in York, including analyses on how they were constructed, their orientation and the use of the performance space. However, acoustic considerations have played a minor part in such studies. Moreover, when researchers have considered the York Mystery Plays through the study of other processional events they seem to refer to events that do not have an emphasis on the spoken word (the Flemish *ommegang* and the Spanish Holy Week processions) or where there is a limited amount of musical content, as is the case of the Flemish *ommegang* (Twycross 1980). It seems reasonable to assume that the staging choices in these processional events were mainly motivated by the visual requirements, but such choices might not have been suitable for the York Cycle.

Such reflection on the impact of acoustics on the York Mystery Plays cannot only include considerations on the characteristics of the stations and the wagons but should also investigate the different possible positions of performers (actors, singers) within the performance area, such as their position at street level or atop the wagon. Moreover, the different positions of audience members (standing, on scaffolds, within buildings) should also be contemplated in relation to the variations on the reception of spoken and sung elements.

Besides speech and music, intentional sounds would have also included laughs and coughs by the characters, although not necessarily scripted, and sound effects that might have been used to represent hell, for example, the use of a thunder machine (King 2013).

The second type of sounds populating the soundscape on the Corpus Christi day was a result of the performance but not part of the narrative. They included the sound of the mechanisms used to move God between Heaven and Earth in the Mercers' pageant, the sound of the wagon wheels as they were moved along the pageant route and the conversations among men pushing them from station to station (Davidson 2013, King 2013). Audiences would have also contributed to the soundscape by chattering between plays and, in the case of those watching the plays from within buildings, the sound coming from their feasts (Davidson 2013).

The last type of sounds includes those independent of the performance. Since Corpus Christi was a holiday the sounds associated with the usual jobs of the craft-guilds and the markets would have ceased (Davidson 2013), although some of those sounds such as hammering and nailing were very likely to have been intentionally introduced to the performance of *The Crucifixion* and *The Building of the Ark* (King 2013). The church bells would have rung to mark the canonical hours and the sound from the liturgical services emanating from the religious institutions would have been audible from the city streets (Davidson 2013, King 2013). Keynote sounds (Schafer 1977) resulting from the presence of both domestic and wild animals as well as sounds associated with weather conditions such as wind and rain would have completed the soundscape (Davidson 2013, King 2013).

The three types of sounds listed above are interconnected and the consideration of speech and vocal music in relation to the acoustics of the performance spaces needs to include an awareness of the possible impact other sounds had on them. It is very likely that sounds such as the church bells or the chatter of mobile audiences affected the intelligibility of the plays and the audience's involvement. Furthermore, there might have been instances in which the convergence of different types of sounds aided the overall reception of the plays. For example, music could have been used while God moved between Heaven and Earth to mask the sound produced by the lifting mechanism (King 2013). Furthermore, practical experiments in modern York have shown that processional staging results in sound leaking from one station to the other which would have created an unscripted connection between the actions watched and the sounds heard; this can be exemplified through the successive plays *The Flight into Egypt* and *The Slaughter of the Innocents* (King 2000). Audiences watching *The Flight into Egypt*, where Joseph and Mary escape after the angel Gabriel warns them that Herod would try to kill the new-born Jesus, would have seen Mary and Joseph escape as they heard Herod raging as a result of his failure in the next station, at the end of *The Slaughter of the Innocents* (King 2000). This connection emphasises the links among the plays of the York

Cycle and points out how the mode of staging itself can generate meanings that are not necessarily evident when reading the text.

2.8 Conclusions

The present chapter has studied the York Mystery Plays through references to the text, dramatic directions, performance, staging and reception, while bearing in mind the historical, political and cultural context surrounding their genesis, development and cessation. Such analysis has revealed the importance of aural elements for the performance of the plays. Speech and voice are key in conveying the religious message, directing the attention of spectators' away from other distractions, overcoming the limitations of the visual representations as well as creating theatrical effects. Vocal music, in the form of plainchant or polyphonic items, represented the praise of God by angels as well as non-divine characters. The performance of musical pieces from the liturgy would have created an association in the spectators' minds between the plays being performed for the honour and reverence of Jesus and the liturgical services they attended within their parish churches or other religious institutions. Such familiarity might have gone beyond just aiding the conveyance of the religious message and might have resulted in the participation of audiences in the dramatic events by joining in when the simpler plainchant items were performed.

Although aural elements are an indispensable part of the performance of the York Mystery Plays, little consideration has been given to the effects of the acoustics of the performance spaces on matters of staging, performance and reception. There are several questions surrounding the staging of the plays and scholars have developed different theories by relying on knowledge and techniques from different disciplines including history, early drama and archaeology, among others. To these disciplines it is also possible to add the study of acoustics as an essential means of furthering our knowledge on the effects of the performance spaces on speech and vocal music, including the impact of the playing stations, the wagons used, their orientation as well as performers' and audiences' positions.

Chapter 3 will introduce how virtual acoustics can be applied to the study of the York Mystery Plays and will present the concepts necessary for the analysis of speech and music in connection to the performance space as well as performers and audiences.

Chapter 3: Virtual Acoustics – Spaces, Performers and Listeners

3.1 Introduction

The present chapter introduces the acoustical concepts that are essential for the study of the performance spaces of the York Mystery Plays. It starts by presenting the concept of virtual acoustics, the work involved in its application and its relevance for the study of heritage sites. The chapter then turns to the consideration of concepts related to the acoustics of spaces, both indoors and outdoors, the human voice as a sound source, and sound perception. The focus on such concepts helps establish the interactions among spaces, performers and listeners, which are essential for the study of the spoken and sung content of the York Mystery Plays. Objective parameters for the study of room acoustics are then explained as well as accompanied by notions on suitable values for the performance of speech and music. Finally, concepts related to acoustic modelling techniques, in particular those utilised within this project, are introduced.

3.2 Virtual Acoustics

Virtual acoustics can be described as the design of computer models, using specialised software, to study the acoustics of spaces. It can be used for assessing the acoustics of existing buildings and devising ways in which to improve them. It could also aid in the design of new buildings such as concert halls or theatres, where virtual models could alert to potential problems that if ignored could result in construction modifications or redesign with undesirable financial implications. However, it is in the study of heritage sites that virtual acoustics becomes truly indispensable. It allows researchers to investigate the acoustics of sites that no longer exist or those that do survive but not in their original form, maybe as a result of demolitions due to changes in the infrastructure of the surrounding area, destruction as a consequence of wars or their deterioration as a result of the passage of time. It is also possible to apply virtual acoustics to the study of sites that, although partially or fully preserved, have limited the access to visitors. An example of such a site is found at Chavín de Huántar in Peru, whose ceremonial centre has been studied in relation to its acoustic characteristics and the use of virtual acoustics was proposed for the reconstruction of those parts of the site that are now inaccessible (Kolar *et al.* 2010). A similar approach has been used in the study of the Anta Pintada of Antelas, Portugal, which is a Neolithic tomb with restricted access to visitors, and that has been studied in order to create immersive virtual models that reconstruct the visual and acoustic aspects of the space with the aim of promoting the site through the Internet as well as within museums (Dias *et al.* 2008).

Acoustical studies using computer models can consist in the analysis of the characteristics of a space through a series of objective parameters, which will be discussed in section 3.3.3, but they can also include the process of auralization. Auralization, which is a term analogous to visualisation, describes a computer-aided process that renders audible a particular sound field, that is, it allows the user to hear the way sound is modified by the characteristics of an indoor or outdoor space (Kleiner, Dalenbäck and Svensson 1993). The user does not need to be in the space to hear its impact on sound and what is more, it is not necessary for the space to exist.

When working with virtual acoustics the first step is the creation of a computer model of the space to be analysed. The space is drawn by inputting data on its geometry, as well as that of any objects within it, in an x-y-z coordinate system to create a three-dimensional model (see Figure 3.1). In the model, appropriate materials are assigned to the surfaces of walls and objects by entering their absorption and scattering coefficients (see sections 3.3.1 and 3.4).

The second step is to create and position different sound sources and receivers within the modelled space. Sound sources could represent actors or singers and information on their location within the virtual space should be accompanied by data regarding directivity, aim and level (see section

3.3.2) (see Figure 3.2). Receivers represent listeners, for example within an audience, and need to be assigned a head direction (see Figure 3.2).

Figure 3.1 – Virtual Model of Modern Stonegate with its coordinate system

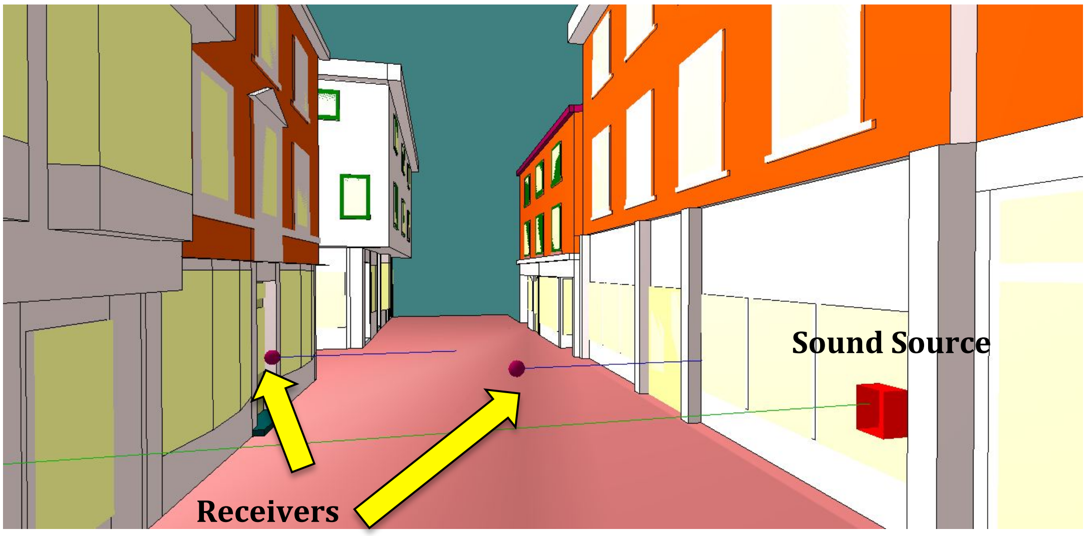


Figure 3.2 – Virtual Model of Modern Stonegate with a sound source and two receivers. Projecting lines indicate the aim of the sound source and the receivers.

For every source-receiver combination an impulse response is generated. An impulse response describes how a system reacts to an impulse, which is a sound of short duration and with a wide frequency range, such as a hand clap. In acoustics a space is considered as a system, therefore, an impulse response (IR) is the way a room responds to any such impulse and modifies it. Impulse responses can be thought of as snapshots of the acoustics of a space, from which a deeper understanding of the behaviour of sound can be derived (see section 3.3.3).

If the researcher wishes to auralize sound samples then it is necessary to carry out recordings in an anechoic chamber. An anechoic chamber is a room that is especially designed to eliminate all sound reflections by the use of sound absorbing material. Anechoic chambers recreate sound propagation in the free field, that is, in a space where there are no reflections. Recordings done in an anechoic chamber are "dry", which means that they do not contain any spatial information.

Once the audio material has been recorded it is necessary to convolve it (combine it) with the acoustic characteristics derived from the virtual model. Convolution is a mathematical operation that can be used to apply the acoustic characteristics of a space to an audio signal. The operation of convolution determines how an input signal is modified when it passes through a linear time invariant system (LTI). A linear time invariant system is a system whose response to an audio signal does not change in time, this is, if we input a signal now or in five minutes' time, the results will not vary (the system is invariant). Another characteristic of this kind of system is that if we double the intensity of the input to the system, then the output signal will also double (the system is linear). Such a system can be described by an impulse response.

Let's consider $x(n)$ as the input signal, this can be the dry recording of someone talking or singing. The impulse response of a system will be denoted by $h(n)$, which is in this case one of the impulse responses calculated from the virtual space modelled. The output signal will be denoted by $y(n)$. The convolution operation can then be written in mathematical symbols as follows

$$y(n) = x(n) * h(n) \tag{3.1}$$

When the input audio signal is convolved (*) with the impulse response of an acoustic system it results in an output signal that sounds as if it had been recorded in the acoustic environment in question (see Figure 3.3). In other words, the dry recording will now exhibit the acoustic characteristics of the space.

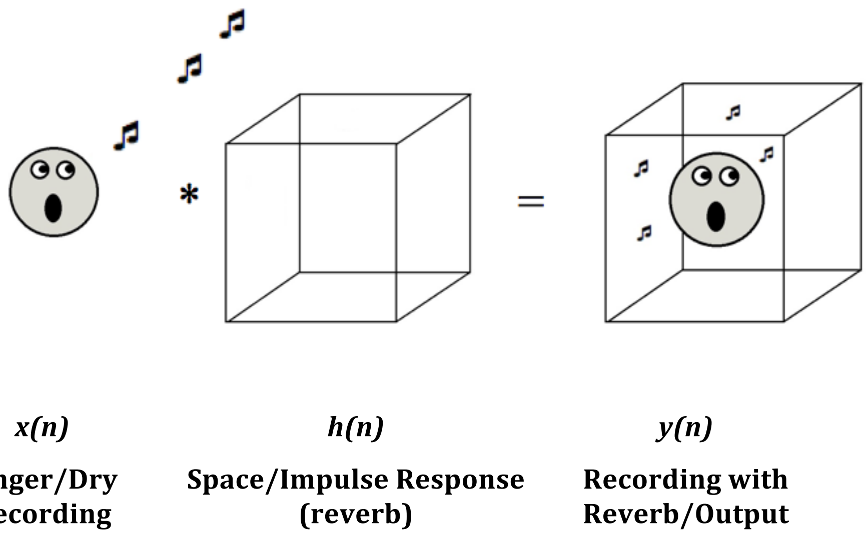


Figure 3.3 - Representation of the process of convolution.

Virtual models provide great flexibility for the study of the acoustics of spaces, especially when compared with the use of scale models, which require building scaled down versions of the space, finding appropriate surface materials and the use of specialised equipment for the measurement of ultrasonic signals (Kleiner, Orlowski and Kirszenstein 1993; Rindel 1995; Blesser 2007). Contrastingly, computer models allow fast changes in geometry as well as the acoustic properties of surface materials, by modifying the data inputted. It also facilitates experimentation regarding the positions of sound sources and receivers, as no specialised equipment is needed, with the exception of the software used.

3.3 Spaces, Performers and Audiences

Both performers and audiences have particular expectations when it comes to a performance space. Actors and singers want to listen to themselves so as to monitor their performance and avoid straining their vocal cords by singing or speaking louder than they need to (Howard and Angus 2001). The lack of auditory feedback is particularly challenging for singers as it might result in difficulties keeping in tune and although this can be compensated for by relying on bone-conducted sound and kinesthetic feedback, the problems can be exacerbated with certain musical styles; for instance, large musical intervals, a staccato style and a fast tempo are more challenging without auditory feedback than pieces with small musical intervals, a legato style and a slower tempo (Brereton, Murphy and Howard 2011; Mürbe et al. 2002). Performers in an ensemble also need to be able to hear each other clearly as this reinforces the tuning and rhythmic accuracy among singers as well as enables the performance to be balanced in regards to level, timbre and expression (Gade 1989b).

An audience, on the other hand, will expect sound (particularly speech), to be intelligible and at an adequate level to provide a clear perception of the performance. Additionally, in the case of music, the audience may wish to feel enveloped by the sound. These expectations will be explored in section 3.3.3 in relation to different room acoustics parameters.

Experiencing sound within a space is related to three main elements: the propagation of sound within a space, the properties of the sound source and the listeners' auditory perception. The following sections will explore these three elements in detail.

3.3.1 Sound Propagation

Sound propagation can be examined by considering a point source and a listener (**L**). A point source is an omnidirectional source that is smaller than the wavelength of the sound it emits and the wavelength of sound can be defined as the distance travelled by a wave within a cycle (see Figure 3.4). In the free field, where sound encounters no boundaries or obstacles, sound from the source spreads away spherically and as sound travels further away from the source the area of the sphere over which it propagates increases. As a consequence, the same sound intensity must spread over an increasing area suffering a loss of intensity when arriving at a listener positioned further away from the source (at positions that represent the increasing radius of the sphere).

The area of a sphere is

$$4\pi r^2 \tag{3.2}$$

The squaring of the radius (r^2) means that the area of the sphere increases by four (2^2) when the distance between source and listener is doubled, reducing sound intensity at **L2** (listener positioned at a distance of 2r from the source) to a quarter of the intensity at **L**. At **L3** (listener positioned at a distance of 3r from the source) the distance between source and listener is tripled, and the sphere has increased its area by nine (3^2) producing a reduction of intensity to a ninth (see Figure 3.5). This phenomenon is denominated the *Inverse Square Law* and it asserts that the "Intensity of sound is inversely proportional to the square of the distance in a free field." (Everest 2001: 84). This phenomenon can be defined as

$$I = \frac{W}{4\pi r^2} \tag{3.3}$$

where I is the sound intensity (Watts per metre square), W is the power of the source in Watts and r is the radius of the sphere (the distance of the listener from the source in metres). In practical terms, the inverse square law indicates a drop in intensity of 6dB for every doubling of distance and can be calculated by the equation

$$SIL_2\text{-}SIL_1 = 20log(^{r1}/_{r2}) \qquad (3.4)$$

where *SIL* refers to Sound Intensity Level at the second and first listener positions and *r1* and *r2* refer to the position of the listener in terms of the radius of the sphere (Hall 2002: 78).

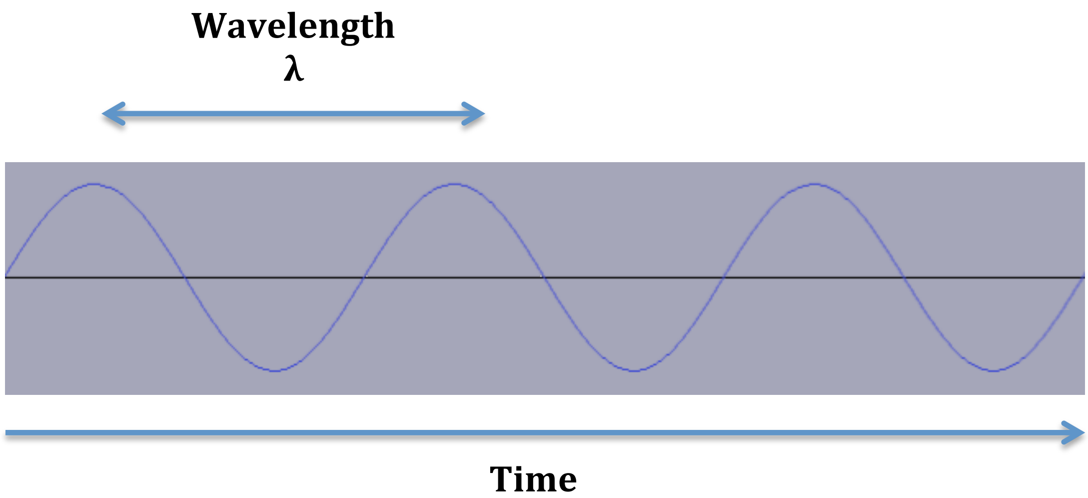


Figure 3.4 – Representation of a sine wave and its wavelength.

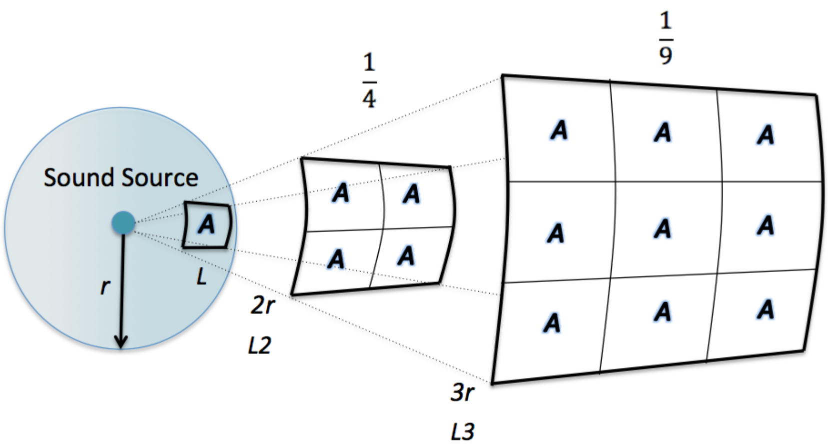


Figure 3.5 - Representation of the Inverse Square Law
(Adapted from Kearney 2009: 14)
L is a listener positioned at the radius of the sphere (*r*), **L2** is a listener positioned at a distance of 2*r* from the source and **L3** is a listener positioned at a distance of 3*r* from the source.

When a space presents boundaries or objects, although there is still a reduction of intensity as the distance between source and listener increases, such a relationship is affected by the reflection and absorption of acoustic energy in connection to the surfaces present in the space.

The relationship between sound source and receiver in enclosed or semi-enclosed spaces requires the consideration of the different components of the received sound: **direct sound**, **early reflections** and the **reverberant sound**.

Direct sound is the sound that travels in a straight line, which is the shortest path, between source and receiver. Direct sound is heard first and provides information about the location of the sound source. The delay between the emission of sound at the source and the arrival at the listeners' ears is very short and it can be established by considering

$$\frac{Distance\ between\ Source\ and\ Listener\ (m)}{Speed\ of\ Sound\ (344ms^{-1}\ at\ 20^{\circ}C)} \qquad (3.5)$$

(Howard and Angus 2006: 261-262)

The inverse square law can be used to study direct sound as it is unaffected by room boundaries and objects and as a result behaves in the same way as in the free field. Nevertheless, it is worth considering that sound sources will, in most cases, be directional instead of presenting the omnidirectional directivity assumed in the inverse square law (see section 3.3.2). Since direct sound is not affected by the characteristics of the space it is key to ensuring intelligibility (Howard and Angus 2006).

Early reflections are the discrete sounds that arrive at the listener after the direct sound, and which have reflected off one or more surfaces such as walls and ceiling (see Figure 3.6). The number of surfaces they have bounced off before arriving at the listener indicates their order. A first order reflection would have bounced off one surface before arriving at the listener, whereas a second order reflection would have bounced off two.

Early reflections are highly dependent on the position of the source and listener as well as the shape of the room. Although drops in the levels of early reflections can be related to the distance travelled, they are also affected by sound absorption. Sound absorption is the removal of acoustic energy from a space as a consequence of the presence of different surface materials. The amount of absorption by a material is indicated by the absorption coefficient, which may vary at different frequency bands. Early reflections are thought to affect sound by increasing the sense of loudness, augmenting the sense of spaciousness (if arriving at the side of the listener), increasing intelligibility and providing a sense of intimacy (Barron 1993).

Beranek (1962) analysed the effect of acoustical intimacy as a result of the Initial Time Delay Gap (ITDG), which is the difference in time (ms) between the arrival of direct sound and the first reflection at the listener. ITDG gives the listener an indication of the size of the space and it is connected to the subjective effect of intimacy of a performance (Beranek 1962). Acoustical intimacy occurs when, for example, a musical piece played in a large space sounds as if it was being played in a small room (Beranek 1962). ITDG values below 20ms are considered optimum whereas those between 20-70ms seem to affect the perception of musical quality negatively; values above 70ms are perceived as an annoyance, which is emphasised if the intensity of the first reflection has not dropped by over 10dB in comparison to the direct sound (Beranek 1962).

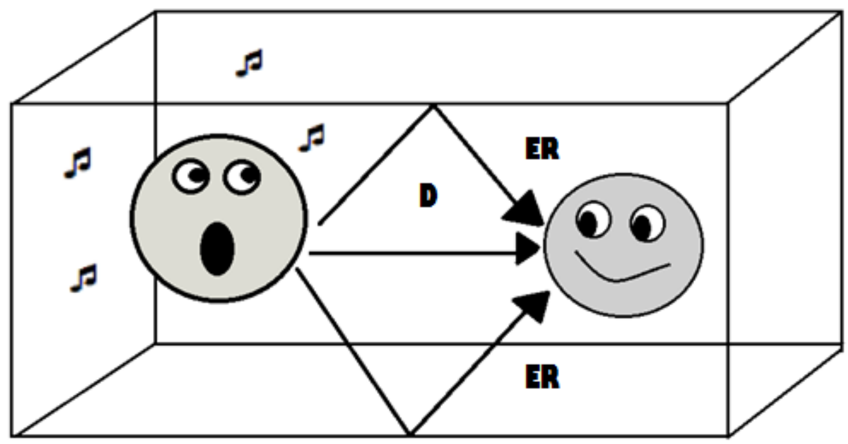


Figure 3.6 - The direct sound (**D**) and the early reflections (**ER**) arrive at the listener

The **reverberant sound** is the sound arriving after the early reflections and which has travelled through numerous reflection paths. Reflections arrive at the listener very close one from the other and from all directions. "The listener has the sensuous experience of feeling bathed in a sea of sound" (Beranek 1962: 23). The reflections also drop in level as a result of the acoustic absorption that takes place at the numerous surfaces they have bounced off. Whereas early reflections are greatly affected by changes in source and listener positions, reverberant sound remains constant regardless of such changes. This is a result of the fact that reverberant sound is diffuse, that is, there is equal probability of it visiting any of the parts of the room.

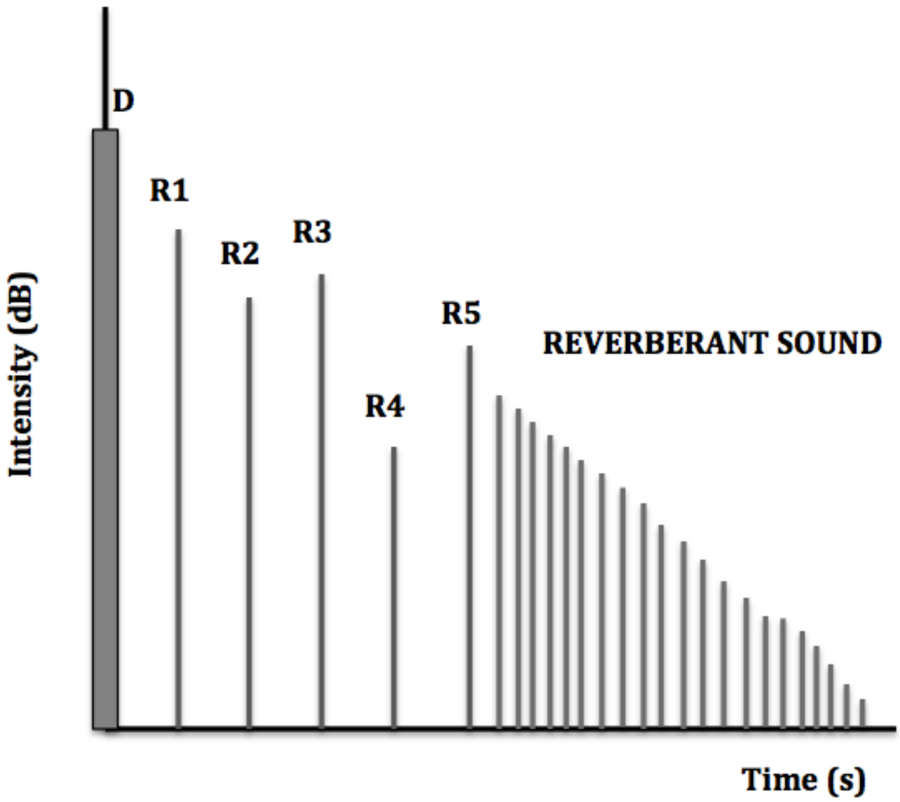


Figure 3.7 – Time plot graph showing direct sound (**D**), early reflections (**R1-R5**) and the reverberant sound. (Adapted from Murphy 2000: 15)

The description of reverberant sound presented above corresponds to the use of a short impulsive sound, but when considering sounds with a longer duration such as speech and music the space receives a constant input of acoustic energy and the reverberant sound creates a **reverberant field** (Howard and Angus 2006, Howard and Murphy 2008).

The **reverberant or diffuse field** presents three different stages: *the build-up*, *the steady state* and the *decay* (Howard and Angus 2006; Howard and Murphy 2008) (see Figure 3.8). The *build-up* is the time it takes for the reverberant field to reach its highest sound level. The *steady-state* is the state in which the sound that is being emitted in a space is equal to the sound that is being absorbed. Finally, the *decay* stage takes place when the sound source stops emitting sound and the acoustic energy decays because sound absorption takes place in each surface reflection. Howard and Murphy (2008: 76) explain that the reverberant field gives a space its "acoustic *signature*", it characterises it, allowing us to become familiar with its sound.

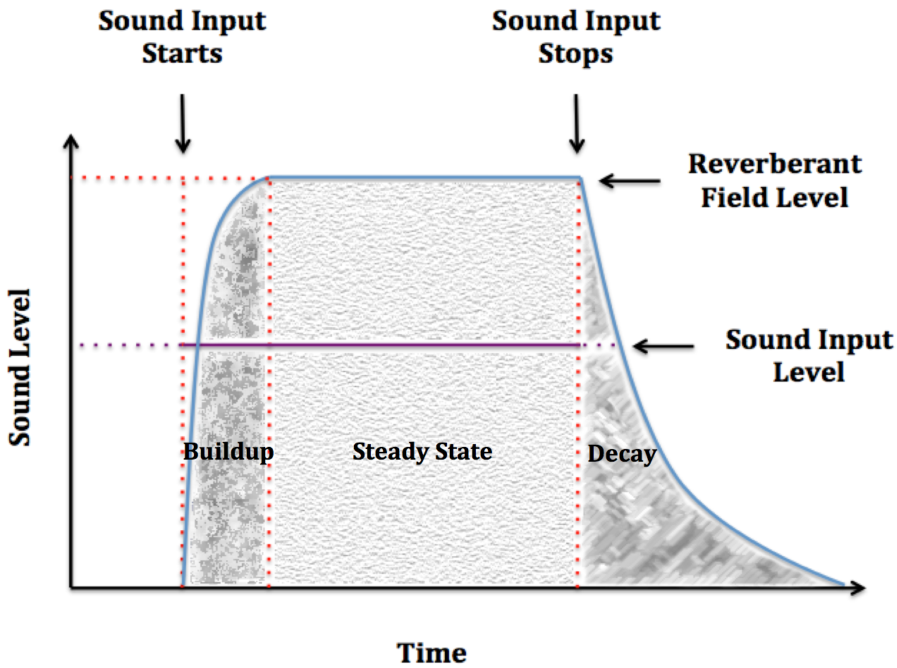


Figure 3.8 - Graphic representation of the reverberant field.
(Adapted from Howard and Murphy 2008: 75).

The point in a space where the reverberant sound energy and the direct sound energy are equal is referred to as the **critical distance**. If the distance between the sound source and the listener is less than the critical distance then the direct sound is predominant and the receiver is positioned within the direct field, whereas if the distance is larger than the critical distance, then the reverberant sound is the dominant one and the receiver is positioned in the reverberant/diffuse field.

Griesinger (2009) argues that the direct-to-reverberant ratio (D/R) is the key to improving speech intelligibility, instead of the early reflections (Barron 1993). When the level of the direct sound is high in comparison to the level of the reflected sound and the time between the direct sound and the onset of reverberation is long enough so as to allow the direct sound to be perceived separately, then both speech intelligibility and audience engagement are improved (Griesinger 2009).

Reverberant sound is also essential to singers when considering "ease of singing" and "ease of ensemble", two categories which are highly correlated (Marshall and Meyer 1985). The majority of singers seem to prefer reverberant sound to early reflections but the faster that sound decays the more important the early reflections become (Marshall and Meyer 1985). Furthermore, early reflections that are delayed by about 40ms result in a drastic drop in preference for the space (Marshall and Meyer 1985).

3.3.2 Sound Source: The Human Voice

Two features of the human voice that need to be considered when studying acoustics are its frequency range (vocal range) and its directivity. The frequency range is relevant because spaces affect different frequency bands in different ways, and an acoustical analysis that bears this in mind can determine the effect of the acoustics on different voices. Directivity refers to the changes in sound intensity around the source, for instance, how it differs at the back of the speaker compared to the intensity at the front. The understanding of directivity enables the correct modelling of the sources within the virtual models.

When considering speech, the fundamental frequency (f0) presents different ranges depending on age and gender. Children have a range within 208-466Hz, whereas for female adults it is 156-349Hz and for adult males

87-196Hz (Howard and Murphy 2008). Kuttruff (1973) clarifies that overtones can be more important than the fundamental frequency and can go to about 3.5 kHz. Furthermore, consonants have spectral components at a frequency of 10kHz or higher (Kuttruff 1973). Singing ranges are much broader than those for speech and they indicate the classification of vocal ranges for singers. Female singers have fundamental frequency ranges between 208Hz-1.5kHz for a soprano, 175-932Hz for a mezzo-soprano and 139-659Hz for a contralto (Howard and Murphy 2008). Male singers have ranges between 185Hz-1kHz for a treble, 131-699Hz for a counter tenor, 103-554Hz for a tenor, 73-392Hz for a baritone and 65-294Hz for a bass (Howard and Murphy 2008).

Kuttruff (1973) highlights that the most relevant range is from 100Hz to 5 kHz, which is the range in which the sounds studied present most of their properties. Below 100Hz neither speech nor singing contain predominant frequencies and above 10kHz the effects of air absorption are predominant (Kuttruff 1973).

Voice directivity is a result of the interaction between the wavelength of sound (λ) and the dimensions of the head and torso of the performer. If the wavelength is small in comparison to the head/torso then a shadowing effect is produced in which sound intensity is reduced at the sides and at the rear, resulting in increased directivity. On the contrary, if the wavelength is larger than the head/torso, sound will travel around the body (diffraction), resulting in omnidirectional sound propagation (see Table 3.1).

The relation between frequency and wavelength can be calculated using Equation 3.5

$$f = \frac{c}{\lambda} \tag{3.6}$$

where f is frequency, c is the speed of sound and λ is the wavelength of sound.

Mouth aperture can also affect sound directivity in singers. Small apertures would result in a tendency towards omnidirectional sound, as the aperture is smaller than the wavelength, whereas bigger apertures would increase directivity (Cabrera, Davis and Connolly 2011). Such effects would only be relevant at higher frequencies (above 2kHz), where wavelengths are comparable to the size of mouth apertures (Cabrera, Davis and Connolly 2011).

	Sound Source	
	Talker	**Opera Singer**
	90º	
500Hz	-1.8	-0.5
1kHz	-0.3	+1.5
2kHz	-5.6	-7.5
4kHz	-5.5	-7.5
	180º	
500Hz	-6.1	-7.5
1kHz	-5.0	-5.5
2kHz	-10.9	-16.0
4kHz	-16.6	-15.5

Table 3.1 – Attenuation of sound energy at the side of the source (90º) and at the rear (180º) compared to the sound energy at the front (0º). The data regarding the directivity of an opera singer was sourced from (Cabrera, Davis and Connolly 2011), whereas the directivity of a talker was sourced from (Chu and Warnock 2002).

3.3.3 Listeners

This section introduces concepts related to auditory perception that are relevant to the study of room acoustics, including those related to the perception of direct sound and reflections, sound localisation and filtering.

When sound is perceived in an enclosed or semi-enclosed environment the listener receives both the direct sound and the reflections. The time interval between direct sound (leading sound) and the reflections (lagging sound) has been studied and considered as an essential factor in their perception as fused or separate events. In 1949 Wallach et al. used the nomenclature *precedence effect* to describe the phenomenon by which two sounds separated by a short time interval and perceived as fused, are located in the direction of the leading sound. The time interval needed between sounds for the *precedence effect* to take place varies according to the sound considered, for clicks the time delay could go to up to 5ms, while with complex sounds such as music it could go to up to 40ms (Wallach et al. 1949).

A related study that investigated the effect of a single sound reflection on the perception of speech was conducted in 1949/51 by Haas and resulted in what is known as the *Haas effect*. Haas designed an experiment in which two loudspeakers were located facing a listener, 3m away and at 45º to the left and right. These loudspeakers played a speech recording at equal loudness. When both loudspeakers played the sound sample simultaneously sound was perceived as coming from the centre position, between the loudspeakers. When a delay of up to 30ms was introduced between the loudspeakers Haas observed that speech was perceived as coming from the direction of the primary loudspeaker, the sound from the secondary loudspeaker was fused with the one from the primary loudspeaker. Primary loudspeaker refers to the loudspeaker that played the sound first and which represents the direct sound. The presence of the secondary loudspeaker, which represents a sound reflection, was seen to contribute to the perception of speech by increasing the overall loudness and broadening the primary source. The experiment also demonstrated that with a delay of up to 30ms the secondary source would be perceived as a separate event if played 10dB above the primary source. When the speech samples were played at equal loudness with delays between 30-50ms sound could still be located as coming from the primary loudspeaker but the reflection could be distinguished from the direct sound.

Besides the effects on sound localisation produced by the presence of direct sound and early reflections it is also necessary to consider the hearing mechanisms involved in localising sounds. In the early twentieth century

Lord Rayleigh developed the *duplex theory* (1907) in which sound localisation was explained as a result of two hearing mechanisms: the *Interaural Time Difference* (*ITD*) and the *Interaural Level Difference* (*ILD*). *Interaural time difference* (*ITD*) (see Figure 3.9) refers to the time difference in the arrival of sound at each ear. If a sound source is positioned exactly in front of the listener then sound will arrive simultaneously at both ears, however, if this sound source's position is shifted towards one side then sound will arrive first at the ear nearer to the source and after a short delay, at the ear further away.

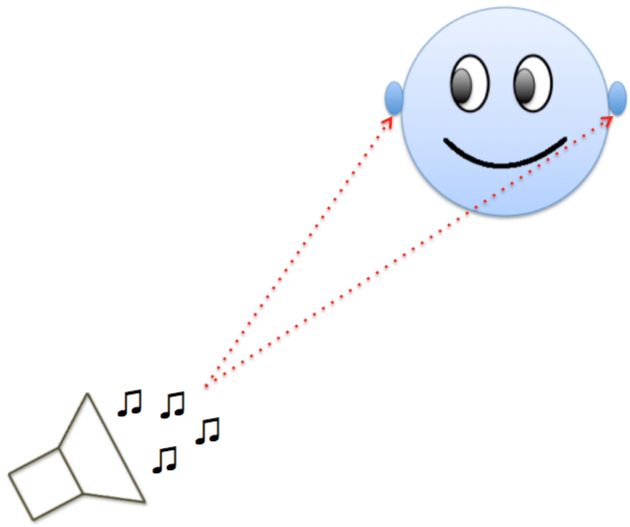


Figure 3.9 - Representation of Interaural Time Difference

Interaural level difference (ILD) (see Figure 3.10) is the difference in the perceived level of sound that exists between the ears when a sound source is positioned laterally. Sound will be louder at the ear nearer to the sound source and quieter at the other ear. The lower levels at the ear that is at a greater distance from the source are the consequence of the shadowing effect of the head and because sound needs to travel further to reach that ear.

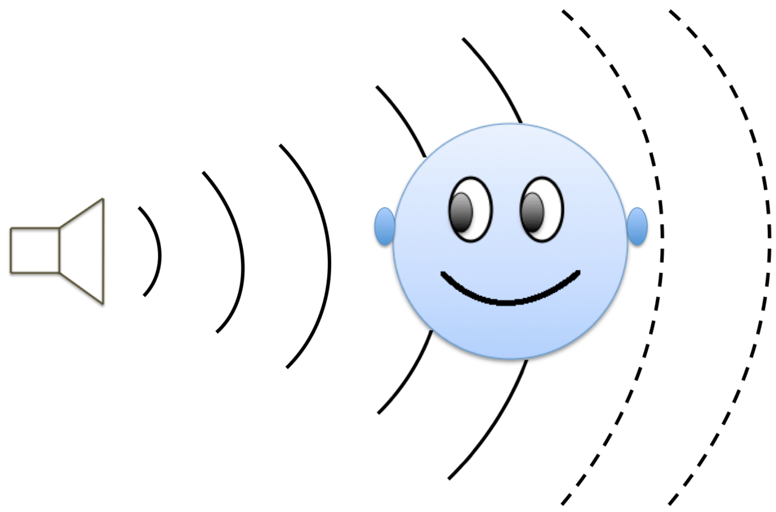


Figure 3.10 - Representation of Interaural Level Difference. The dashed lines represent the drop in sound level at the ear at a greater distance from the sound source

The outer ear, formed by the pinnae and the ear canal, also has an important effect on sound perception and it can be thought of as a LTI (linear time invariant) system whose impulse response affects sound going through the system (Blauert 1997). This filtering effect that is dependent on the shape of the pinna, together with the diffracting and reflecting characteristics of the head and torso of a listener can be modelled, and the outcome of this modelling process is known as *Head-Related Transfer Function* (HRTF). Binaural room simulations utilise HRTFs in order to attempt to match the perception of the simulation as closely as possible to the perception the listener would have had in the real space, increasing the sense of reality of the reproduction process (Blauert 1997).

The impact of the ITD and ILD hearing mechanisms as well as the effect of the pinna, head and torso on sound localisation is dependent on the frequency content of the audio signal. The ILD and the physical characteristics of the pinna, head and torso are essential for high-frequency sounds, because the wavelength of sound is smaller than the dimensions of the head and, as a result, sound is affected by the shadowing effect. The ITD, on the other hand, is more accurate for the localisation of low-frequency sounds.

3.3.4 Room Acoustics Parameters

A study of room acoustics that considers the physical characteristics of the space as well as the sound source and the listener can be conducted through the calculation and analysis of a series of objective parameters derived from measured or simulated room impulse responses. The present section only includes a description of those parameters that were considered relevant to the study of the York Mystery Plays and whose application and results are analysed in chapters 4 and 5.

A. Reverberation Time: RT_{60}, T_{20}, T_{30} and EDT

Reverberation time, which is often referred to as RT_{60}, can be defined as the time, expressed in seconds, that it takes for sound to decay by 60dB after the sound source has stopped emitting sound. The concept of reverberation time was first formulated by W.C. Sabine at the end of the nineteenth century and resulted in the development of the Sabine equation (Equation 3.6), which describes the connection between the reverberation time of a space, its dimensions, the absorption coefficients of the surface materials and their area. It is defined as

$$RT60 = \frac{-0.161V}{S_1 1n(1-\alpha_1) + S_2 1n(1-\alpha_2) + \ldots} \qquad (3.7)$$

where V is the volume of the room (length x width x height), α are the absorption coefficients that correspond to different materials present in the room and S are the surface areas for each material. The equation indicates that the reverberation time of a space is directly proportional to the volume of a room, while being inversely proportional to the absorption of the surface materials.

The reverberation time can also be calculated through a measured impulse response, from which decay curves per octave band are generated; these decay curves are obtained through the backward integration of the squared impulse response (ISO 3382, 1997). Although the definition of reverberation time considers a 60dB dynamic range, values are often measured over a narrower range of 20 or 30dB and referred to as T_{20} and T_{30} respectively. Whereas T_{20} calculates the reverberation time from the decay curve ranging from -5 to -25dB, requiring the decay curve to start 35dB above the background noise level, T_{30} considers the -5 to -35dB range and the decay curve needs to start 45dB above the background noise level (ISO 3382, 1997). A choice between the analysis of T_{20} or T_{30} when acoustic measurements are conducted on site can be a consequence of the background noise level and the resulting signal-to-noise ratio (see chapter 4). It is worth pointing out that even though T_{20} and T_{30} consider a dynamic range of 20 and 30dB respectively, they are still measurements of the time required for sound to decay by 60dB; the measurements using these dynamic ranges are extrapolated to a 60dB decay time (Campanini and Farina 2009; ISO 3382, 2009).

If the sound decay in a space is linear then values for RT_{60}, T_{20} and T_{30} should be comparable (Campanini and Farina 2009); large differences between values could be an indication of a non-linear decay (Barron 2011). The two most common causes for non-linearity are coupled spaces and the presence of a non-diffuse soundfield (Barron 1993, 2011). The term coupled spaces refers to buildings in which there are different acoustic subspaces that can be the result of the presence of arches, for example in churches, balconies for audiences in theatres or concert halls, as well as proscenium openings that divide stage from auditorium (Rossing 2007). Such subspaces are adjacent and present different characteristics in relation to the reverberant sound (Barron 1993). Decays for coupled spaces result in a double-slope with an initial decay rate, which corresponds to the space measured if it was the least reverberant one, and then followed by the terminal decay rate, which corresponds to the adjacent space (Barron 1993, 2011).

Barron (2011) explores non-linearity and indicates how it could be an asset when considering multi-purpose spaces. The non-linear decays that Barron (2011) explores in relation to concert halls, lecture theatres and multi-purpose spaces, show a longer terminal decay rate. The longer terminal decay is a consequence of modifications to the reverberation time of the sound travelling above the audience area, which in the cases studied is only affected by reflections off the walls and is not affected by the absorption and scattering off audience or ceilings (Barron 2011). Such characteristics could result in spaces that provide sufficient intelligibility for speech but also provide more suitable decay times for music than those present in spaces with short and linear decay rates (Barron 2011). Barron (2011) clarifies that although these effects can be observed through an objective analysis, subjective studies seems to indicate that listeners do not perceive such changes; non-linearity is mostly perceptible when it is a result of poor diffusion and as a consequence clearly different reverberation arrives at the listeners from different directions.

Another parameter that can be considered is the Early Decay Time (EDT), which calculates reverberation time considering the first 10dB of the decay curve. EDT is of importance at it has been proven to be the parameter more closely related to the perception of reverberation (Jordan 1970, 1981).

Whereas values for reverberation time have a tendency to remain constant throughout a space, EDT values are greatly affected by the position of the listener and are often shorter than the reverberation time (Barron 1995). As a result of the sensitivity of EDT to the listener position, spaces might present a wide range of values (Barron 1995). Moreover, since EDT is more strongly correlated to the perception of reverberation in spaces, such a variance in values would cause a space with a constant reverberation time to be perceived as having non-uniform reverberation (Barron 1995). A linear relationship between EDT values and source-receiver distance exists in spaces with a wide variety of EDT values, with values calculated for receivers close to the source being shorter due to the strength of the direct sound (Barron 1995, 2005).

The optimum reverberation time for a space depends on its function. If a space is used mainly for the spoken word then speech intelligibility is of the utmost importance; therefore, short reverberation times will be preferred. The ideal reverberation time for speech has been considered as 1s, although theatres analysed have been found to range between 0.7-1.2s (Barron 1993). Below 0.5s, although speech will be intelligible, listeners might feel aural discomfort (Barron 1993). Such aural discomfort is related to the fact that most people are used to inhabiting and frequenting spaces with reverberation times of 0.5s or above. As a result, spaces with very low reverberation times might be perceived as unnatural. Blesser and Salter (2007) point out that, on the one hand, if reverberation is excessive it might degrade speech intelligibility, increase the background noise level and make a space unpleasant. On the other hand, if the reverberation is inadequate, the space will be perceived as "aurally dead, unresponsive, and uninviting." (Blesser and Salter 2007: 61).

If a space is used for music performances the optimum reverberation time may depend on the type of music performed. Music that is characterised by short notes and complex rhythmic patterns will benefit from short reverberation times that will enable the listener to distinguish every note, while music that is slow and rhythmically simple would benefit from longer reverberation times (Beranek 1962). Optimum values of reverberation times at mid-frequencies for concert halls have been considered between 1.8-2.2s (Barron 1993). Beranek (1962) provides more specific values by establishing the ideal reverberation time at mid-frequencies for different types of music: 1.5s for Baroque music, 1.7s for Classical music and Wagnerian opera, 1.9s for symphonic music and 2.2s for Romantic music.

Due to the close correlation between EDT and the subjective perception of reverberation, any deviations from the optimum values by the measured EDT should be considered of more relevance than deviations in the reverberation time (Barron 2005).

B. Clarity: C_{50} and C_{80}

Clarity is an early-to-late arriving energy ratio expressed in decibels, which can be calculated using C_{50} or C_{80}. C_{50} considers the division between early and late energy as 50ms and gives an indication of speech intelligibility and definition in a space whereas C_{80} is more suitable for the analysis of music and uses 80ms to divide early from late energy. Both direct sound and early reflections are considered within the early energy, whereas reverberant sound constitutes the late arriving energy. A predominance of early energy will result in higher clarity values since early reflections fuse with the direct sound and provide higher definition (Soulodre and Bradley 1995), which would result in better speech intelligibility and the perception of musical detail. Furthermore, clarity is higher when the listener is nearer to the source due to the prominence of the direct sound.

Clarity is inversely proportional to the reverberation time; this is particularly true when considering EDT values, higher clarity resulting in a lower EDT and vice versa (Barron 1995, 2005).

As was noted in connection to reverberation time, optimum values are highly dependent on the use of the space and are influenced by subjective preference (Barron 1993). In the case of rhythmically complex musical items high levels of clarity will be preferable since each sound will be more distinct, whereas in the case of performances of, for instance, plainchant items, which present slow melodic lines, lower values of C_{80} would be beneficial. Barron (1993) indicates that optimum values of C_{50} and C_{80} for concert halls are within the range of -2dB to +2dB. Although it is unlikely that higher values would indicate an excess of clarity, it is necessary to assess whether higher values are not indicating very low results in other parameters, such as reverberation time (Barron 2005). Beranek (1996) relates preferences on clarity values to different contexts; for instance, a conductor rehearsing for a performance might prefer C_{80} values at 500Hz-2kHz to range between 1-5dB so as to hear as much detail as possible, whereas in the context of a performance values between -1 to 4dB might be preferred.

C. Spatial Impression: $IACC_E$, LF and $IACC_L$

When referring to spatial impression two different effects, associated with the arrival of lateral reflections at the listener, will be considered: the Apparent Source Width (ASW) and the Listener Envelopment (LEV) (Bradley and Soulodre 1995). This section will first consider the meaning and significance of these effects and will then proceed to explain in detail how changes in the ASW can be analysed by using the parameters $IACC_E$ (Interaural Cross-Correlation Coefficient-Early) and LF (Early Lateral Energy Fraction), whereas the $IACC_L$ parameter (Interaural Cross-Correlation Coefficient-Late) can be used to study LEV.

The ASW is associated with the perceptual broadening of the sound source, whereas the LEV is the effect by which listeners feel surrounded by sound, "the sensation of spatial impression [listener envelopment] corresponds to the difference between feeling *inside* the music and looking at it, as through a window." (Barron and Marshall 1981). Although the original quote uses the term "spatial impression", Barron and Marshall are referring to listener envelopment (Griesinger 1999), terms that have often been used as synonyms (Barron 2000). Nevertheless, it is important to bear in mind that the term spatial impression has also been used in research prior to the 1990s to refer to source broadening (Barron 2000).

Whereas the ASW is determined by the presence of early lateral reflections, the LEV is affected by the late lateral reflections; 80ms after the arrival of the direct sound is used to differentiate early from late reflections (Bradley and Soulodre 1995). The connection between an increase in the ASW and early lateral reflections is a result of the phenomenon described as the Haas effect (see section 3.3.2). Direct sound and early reflections are fused, resulting in an increase of the perceived level of the direct sound (Bradley and Soulodre 1995). On the other hand, late reflections are not fused with the direct sound and are perceived as separate events that are distributed around the space (Bradley and Soulodre 1995).

Barron and Marshall (1981) studied the factors influencing lateral reflections and causing the broadening of the ASW. It was determined that the change in the delay of the reflections only had an impact in the first 9ms, whereas changes in the direction of the reflections had a greater influence, with reflections arriving at the sides of the listener (90º) resulting in the most prominent effects (Barron and Marshall 1981). Changes in the level of the reflections as well as variations in listening level both produced changes in relation to spatial impression (Barron and Marshall 1981). Higher listening levels resulted in an increase of ASW to the extent that differences were detected even within musical items with soft and loud passages (Barron and Marshall 1981).

Bradley and Soulodre (1995) studied the influence of late arriving reflections on the perception of LEV and determined that an increase in envelopment was the result of the direction of the reflections, with the largest effect being produced by reflections arriving at 90º (at the sides of the listener). Furthermore, they also established that an increase in reverberation time and a decrease in clarity values resulted in higher levels of LEV (Bradley and Soulodre 1995). Finally, late arriving energy was shown to hinder the perception of early lateral energy and as a result the ability to differentiate changes in the ASW; therefore, the study of early lateral reflections in a space needs to be assessed in relation to LEV to determine the actual impact of the early lateral energy on perception (Bradley and Soulodre 1995).

Changes in the ASW can been analysed by using the aforementioned parameters $IACC_E$ and LF. The $IACC_E$ parameter measures the dissimilarity of signals arriving at both ears considering the first 80ms of the impulse response. It has been identified as being of importance for the subjective preference of concert halls, with audiences preferring lower values of $IACC_E$ which correspond to a greater dissimilarity between the signals (Schroeder, Gottlob and Siebrasse 1974; Ando 1985) and indicate a perceptual broadening of the source. Measurements of IACC can be conducted using a dummy head with microphones positioned at the entrance of the ear canals (ISO 3382, 1997).

The LF parameter is the ratio between early lateral energy (5-80ms, early reflections) and early omnidirectional energy (0-80ms, direct sound and early reflections). It is measured using microphones with omnidirectional and figure-of-eight polar patterns, directing the null of the figure-of-eight microphone towards the source (Barron 2000). Small values of LF are often associated with the proximity of the receiver (listener, microphone) to the source, which is a consequence of the predominance, at those positions, of the direct sound (Barron 2000). Nevertheless, when analysing such results it is necessary to bear in mind that although source broadening will be minimal, the physical proximity of the listener to the source, for example an orchestra, will act as compensation (Barron 2000).

The LEV can be studied by considering the $IACC_L$ parameter which takes into account the sound arriving 80ms or more after the direct sound, with lower values indicating a greater sense of envelopment, meaning that the sound arrives uniformly at the listeners from all directions (Beranek 1996). $IACC_L$ is measured, the same as $IACC_E$, through the placement of microphones at the entrance of the ear canals of a dummy head (ISO 3382, 1997).

Both the $IACC_E$ and $IACC_L$ parameters can be calculated as $IACC_{E3}$ and $IACC_{L3}$ when the results are the mean across 500Hz-2kHz (Barron 2000). These frequencies are used due to the fact that the wavelength is similar or smaller than the dimensions of the head of an average listener (Okano, Beranek and Hidaka 1998). Studies on LF have determined that low frequencies are essential for perceptual source broadening, whereas frequencies above 1.5kHz do not seem to contribute to the process (Barron and Marshall 1981). As a result it is possible to study LF values as LF_{E4}, which is the mean across 125Hz-1kHz (Hidaka, Beranek and Okano 1995).

Okano, Beranek and Hidaka (1998) provide the values of IACC and LF parameters for concert halls ranked as being of different quality. “Superior” and “Excellent” concert halls present $IACC_{E3}$ values in the range of 0.36-0.46 and LF_{E4} values between 0.16-0.20, whereas “Good to Excellent” halls have values of $IACC_{E3}$ of 0.38-0.54 and LF_{E4} of 0.13-0.23, and finally, the halls categorised as “Good” have values of 0.53-0.59 for $IACC_{E3}$ and 0.08-0.17 for LF_{E4} (Okano, Beranek and Hidaka 1998). Barron indicates that acceptable values for LF could be considered as being between 0.1-0.35 (Barron 1993), which seems to correspond to the values indicated for "Superior", "Excellent" and "Good to Excellent" concert halls (Okano, Beranek and Hidaka 1998). $IACC_{E3}$ measurements have been considered as providing a better match with subjective categorisations of concert halls than the LF_{E4} values (Okano, Beranek and Hidaka 1998).

Regarding the $IACC_{L3}$ parameter, Beranek (1996) indicates values within the range of 0.10-0.16 for "Superior" and "Excellent" concert halls, 0.12-0.22 for those ranked as "Good to Excellent" and 0.12-0.28 for those ranked as "Good" and "Fair to Good". As these ranges demonstrate, there are overlaps in values among halls that have different rankings, which might be an indication that this parameter is not sensitive enough to be significant to these classifications (Beranek 1996) and reference values should be used with caution.

3.4 Acoustic Modelling Techniques: Geometrical Acoustics

The present section introduces the theoretical basis of geometrical acoustics, which is the method for the study of sound propagation that has been applied to this project though the use of the software CATT-Acoustic and TUCT. The way geometrical acoustics considers source, receiver and space are introduced, as they are the means by which impulse responses are calculated, allowing the analysis of the objective parameters introduced in the previous section.

Geometrical acoustics studies sound propagation by considering sound waves as rays that carry energy and travel in straight lines. Kuttruff explains that a sound ray is "a small portion of a spherical wave with vanishing aperture [that becomes zero], which originates from a certain point." (1973: 78). The point from which the rays originate is the sound source to be modelled.

Geometrical acoustics takes into account specular reflections, which are defined as being those reflections where the angle of incidence is equal to the angle of reflection (see Figure 3.10). It also considers the loss of energy carried by the rays in relation to the absorption coefficients (α) of the surfaces the rays encounter, as well as air absorption in relation to the distance travelled (Murphy 2000: 49). Sound rays continue travelling in the space until all their energy has been absorbed.

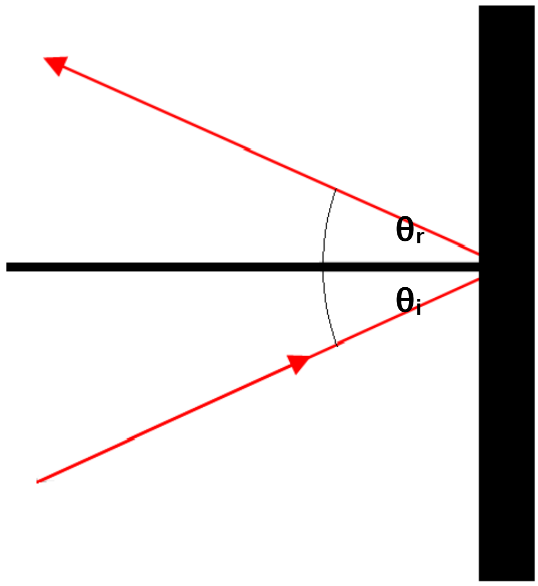


Figure 3.11 - Representation of a specular reflection, where **θ_i** is the angle of incidence, **θ_r** is the angle of reflection and **θ_i** = **θ_r**.

Geometrical acoustics works on the premise that the wavelength of sound (λ) is small in relation to the dimensions of the surfaces of the space studied. As a result it can be less reliable when studying the behaviour of low frequencies, although the frequency bands at which it is affected will depend on the dimensions of the space studied. Another limitation of geometrical acoustics is that, since it represents sound propagation with straight lines, it does not take into account phenomena specifically related to the behaviour of waves such as diffraction and interference. Diffraction is the phenomenon by which a sound wave bends when encountering an obstacle because its wavelength is larger than the object encountered, while interference is the effect resulting from the relation between the phases of different sound waves, which can result in wave cancellation. Geometrical acoustics also assumes that surfaces are smooth or that the irregularities in the surfaces are larger than the sound wavelength. If the irregularities in a surface are smaller than the sound wavelength reflections off that surface are no longer specular, they are diffuse or scattered (see Figure 3.11). In a diffuse or scattered reflection the angle of reflection is no longer the same than the angle of incidence. Scattered reflections are not taken into account in geometrical acoustics but a scattering coefficient can be utilized to account for this effect. The scattering coefficient of a surface can be defined as the "ratio between reflected sound power in non-specular directions and the total reflected sound power." (Rindel 1995: 5)

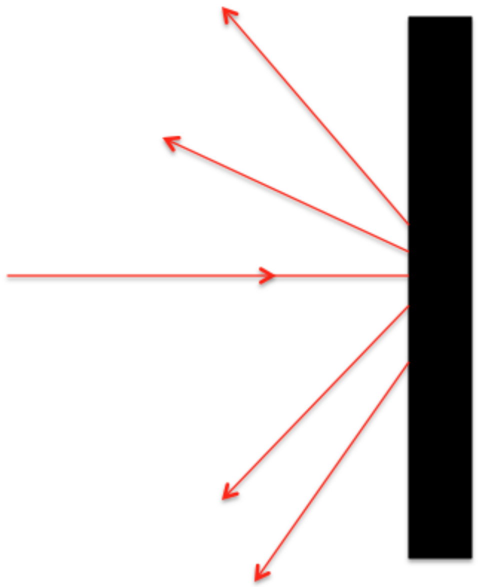


Figure 3.12 - Representation of scattered reflections

There are two main forms of geometrical acoustics: the image source method and the ray tracing method and they differ in the way in which the calculation of the reflection paths is carried out.

In 1968 Krokstad *et al*. presented a method to calculate the impulse responses of concert halls through the use of ray tracing techniques. Ray tracing conceives the sound source as simultaneously releasing sound rays in all directions. These sound rays are distributed evenly from the sound source and they arrive at a receiver, which is modelled as a sphere of a certain volume. Spheres are implemented in order to increase the chances of the thin rays hitting the receiver, which would be minimised if it were modelled as a point. At the receiver, the energy of the ray at arrival and its direction are recorded.

A variation from the ray tracing technique is the cone tracing technique, which replaces the use of rays with cones. This technique may reduce the calculation time of acoustic predictions and it allows the modelling of the receiver as a point since the opening of the cone can detect the receiver. In order to cover the whole sound source it is necessary for the adjacent cones to overlap, which might result in the detection of the same path several times; such a problem can be solved by the use of beams in the shape of pyramids (Farina 1995) (see Figure 3.12).

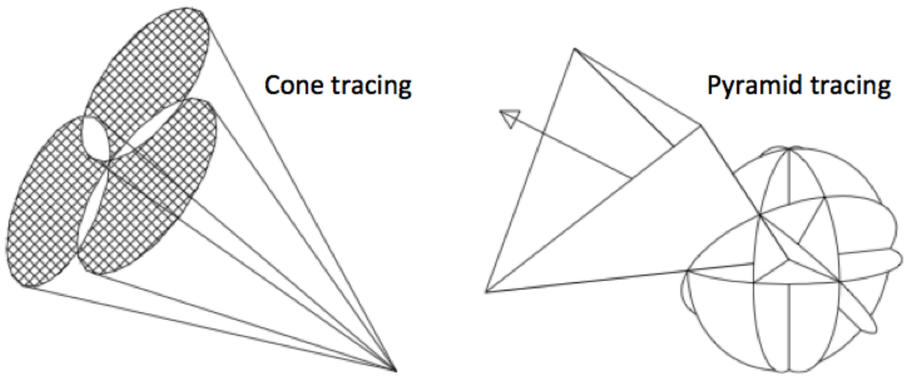


Figure 3.13- Cone tracing and Pyramid tracing techniques
Farina (2000: 51)

In 1979 Allen and Berkley developed the idea of the simulation of an acoustic space through the use of the image source method. This method is based on the concept that room reflections can be calculated by considering the path between the receiver and an image source. This image-source is a mirrored version of the sound source and it is imagined to exist beyond a reflecting surface, such as a wall. Since in a room there is more than one reflecting surface the mirroring process will be carried out more than once, and image sources will be created from the ones previously constructed and referred to in relation to the number of reflections that were involved in their creation (Borish 1984) (see Figure 3.13).

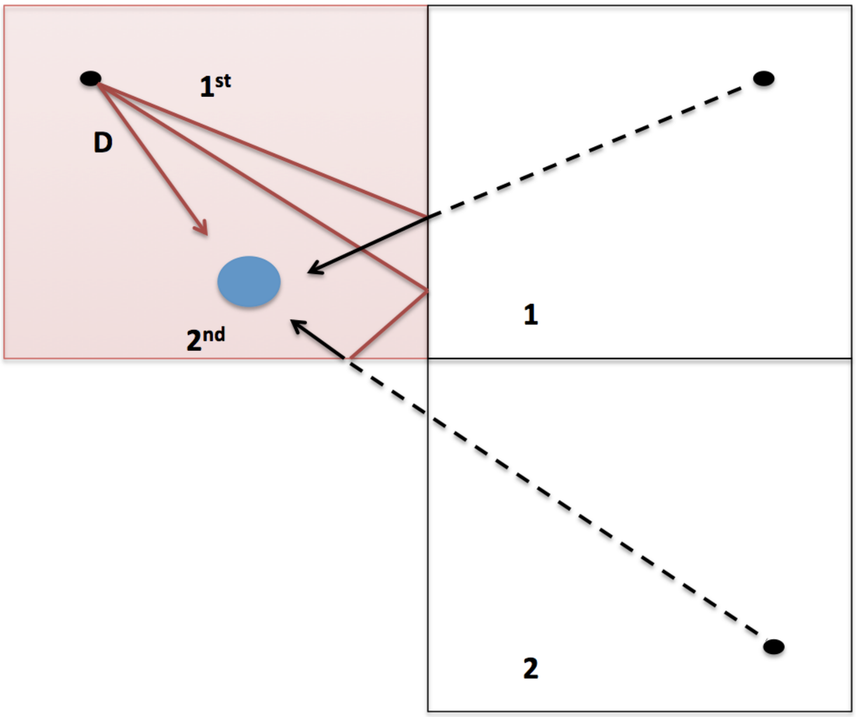


Figure 3.14 – Representation of the Image-Source Method. (Adapted from Begault 1994: 151).
The direct sound (**D**) travels in a straight line from sound to receiver. The first order reflection (**1st**) is imagined as coming from an image source (**1**). The second order reflection (**2nd**) is seen as coming from an image source (**2**), which is created by mirroring the first image source.

For each image source/receiver combination the source in question will only emit one ray whose direction is defined by the receiver's position. There is no need to take into account the size and shape of the receiver, since the path of the ray goes from image source to receiver making concerns about rays not hitting the receiver redundant. The image source model is capable of finding all the sound reflection paths but is very computationally intensive, which means that higher order reflections are often ignored.

Borish (1984) explains that although the image source method can deal with complex structures it requires carrying out visibility checks since image sources need to be visible to the listener for them to be taken into account. If image-sources are not visible then they do not contribute to the sound energy of the space. Stephenson (1990) explains that mathematically constructed image-sources cannot always physically exist; it is not always possible to trace a path between image-source and receiver involving the walls used for mirroring. The reason for this is that walls are not infinite and "the geometrically constructed reflection points may lie outside the limited wall areas." (Stephenson 1990: 39). This process increases calculations times, especially when dealing with higher order reflections which require more visibility checks.

3.4.1 Acoustic Predictions with CATT-A and TUCT

The present project utilises the software CATT-A to generate the virtual models by entering geometrical data, information on sources and receivers as well as absorption and scattering coefficients. The application TUCT (The Universal Cone Tracer) is then used to conduct the acoustic predictions associated with the virtual models.

Acoustics predictions within TUCT can be conducted through three different algorithms. For this particular project the algorithm capable of handling outdoors spaces, referred to as algorithm 3, was chosen (TUCT 2012) as it eliminates the need, present in other software packages, of modelling a "box" surrounding the model and assigning it total absorption. Predictions with this algorithm take into account direct sound, specular and diffuse reflections (TUCT 2012). Deterministic calculations, without employing rays, are used for the direct sound and specular reflections of the first order, whereas first order diffuse reflections are also deterministic but are calculated using ray split-up, which takes place when a ray hits a diffuse surface and gives rise to many other rays (TUCT 2012). Algorithm 3 has the greatest number of deterministic reflection paths available for calculation with TUCT; these paths are S^i, S^iD, S^iDS^i, S^iDD, DS^i and DD, where S refers to specular reflection paths, D to diffuse reflection paths and the (i) indicates all possible successive reflections of that base (TUCT 2012) (see Figure 3.14).

The reflection paths that are not deterministic are calculated through a stochastic process. For example, a surface with a scattering coefficient of 0.7 (70%) will result in 7 out of 10 rays having a random reflection whereas

3 out of 10 will present a specular reflection (TUCT 2012). From the inclusion of a stochastic process for room acoustics calculations it follows that no two runs of predictions for the same space will be identical (TUCT 2012). Nevertheless, such effects are non-significant when using algorithm 3, which has a larger number of deterministically calculated paths and whose random paths coincide with reflections with very low energy content (TUCT 2012).

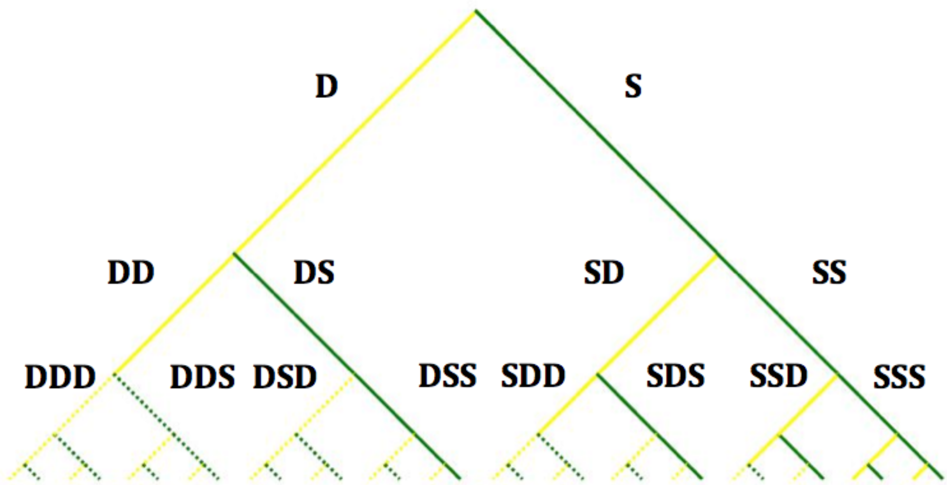


Figure 3.15 – Representation of Algorithm 3 as a ray reflection tree. The specular paths are indicated in green and with the letter **S**, diffuse paths are marked in yellow and with the letter **D**. Deterministic paths are identified by solid lines whereas random paths are dashed.
(Adapted from TUCT 2012: 71).

The Image Source Model application within TUCT allows the study of the acoustics of the space through the image source method. This application considers scattering as additional absorption and the visualisation of the strength of reflections throughout time only includes specular reflections up to the ninth order.

3.5 Conclusions

The present chapter has explained concepts related to the propagation of sound, the characteristics of the human voice and mechanisms involved in sound perception. An understanding of these concepts together with knowledge on room acoustics parameters and geometrical acoustics are, as will be shown in chapters 4 and 5, at the core of the analysis of the York Cycle, its performance, reception and staging. Furthermore, such knowledge has informed the use of virtual acoustics by suggesting its strengths and weakness, which will allow a more accurate interpretation of the results obtained.

The acoustical parameters reviewed in this chapter have been studied by various researchers in relation to speech in theatres and, more commonly, to music performance and reception in concert halls. The vast corpus of research on this matter and the availability of data in relation to preferred values makes it a good starting point for the analysis of the performance spaces used for the York Mystery Plays. Nevertheless, it is essential to bear in mind that the acoustics of the spaces studied present different characteristics. They can be considered as semi-enclosed since, although the plays were performed in the street of York, the characteristics of the medieval streets and the presence of wagons would have created a greater sense of enclosure. Besides the consideration of the room acoustics parameters in relation to theatres and concert halls, it is also relevant to consider the acoustic characteristics of medieval religious establishments in which plainchant and polyphonic items would have been performed and which performers and audiences of the York Cycle might have been familiar with.

Moreover, when considering the results for different acoustic parameters it is always necessary to bear in mind how they might interact with one another to provide an auditory experience. Additionally, it is worth noting that personal preferences have been found to have an influence on what is judged as suitable acoustics (Barron 2005), meaning that although a space might be within a range of recommended parameters this does not necessarily imply that the space would be suitable for all types of performance or found pleasing by all performers and audiences. This is of particular importance when studying performance spaces and heritage sites from past cultures, as auditory perception is not only influenced by the mechanisms of the auditory system, it is also influenced by cultural and social factors. Modern ways of seeing and listening cannot be assumed to have been the same in other historical periods. In this respect Blesser and Salter (2007) refer to the concept of *auditory spatial awareness*, which is the response of individuals to the way in which the acoustics of a space modifies sound, a response that is influenced by cultural, social and personal aspects. As a result the notions of hearing and listening associated with medieval times and reviewed in the chapter 1 are essential in all acoustical analyses conducted in this project and similar considerations should be a key element in every project analysing the acoustics of heritage sites.

Chapter 4 will combine the study of the York Mystery Plays and the study of acoustics by focussing on the analysis of Stonegate, the best-preserved station of the York Cycle.

Chapter 4: The Acoustics of Stonegate:
A Station of the York Mystery Plays

4.1 Introduction

This chapter introduces some of the key aspects of the development of the topography of York from the Roman to the Tudor period, focussing on the effects these changes might have had on Stonegate, a street in central York that was used as a site for the performance of the York Mystery Plays. Findings from the House Books and the wardmote courts records detailing the use and appearance of the streets of York in the fifteenth and sixteenth centuries are presented as well as the characteristics of urban secular buildings of the period. The buildings standing today in Stonegate are also researched in order to determine the features that date from the centuries in question.

Subsequently, the methodology used for the study of the acoustics of Stonegate is presented. Significantly, the state of preservation of several buildings dating from the fourteenth and fifteenth centuries enables research on the acoustics of the space to use contemporary Stonegate as a starting point for the analysis. This entails determining the best impulse response measurement method for outdoors spaces, which needs to be suitable for sites that are frequented by visitors and subject to changes in noise levels and environmental conditions.

A computer model of contemporary Stonegate is then compared, through both objective and subjective methods, with real-world acoustic measurements of the space. This validation of the simulation of contemporary Stonegate along with the application of research into secular buildings in the sixteenth century forms the basis for the design of eight virtual models. The aim of the virtual models is to attempt to arrive at an approximation of the acoustics of the space in the period of interest and enable its consideration in relation to the performance of the York Mystery Plays.

4.2 Stonegate: From Eboracum to Tudor York

The York Mystery Plays followed a processional mode of performance and the same pageant route was used throughout the life of the Cycle (see chapter 2). The plays were performed at different sites along the route, which were not necessarily the same at every performance but seem to have remained remarkably consistent throughout the years (see chapter 2). The locations of the stations can be derived from their relative position to important sites within the city, such as the Common Hall or the Minster Gates, or in relation to the stationholders who had arranged to have the plays performed outside their properties.

One of the sites that was used for staging the plays and that has suffered the least changes since the sixteenth century is Stonegate. There were two playing stations associated with Stonegate from the fourteenth to the sixteenth century. One was at a location along the street, the portion that is now known as Stonegate, and determined by the name of the stationholder/s. Such a station is mentioned in all extant documents on the playing stations, with exception of the 1486, 1506 and 1516 records. The other station was located towards the junction of Stonegate and Petergate and in many cases was associated with the Minster Gates; this site is only missing from the 1454, 1462 and 1516 lists of playing stations (see Appendix Table 4.1).

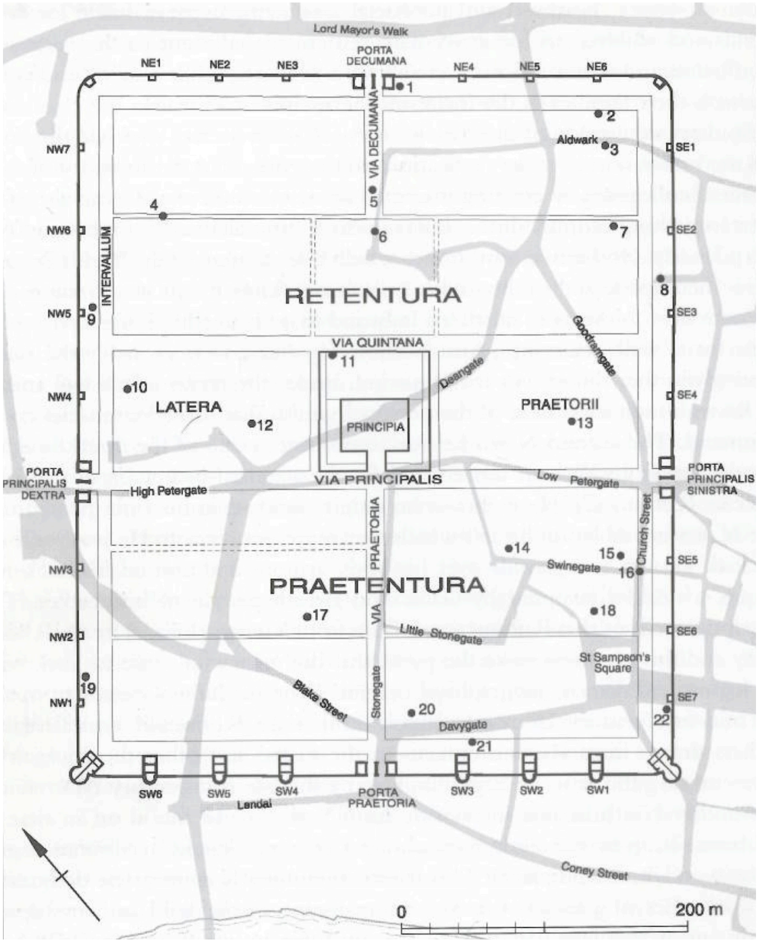
Stonegate has been an important part of the city of York since its foundation in the Roman era (AD71) by the Ninth Legion under the name *Eboracum*. The Roman fortress, which was a rectangular enclosure of approximately 50 acres and provided accommodation for the members of the legion, had two main streets, the *via principalis* and the *via praetoria* (Ottaway 2003). The *via principalis* connected two gates, the *porta principalis dextra* and the *porta principalis sinistra* and it is discernible in Map 4.1 that Petergate follows the line of this street, albeit with a slight deviation (Ottaway 2003). The *via praetoria* connected the *porta praetoria* (main gate) to the *principia*, which was the headquarters of the legion, and it is Stonegate that follows closely the line of this Roman street (Ottaway

2003) (see Map 4.1). The reason for the correlation between Petergate and Stonegate and the main Roman streets is not related to the continuing use of Roman streets into the medieval period but to the continuity in use of the main gates of the Fortress, which were connected via these streets (Hall 2007; Ottaway 2003).

The Anglo-Scandinavian period in York (*c.*850-1068), also known as the Viking Age, was of great importance to the development of the medieval town (Hall 2007). Stonegate, which means “stone-paved street” (RCHM, V, 1962-81: 220), might owe its name to this period, during which the suffix-gate was used to refer to streets (Daniell 2007). The word “stone” could either be due to the presence until 1069 at the bottom of Stonegate of the *porta praetoria*, which was made of stone, or a reference to the fact that the stone used to build the pre-Norman minster was brought into the Fortress through this gate (Raine 1955). The very early origins of the medieval craft guilds date from the Viking Age with the commencement of mass production conducted by specialists in workshops (Hall 2007). This period also saw the establishment of fifteen churches (Hall 2007), a number that would increase in the Norman era.

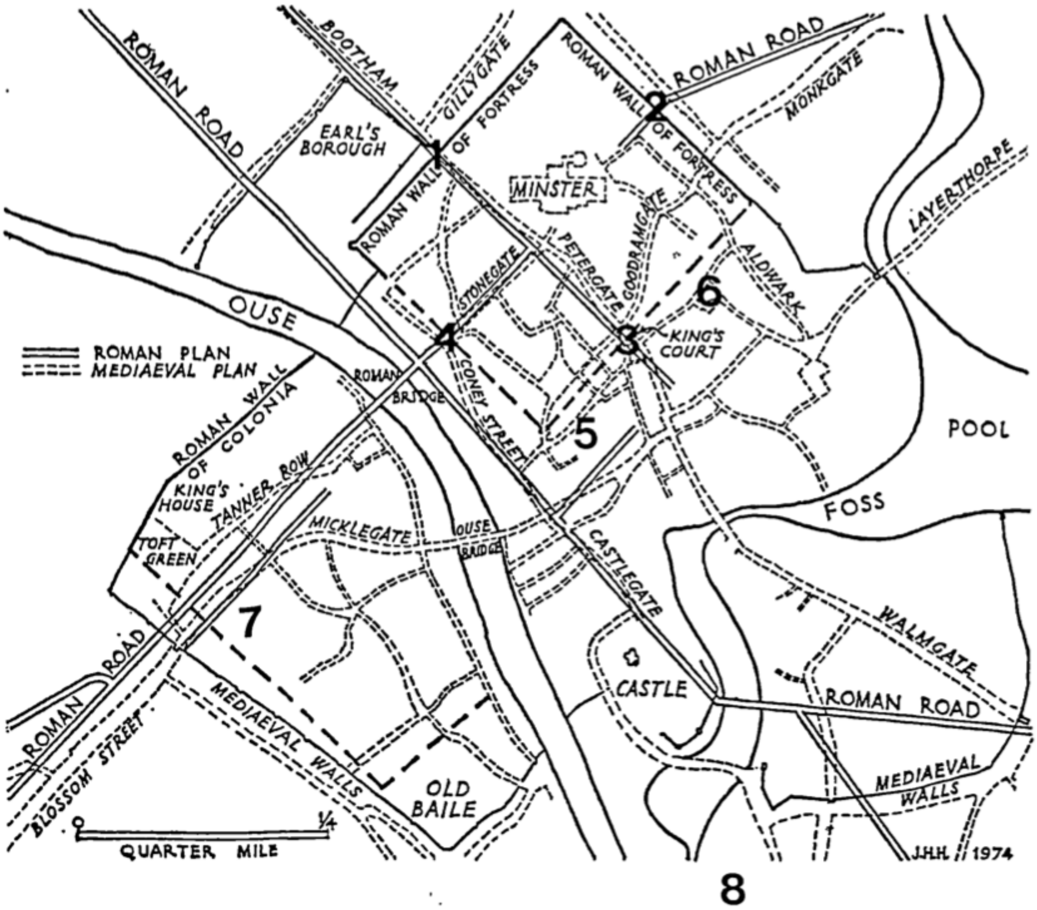
The Norman period in York, marked by the arrival of William the Conqueror in 1068, greatly influenced the topography of the city. The number of parish churches grew from fifteen to forty by the end of the twelfth century (Daniell 2007). These parish churches were key to the religious beliefs of the laity, who often chose them for the foundation of chantries, which were closely related to the doctrine of purgatory and the possibility of assisting the transition of souls to heaven through prayers (Dobson 2007). The Norman period also saw the construction of major buildings within the city. Among these was the Norman Minster, which was constructed under the supervision of Thomas of Bayeaux, Archbishop of York (Daniell 2007) and was completed as a Gothic cathedral in 1472. St Mary’s Abbey and Holy Trinity Micklegate were two Benedictine monasteries that were built in the early years after the Norman Conquest (Daniell 2007). The former was by the late Middle Ages the wealthiest abbey in the north (Dobson 2007) and as discussed in chapter 2 the Gates of

Holy Trinity in Micklegate was the site of the first station of the York Mystery Plays.



1. Intervallum building	12. First cohort barracks
2. Barracks	13. Low Petergate: buildings
3. Barracks	14. Legionary baths
4. Street and barracks	15. Legionary baths and sewer
5. Via decumana	16. Intervallum, street and wall
6. Via decumana or entrance to praetorium	17. Accommodation block, street and barracks
7. Buildings	18. Legionary baths caldarium
8. Buildings and defences	19. The ‘Anglian Tower’
9. Internal Tower NW5 and intervallum building	20. Barracks
10. First cohort barracks	21. Barracks and defences
11. Headquarters buildings	22. 16 Parliament Street

Map 4.1 – The Roman Fortress (Ottaway 2003: 32)



1. porta dextra (Bootham Bar)	5. Jubbergate
2. porta decumana	6. St. Andrewgate
3. porta sinistra (King's Court)	7. Holy Trinity Priory
4. porta praetoria (St. Helen's Square)	8. Fishergate

Map 4.2 - The Roman Fortress and Medieval York (Jones 1987a, Map 2)

The dissolution of the monasteries by the crown in the Tudor era also lead to changes in the topography of the city; it started in 1536 and by 1538, the crown had requested all religious houses to surrender their properties (Cross 2007). Major buildings had lost their purpose and had consequently fallen into ruin and turned into stone quarries (Cross 2007). Monastic buildings, with the exception of St Mary's Abbey that was retained by the crown until the early nineteenth century, also became available in the market together with the messuages and tenements that they had previously owned (Cross 2007). A further change was precipitated by the reduction in the number of parish churches to twenty-five in 1547 and even more significant was the seizure of chantries by the crown in 1548 (Crown 2007).

The whole city would have been affected by these events, and Stonegate would have been no exception to this. Stonegate had close links to the Church, having its upper section within the Liberty of St Peter (RCHM, V, 1962-81), which was the name given to the area which was not under the jurisdiction of the civic government but under the control of the Dean and Chapter (Daniell 2007). Several of the properties in this street were either owned by, or were accommodating trades related to the Church (Jones 1987; RCHM, V, 1962-81). Goldsmiths and glaziers are among the trades known to have had strong ties to Stonegate from the fifteenth century (Raine 1955; RCHM 1962-81). The goldsmiths resided in Stonegate and their work was connected to the church, whereas the glaziers owned workshops in Stonegate and were associated with St Helen's Church (Raine 1955; RCHM 1962-81). Moreover, goldsmiths were stationholders in Stonegate in 1475, when John Tirry shared a place with John Wilkynson and in 1501 and 1508, when William Couke took a station (Twycross 1978) (see Appendix Table 4.1). Printers and booksellers, who were essential for the provision of liturgical books, could also be found in this street from around 1500 (Raine 1955; RCHM 1962-81)

It is this later period in the history of the city, the sixteenth century, which will be the focus of the following sections. Of particular interest will be the characteristics of the streets and buildings of York in general and of Stonegate in particular. The decision to focus on the later years of the plays resulted from the greater amount of information on Stonegate for this century in comparison to the data available for the earlier life of the Cycle. By focussing on this period it is then possible to produce more historically accurate acoustic simulations of the site.

4.3 Streets and Buildings in Medieval and Tudor York

The present section introduces the context for the understanding of the street space in medieval and Tudor York. It concentrates on the features that are deemed necessary for the construction of virtual models of the performance area, that is, information related to the exterior characteristics of the structures as well as street paving. References related to the interior attributes of the buildings have not been included since these are not required for the study of the performance of the plays.

Vital information on the streets of York in the fifteenth and sixteenth centuries can be drawn from two main sets of documents, the House Books and the records of the wardmote courts (Hartshorne 2004). Whereas the House Books record the business dealt with at civic council meetings (Dobson 2007), the records of the wardmote courts, deal with local issues pertaining to a particular ward (Hartshorne 2004). The documents reveal the concerns of the civic authorities as regards the physical appearance of the streets, their use, and in particular the cleanliness and the paving of public spaces (Hartshorne 2004). Although the documents demonstrate that the ideal street place included notions of evenness, smoothness, regularity, ease of access and uniformity, they also indicate that such ideals were not always fulfilled (Hartshorne 2004).

One specific concern was paving and common materials used in medieval York were stones, cobbles and gravel, cobbles being the most common (Dean 2008, Hartshorne 2004). During the sixteenth century references to paving often associated the smoothness of the street surface, its regularity and its cleanliness (Hartshorne 2004). Flat, even paving was necessary for the prevention of accidents, as well as avoiding problems related to the circulation of water in sewers and gutters in the streets (Hartshorne 2004).

There were three main concerns regarding the street façades; these were the continuity of the fronts of the buildings, the state of repair, and the uniformity of the buildings (Hartshorne 2004). Incidents involving individuals encroaching into the public space were also recorded, with nuisances including individuals unlawfully extending their properties, setting up stalls before their tenements and placing building materials in the street (Hartshorne 2004). This encroachment upon the public space was a major issue for the streets of medieval York, which were narrower than they are today (Dean 2008) and such appropriation of the street space jeopardised the movement of pedestrians, carts and carriages (Hartshorne 2004).

In order to further explore the features of the street façades it will also be necessary to consider the characteristics of urban secular buildings in medieval and Tudor England. The practice of timber framing was prevalent in this period, (Rimmer 2007; Schofield and Stell 2000), the earliest examples dating from the thirteenth century (Harris 1993).

Timber-framed buildings are often described by referring to the number of bays. A bay can be defined as a section between principal supporting timbers (Alcock *et al.* 1996) and the number of bays gives an indication of the size of the building. However, not all bays in a building are necessarily of the same width, varying from 1.5 to 6 metres (Harris 1993). Furthermore, bays 1.52, 2.44 and 3.05 metres wide were common for properties with shops onto the street as well as for passages leading to buildings with no street frontage (Jones 1987b).

The most commonly used material for timber-framed structures was oak (Grenville 1997; Harris 1993) and in the late Middle Ages timber for construction in York was often sourced from monastic woods such as the ones belonging to St Mary's Abbey, Selby Abbey and Fountains Abbey (Rimmer 2007). The panels placed between the timbers could be infilled using wattle and daub (Harris 1993). Wattles made of hazel or oak were woven to form panels and then daubed with a mixture made of clay, dung and straw, before being limewashed or painted (Harris 1993). Timber-framed buildings could also be infilled in brick (called at the time wall-tiles, *waltigill*), which was a common technique in medieval York (Rimmer 2007). Although this material is known to have been imported from Flanders in the late Middle Ages, it is also in this period that the production of brick in Yorkshire started developing (Rimmer 2007). From the fourteenth century brick in York was not only used for timber-framed panels, but it was also a main material for the walls of religious premises or buildings of high-status, such as the Merchant Adventurer's Hall (Dean 2008; Grenville 1997; Rimmer 2007). Although many timber-framed buildings have had their outer walls plastered in later periods, traditionally the timber framing was meant to be visible (Harris 1993).

Many timber-framed buildings in medieval town centres had a shop on the ground floor (Clark 2000). Shops were characterised by their large windows, which allowed enough light into the property as well as the display of goods for sale (Clark 2000). They are thought to have had two shutters, one at the top and another at the bottom. The lower one was referred to as a “stall-board” or “flappet”, it was dropped towards the street and had two legs, forming a shop counter; the upper shutter may have been opened outwards and it is possible that removable shutters were used (Clark 2000).

A distinctive feature of urban timber-framed buildings in the fifteenth and sixteenth centuries is their jetties, which are projecting upper storeys (Harris 1993). Upper storeys could be jettied on the gable end as well as on the sides of the building and the amount of projection of a jetty could vary but the standard in the fifteenth century was 0.53-0.6 metres (Harris 1993). Although jetties symbolised wealth and status (Harris 1993) they also had some practical advantages. Firstly, upper floors had an increase in space (Harris 1993). Secondly, they could protect passers-by from the rain (Harris 1993) and in the case of there being a shop on the ground floor this meant that pedestrians sheltering from the rain had a good opportunity to have a look at the products on display (Clark 2000). Furthermore, the jetty would protect the products from being damaged by the rain (Clark 2000).

The addition of glass to windows did not become a widespread practice until after the late sixteenth century and before this period, if necessary, windows could be closed with wooden shutters (Harris 1993). Initially, leaded lights in line with the wall were added but gradually the use of projecting windows became more common (Harris 1993).

4.3.1 Buildings in Stonegate

The following section explores the characteristics of the buildings that are still present in modern Stonegate, in particular those that date from the fourteenth to the sixteenth centuries. All information has been drawn from the fifth volume of *An Inventory of the historical monuments in the city of York* (RCHM, V, 1962-81). The buildings have been grouped in relation to the left- and right-hand sides of the pageant route and the focus has been placed on those features that will have an effect on the simulation of the acoustics of Stonegate.

The majority of the buildings standing today in Stonegate on the left-hand side of the pageant route date from the seventeenth and eighteenth centuries, with many of them having had their ground floors converted into shops in the nineteenth century. All buildings dating from the seventeenth century are timber-framed with most of them presenting jetties projecting towards Stonegate.

Also present are buildings dating from the fourteenth and fifteenth centuries, which would have been standing at the time of the performances of the plays. Nos. 44 and 46 have a front range thought to date from the fifteenth century and were at one point a timber-framed building of three storeys and four bays. The buildings had jetties but these were cut back and replaced by a brick front, with the shop front of Nº46 dating from the nineteenth century. Nos. 48 and 50 occupy a plastered two-bay timber-framed building with a three-storey structure at the front, dating from the late fifteenth or early sixteenth century. Both the first and the second floors are jettied. A fifteenth-century rendered timber-framed building of three storeys and two bays can be seen at No. 52. The jetties have not been cut back and can be seen at the front of the building. A range of three-storeyed timber-framed buildings with a rendered and jettied front, dating from the early or mid fourteenth century can also be seen at Nos. 54, 56 and 60 (Figure 4.1). These buildings comprise a seven-bay range and it is possible that each bay was originally a separate tenement. The windows date from the eighteenth or nineteenth century and the shop fronts on the ground floor date from the nineteenth century.

Figure 4.1 – The left-hand side of the pageant route. Stonegate Nos. 54, 56 and 60 (2013).

The right-hand side of the pageant route is characterised by the presence of buildings dating from the fifteenth century. Nº13, at the corner of Stonegate and Little Stonegate, is a plastered three-storeyed timber-framed building, whose earliest section is the three-bay range on Stonegate, which dates from the fifteenth century (see Figure 4.2). Originally both the first and second floors were jettied but the jetty on the second floor was cut back in the eighteenth century. The range fronting Little Stonegate has two bays and was built as a separate house in the late fifteenth or early sixteenth century. It was originally a two-storey building but a third storey, which is jettied, was added in the seventeenth century. The shop fronts on the ground floor are from the early nineteenth century.

Figure 4.2 – The right-hand side of the pageant route. Stonegate No. 13 at the corner of Stonegate (left) and Little Stonegate (right) (2013).

The buildings at nos. 15 and 17-19, which nowadays house Mulberry Hall, date back to the fifteenth century. No. 15, located at the corner of Stonegate and Little Stonegate, consists of two timber-framed buildings of three storeys and attics (see Figure 4.3). Although they date from the fifteenth century they were cased in brick in the mid eighteenth century, the jetties on both the front and side were cut back and the shop front was created in the early nineteenth century. The building at Nos. 17-19 is timber-framed with three storeys (see Figure 4.4). It dates from the mid-fifteenth century and was originally of two storeys until in the late sixteenth century a third storey was added. The upper floors are jettied and there are three gables at the front. Oriel windows from the sixteenth/seventeenth centuries can be seen on the front elevation. Nos. 17-19 was depicted by Henry Cave in 1813 (see Figure 4.6). It can be observed that the upper storeys' façade has remained mostly unchanged. The main differences can be found on the ground floor. The building in contemporary York has five glass panels of different widths corresponding to shop windows, whereas in

Cave's depiction only two windows can be seen, a bow window on the extreme left and a shop window with a counter towards the extreme right.

Figure 4.3 – The right-hand side of the pageant route.
Stonegate No. 15 (2013).

Figure 4.4 - The right-hand side of the pageant route.
Stonegate Nos. 17-19 (2013).

Figure 4.5 - Sepia print of Stonegate c.1858 (Imagine York).
Nº15 can be seen occupied by a Public Library. A sign covers part of the façade, including the balusters of the middle window on the first floor.

Figure 4.6 – *Stonegate* (Cave 1813)

The structure at Nos. 21-25 is a four-bay timber framed building dating from the fifteenth century and similar in style to Mulberry Hall (Nos.

17-19) (see Figure 4.7). It was originally a two-storey building but the first and second bays were heightened to provide attics. The first was heightened in the sixteenth century, approximately at the same time that the heightening of Mulberry Hall occurred, whereas the second bay was heightened at a different time. The building has a rendered front elevation and the ground floor has nineteenth century as well as modern shop fronts. The first floor is jettied in all bays whereas the second floor is only jettied in the bay next to Mulberry Hall. The fenestration of the upper floors is from the nineteenth century and later. A portion of this building in the early 1890s can be seen in Figure 4.8 with its timber framing still visible. The most significant changes that can be observed are the ground floor window of No. 21A, which does not seem to have any glazing and the passage in No. 23 where no gate seems to have been in place.

Figure 4.7 – The right-hand side of the pageant route.
Stonegate Nos. 21-25 (2013).

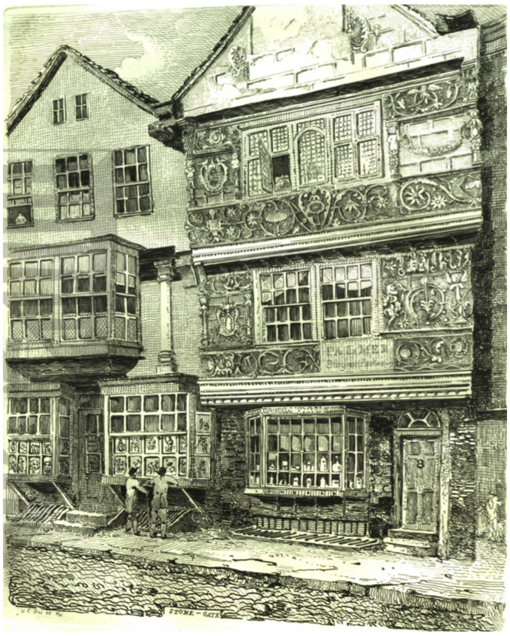
Figure 4.8 - Sepia print of Stonegate in the early 1890s (Imagine York).

No. 27 is also from the fifteenth century and originally had only two storeys and might have been a continuation of the two-storeyed buildings on Nº21-25 (see Figure 4.9). The addition of a third storey took place in the sixteenth or early seventeenth century. The front elevation is rendered and the upper floors are jettied. The fenestration dates from the eighteenth century and later.

No. 35 is also a timber-framed building dating from the fifteenth century (see Figures 4.10-4.11). The front is of three storeys, with jettied upper floors and a rendered front elevation. The decorative details, carved woodwork and shop front date from the late nineteenth century. Most of Nº 35 can be seen in Henry Cave's illustration from 1813 (see Figure 4.11). The ground floor and upper storeys seem to have remained mainly unchanged with the exception of the addition of carved woodwork and decorative details.

Finally, a three-storeyed plastered timber-framed building with jettied upper floors and dating from the late medieval period can be found at No. 43 (see Figure 4.12). The canted windows on each upper floor, the block cornice and the shop window are all from the eighteenth century.

Figure 4.9 – The right-hand side of the pageant route.
Stonegate No. 27 (2013).



Figures 4.10 (left) and 4.11 (right) – The right-hand side of the pageant route. Both images show Stonegate Nos. 33 (towards the right-hand side of the images) and 35 (towards the left-hand side of the images). The image on the left shows the buildings in their modern state (2013) whereas the figure on the right is a depiction by Henry Cave (1813). The building at No. 35 is of particular interest since it dates from the fifteenth century.

Figure 4.12 – The right-hand side of the pageant route.
Stonegate No. 43 (2013).

4.4 The Acoustics of Modern Stonegate

The study of the buildings located in modern Stonegate (see section 4.3.1) demonstrated that although there are several properties dating from the seventeenth to the nineteenth centuries, there are also ten structures with their origins dating back to the fourteenth and fifteenth centuries. Despite the fact that these structures have suffered alterations throughout the years, such as the creation of shop fronts and changes in the fenestration, mostly as a result of work conducted in the eighteenth and nineteenth centuries, they still exhibit some of their salient characteristics, including their timber-framed structure and jetties. These characteristics are clearly displayed by the properties at the right-hand side of the pageant route, in particular those from No. 13 to 25.

The preservation of these buildings together with the fact that the dimensions of Stonegate have been mostly maintained from the period of interest to the present (White 1987), make Stonegate a suitable site for a study of acoustics. Such research relies not only on virtual models but takes real-world acoustics measurements as a starting point by considering the characteristics of the site in its present state.

4.4.1 Impulse Response Measurement Techniques

The study of the acoustics of modern Stonegate can be implemented through impulse response (IR) measurements. In simple words, an IR measurement consists in playing a sound, which acts as an excitation signal, within a space and simultaneously recording via a microphone the response of the space to the signal. Several techniques have been developed throughout the years with the objective of measuring the IRs of spaces accurately. An essential part in IR measurements is the choice of the excitation signal. Acousticians have used a variety of impulsive sounds, including starter pistols, balloon pops, firecrackers and handclaps, but these sources present limitations: they cannot produce sufficient energy at low frequencies, they are not omnidirectional in all frequency bands and repeatability cannot be assumed (Griesinger 1996). In recent years the use of deterministic excitation signals played through loudspeakers has become a popular choice among researchers. Advantages include the fact that they can be precisely reproduced, the measurements can be repeated and they provide a better signal-to-noise ratio (SNR) (ISO 18233, 2006).

Choosing an IR measurement technique appropriate for outdoor measurements requires the consideration of numerous factors, including the background noise level, the state of occupancy of the site at the time of the measurements, city council restrictions and the optimum time for carrying out the measurements in relation to background noise levels. This requires choosing a method that provides sufficient SNR and is robust enough to withstand time-variance, due to changes in environmental conditions that might occur during the measurements.

A popular method for acoustic measurements is the Exponential Sine Sweep method (ESS) (Farina 2000; Farina 2007; Müller and Massarani 2001), which employs an exponential sine sweep with a pink spectrum (equal energy per octave band) and which is then linearly deconvolved using an inverse filter, that is, a time-reversal of the test signal used. When this method is used on weakly nonlinear systems it can separate the harmonic distortion (caused by the loudspeaker) and turn it into pre-delayed signals at the start of the IR. This method is also more robust in the presence of time-variance and presents a better SNR than other methods using deterministic signals, such as the Maximum Length Sequence (MLS) and the Inverse Repeated Sequence (IRS) (Farina 2000; Farina 2007; Müller and Massarani 2001). The sine sweep employed needs to be long enough to allow for the decay of high frequencies and also long enough to ensure that low frequencies decay while the excitation signal is sweeping through the high frequencies (Müller and Massarani 2001). Additionally, the excitation signal needs to be followed by silence to allow the high frequencies to decay completely. The ESS method can be negatively affected by transient sounds occurring during the measurements, which can cause errors in the calculation of the reverberation time. However, in the case of a transient sound occurring during an acoustic measurement, it is possible to minimise its negative effect by identifying the frequency of the sine sweep at the moment of the transient noise and then applying a narrow band pass filter at that same frequency, which as a consequence, will remove all wide band noise produced by the unwanted transient sound (Farina 2007).

If we assume a linear time-invariant (LTI) system, then the averaging of multiple ESS measurements will improve the SNR due to the fact that in every measurement the LTI component will remain the same, while the background noise will be random, resulting in an increase of the SNR by 3dB each time the number of measurements is doubled (ISO 18233, 2006). However, although time-invariance is assumed as a starting point, we must acknowledge that there will be time-variances introduced by changes in air temperature and movement (Bradley 1996; Müller and Massarani 2001) and more significantly in the case of this project, by the presence of passers-by. When time averaging is applied these variances will produce further errors in the calculation of the acoustical parameters (Bradley 1996; ISO 18233, 2006), which can be the result of phase cancellation effects.

When employing the ESS method another approach to improving the SNR is the use of a single, very long sine sweep. Doubling the length of the sweep increases the SNR by 3dB (ISO 18233, 2006). When considering fully enclosed spaces this technique has been shown to provide more reliable results than time averaging (ISO 18233, 2006; Farina 2007), however, when conducting IR measurements outdoors and in particular in urban areas, the results when using a long sine sweep can be affected by the greater number of disturbances that may occur during a lengthier measurement time. This problem could be avoided by employing time averaging with the ESS method, by conducting multiple measurements and carrying out a process of selection of the measurements with better SNR before completing the averaging process (Müller and Massarani 2001).

4.4.2 Acoustical Studies of Urban Spaces

Throughout the years several researchers have studied the propagation of sound in urban areas in relation to different research interests. Studies have focussed on understanding sound propagation in relation to urban noise (Bullen and Ficke 1976; Lyon 1974; Picaut *et al.* 2005; Wiener, Malme and Gogas 1965) and speech intelligibility (Wiener, Malme and Gogas 1965), and great emphasis has been placed on the effects of weather conditions (Wiener, Malme and Gogas 1965), and on the use of modelling techniques to simulate sound propagation (Bullen and Ficke 1976; Kang 2000). Different researchers have chosen to use different excitation signals when carrying out IR measurements. In 1976 Yeow used firecrackers to carry out measurements in Kuala Lumpur, while Picaut *et al.* (2005) carried out IR measurements in Nantes, France, using an alarm pistol and an array of nine microphones setup in a section of the street and then moved along it to record the sound propagation in the whole area.

In recent years acoustical studies have also considered urban spaces in relation to their use for musical performances. Paini *et al.* (2004) carried out measurements in a public square in Copenhagen using a 10.9-second exponential sine sweep played through a dodecahedron loudspeaker. The measurements on site were used to carry out a comparison with the results of a virtual model of the same space.

Thomas *et al.* (2011) also investigated the acoustics of urban squares, in particular those used for open-air rock concerts by studying five squares in Belgium. Acoustic measurements were carried out employing a 12-second exponential sine sweep and the amplification system of the site was used to play the signal.

Despite such an extensive corpus of research on the acoustics of urban sites, to the knowledge of the author no studies have considered urban spaces regularly used by past cultures for drama and music performances. When carrying out measurements of such spaces it is critical that they are informed by an understanding of how the space was utilised in the historical period of interest. For instance, the position of performers and audience in the space is essential when considering the positions of sources (the excitation signal) and receivers (microphones).

4.4.3 Comparison of IR Measurement Techniques in Noisy Environments

The challenges involved in choosing a suitable IR measurement technique for Stonegate include the necessity of achieving a good SNR, selecting a technique that allows fast capture and is robust in the presence of time variance, caused by changing environmental conditions and the presence of visitors. Such difficulties coupled with the limited research studies on similar spaces, indicated the necessity to conduct an experiment in a controlled environment to determine what measurement method might be preferable for carrying out acoustic measurements in Stonegate.

The experiment was setup in the Black Box Theatre of the Department of Theatre, Film and Television (University of York) (see Figures 4.13-4.14) and two IR measurement methods were tested. Both methods followed the ESS technique and used exponential sine sweeps with a frequency range of 22-22000Hz. The first method, referred to as the 90-second sweep method, used a 90-second exponential sine sweep as excitation signal. The second method, referred to as the time averaging method, employed eight 15-second exponential sine sweeps, which were time averaged after the measurements.

The aim of the experiment was not to recreate the soundfield of Stonegate, but to study the effects of different noise sources typically found in this site on the two different measurement methods in order to determine the most reliable technique to conduct measurements on site.

For testing the first method a 90-second exponential sine sweep was utilised. This length was chosen due to its suitability for Stonegate, whose reverberation time was estimated as 1.5s. To achieve acoustic measurements of a high quality the sine sweep used should have a minimum length that equals the reverberation time at high frequencies while allowing enough capture time for the decay of both low and high frequencies (Müller and Massarani 2001), making 1.5s the minimum length possible for the measurements in Stonegate. Using a 90-second sine sweep the SNR will improve by 17.78dB, when compared to this minimum length since doubling the length of the sweep increases the SNR by 3dB (ISO 18233, 2006). Furthermore, this was considered as the maximum length of time traffic and passers-by could be stopped at each measurement. A longer measurement time would have also increased the chances of results being affected by time variance.

The choice of the number of measurements taken for the time averaging technique was selected as a compromise between achieving a similar increase of SNR to the 90-second sweep and keeping the measurement time as short as possible. Therefore an increase of 9dB was achieved with a measurement time of 120s by using eight 15-second sine sweeps.

The speaker used to play the excitation signal was a Genelec 8040A Monitoring System and it was considered appropriate due to its directivity. Although an omnidirectional source is recommended in ISO 3382 (1997) a directional source was used due to the fact that in the measurements in Stonegate it would be representing an actor and/or singer. As discussed in chapter 3 (section 3.3.2), vocal directivity is characterised by being omnidirectional at low frequencies and increasingly directional at higher frequencies. Although the Genelec 8040A speaker does not present the exact same directivity observed for talkers and opera singers it does present the same tendencies towards an increase in directivity at higher frequencies (see Table 4.1). As a result it was considered as a suitable choice for the study of the acoustic response of the space to the directivity of the human voice.

To record the impulse response a Soundfield ST350 microphone was used. The Soundfield microphone combines four sub-cardioid capsules and when the recordings are decoded it results in a signal with four channels, W, X, Y and Z. The W-channel is omnidirectional, whereas the X-channel records the front/back, Y the left-right and Z the up-down directions. The results for many acoustical parameters including reverberation time and clarity can be derived from the W-channel, but it is the combination of the W and Y channels that allows the calculation of the LF parameter.

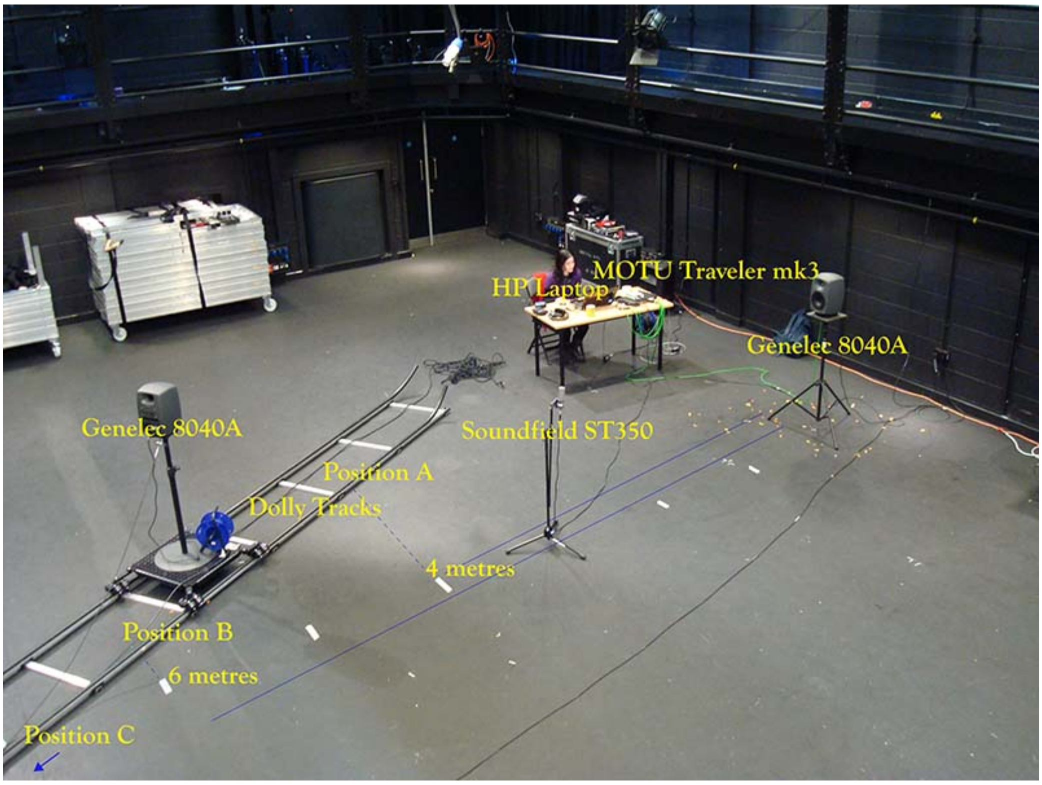


Figure 4.13 - Setup in Black Box Theatre, Department of Theatre, Film and Television, University of York (November 2011).

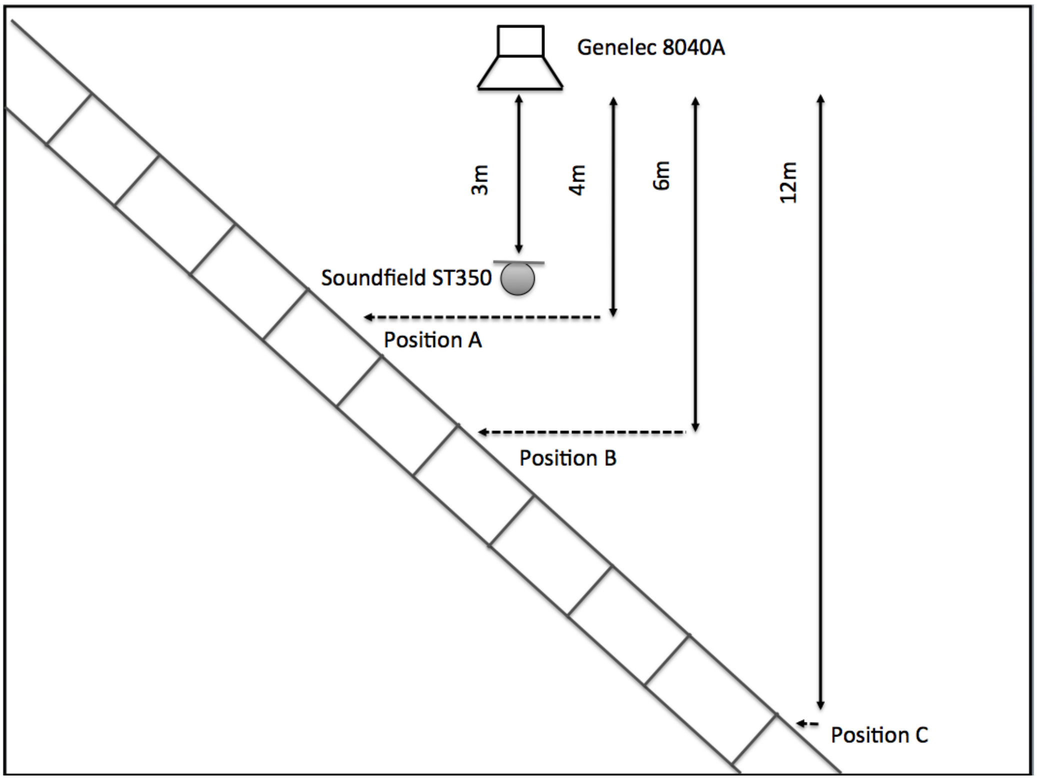


Figure 4.14 - Diagram of the setup in the Black Box Theatre.

	Sound Source		
	Talker	**Opera Singer**	**Genelec 8040A**
		90º	
500Hz	-1.8	-0.5	-3.0dB
1kHz	-0.3	+1.5	-8.0dB
2kHz	-5.6	-7.5	-15.0dB
4kHz	-5.5	-7.5	-15.0dB
		180º	
500Hz	-6.1	-7.5	-10.0dB
1kHz	-5.0	-5.5	-10.0dB
2kHz	-10.9	-16.0	-20.0dB
4kHz	-16.6	-15.5	-25.0dB

Table 4.1 – Attenuation of sound energy at the side of the source (90º) and at the rear (180º) compared to the sound energy at the front (0º). The data regarding the directivity of an opera singer was sourced from (Cabrera, Davis and Connolly 2011), whereas the directivity of a talker was sourced from (Chu and Warnock 2002), the data for the Genelec 8040A was taken from the Common Loudspeaker Format (CLF) file.

Both source (Genelec 8040A) and receiver (Soundfield ST350) were setup at a height of 1.20m. The receiver was positioned 3m away from the source, and the position of the source and receiver remained fixed and constant during all measurements. The soundcard, a MOTU Traveler mk3, and an HP laptop were used for running Pro Tools 9, a digital audio workstation, for signal acquisition and playback. A second Genelec 8040A was mounted on a dolly track and this was used to playback noise sources. A rope was attached to the speaker on the dolly track, which was then pulled along the track to allow the simulation of the movement of the noise sources.

The sources of noise chosen for the experiment were selected due to their presence in Stonegate; these were ambience, York Minster bells, speech, footsteps and footsteps+speech. The impact of these noise sources placed at four different positions was also tested. The critical distance calculated for the space was 8m, therefore positions A and B, which were 4 and 6m away from the source playing the excitation signal were both in the direct field. Position C was in the diffuse field, approximately 12 meters away from the speaker. The fourth position, which was mobile, consisted of the speaker on the dolly track and was manually moved by means of a rope from the diffuse field towards the microphone during the measurements. Measurements were conducted in sixteen different noise setups by locating the noise sources at all the positions mentioned, with the exception of the York Minster bells sample that was only located at Position C (due to its location in relation to Stonegate) and the ambience sample which was only employed at static positions. In addition to the measurements in the presence of noise sources, measurements in optimum conditions (with no added noise sources) were also conducted.

In this particular experiment difficult test conditions in relation to the SNR were purposefully chosen in order to analyse how the excitation methods performed in challenging noise conditions. The reference output level of the loudspeaker was set to 73.5dB(A) at 1m using a -20dBFS pink noise signal. Considering the long-term average SPLdB(A) at 1m from the source, the sine sweeps played at 86.5dB(A) whereas the noise sources ranged from 54.5-63.5dB(A) (see Table 4.2).

SPLdB(A)				
Ambience	York Minster Bells	Speech	Footsteps	Footsteps+Speech
54.5dB(A)	63.5dB(A)	62.5dB(A)	58.5dB(A)	63.5dB(A)

Table 4.2 - Long-term average SPL dB(A) at 1m from the source.

The excitation signals were generated with the Aurora plug-ins and the captured IRs were deconvolved using a Voxengo Deconvolver and subsequently analysed with the Aurora plug-ins. The analysis of the results is focused on the W channel of the Soundfield microphone and the acoustic parameters calculated were T_{20}, T_{30}, EDT and C_{50}. The acoustical parameters selected for analysis are those that are essential for the study of the relationship between speech and acoustics. Since speech is the key element in the performance of the York Mystery Plays it was considered of the utmost importance to determine the optimum method to acquire reliable measurements of these parameters. The changes in the results of the acoustical parameters, as a consequence of the addition of noise sources at different positions, were considered in relation to the Just Noticeable Difference (JND) for the parameters studied. A Just Noticeable Difference can be defined as the smallest perceptible difference between samples. Measurements were considered accurate if the variations between the results in noisy conditions and in optimum conditions were smaller than the JND and inaccurate if they were equal or larger. The JND for T_{20}, T_{30} and EDT was taken to be 5% (ISO 3382, 2009) for values larger than 0.6s. When taking into account parameter results smaller than 0.6s, the JND was considered as an absolute value of 0.03s, based on the findings of Niaounakis and Davies (2002). The JND for C_{50} was considered to be 1.1dB (Bradley, Reich and Norcross 1999).

The results of the measurements with no noise disturbances for both methods were very similar (see Figure 4.15). In the presence of noise both methods presented deviations from the values calculated with no injected noise. This applied to all parameters calculated with the exception of C_{50}. No inaccurate results were found for this parameter with the introduction of noise sources, demonstrating the reliability of the results of C_{50} even in the presence of unfavourable circumstances during the measurements.

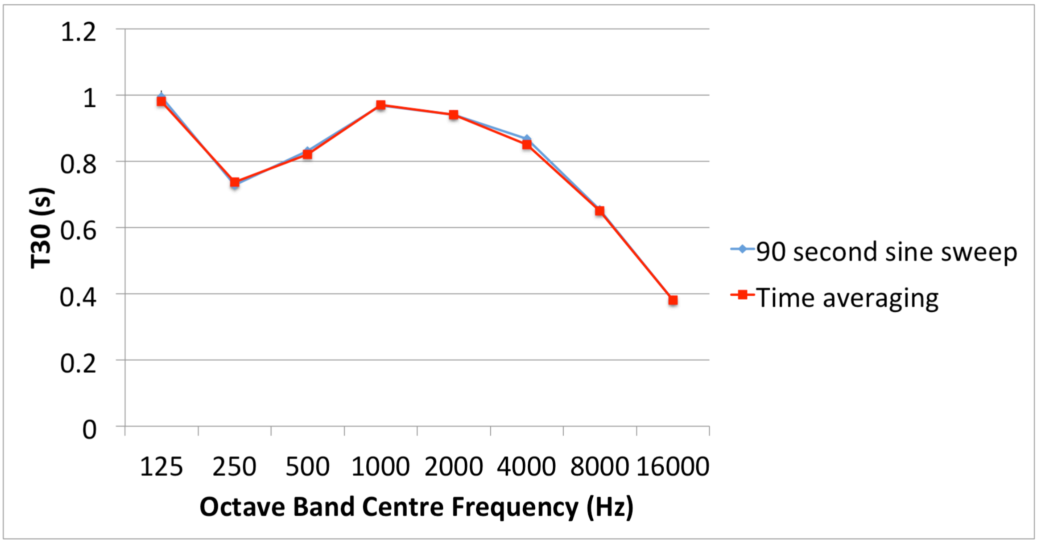


Figure 4.15 - Mean values and standard deviation of the two measurements of T_{30} in a setup with no noise disturbances.

Regarding the parameters related to the reverberation time both methods were affected by the noise sources. Table 4.3 shows that under the test conditions in the presence of noise disturbances it was the time averaging method that presented the largest deviations from the results in optimum conditions. This could be the result of phase cancellation effects during the averaging process, which can produce errors in the estimation of acoustical parameters.

The largest inaccuracies in the results were the consequence of the introduction of speech, footsteps and Footsteps+Speech samples which had the greatest negative effects from 125-500Hz due the high spectral density of those noise sources at those frequency bands (see Figure 4.16). The ambience sample, due to its random spectral content, had a very small impact on the results. The York Minster bells sample affected the results from 250Hz to 1kHz due to the presence of harmonics at these frequency bands. Furthermore, it was the positions in the direct field that had the greatest impact on the results of both methods. There was very little impact resulting from noise sources in the diffuse field due to the fact that the levels of those noise sources at the microphone position were lower compared to the other positions (see Table 4.4).

	90-sececond sine sweep			Time Averaging		
	T20	T30	EDT	T20	T30	EDT
125Hz	2	2	N/A	10.6	1.4	1.11
250-500Hz	7	9	N/A	2.75	10.25	1
1kHz	N/A	3.2	1.25	N/A	2.6	1.33
2-4kHz	N/A	N/A	2.75	N/A	4	4.67
8-16kHz	N/A	N/A	1.33	N/A	1.33	1.33

Table 4.3 - Highest deviations from results in optimum conditions calculated in JNDs. N/A indicates that no significant differences were recorded.

The results presented indicate that the most suitable method for Stonegate, taking into consideration the characteristics of the site and its restrictions, is the 90-second sweep, which confirms the findings explored in section 4.4.1. The following section will explore how this method was applied on site as well as the results obtained.

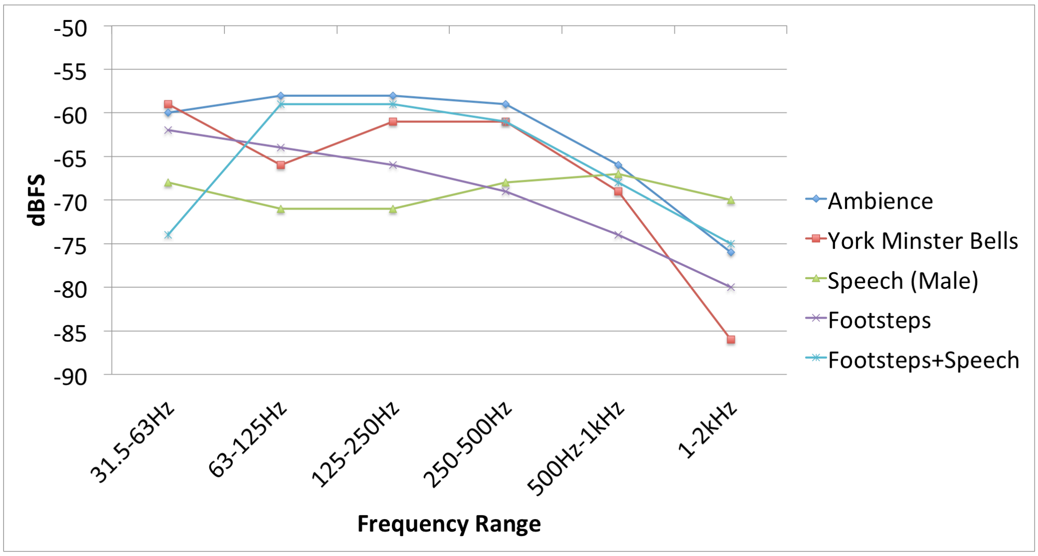


Figure 4.16 - Average frequency content of noise sources. The values indicated in the figure were calculated by averaging the numerical data in dBFS within the frequency ranges specified. This data was generated by analysing the audio samples using Adobe Audition 3.0.

SPL dB(A)					
	Ambience	York Minster Bells	Speech	Footsteps	Footsteps+ Speech
Diffuse Field	30.5dB(A)	32.5dB(A)	31.5dB(A)	31.5dB(A)	33.5dB(A)
Direct Field (6m)	32.5dB(A)	N/A	34.5dB(A)	34.5dB(A)	36.5dB(A)
Direct Field (4m)	33.5dB(A)	N/A	35.5dB(A)	35.5dB(A)	37.5dB(A)

Table 4.4 - Long-term average SPLdB(A) of the noise sources at the receiver position.

4.4.4 Acoustic Measurements in Stonegate

Acoustic measurements in Stonegate that are focussed on the study of the York Mystery Plays require the identification of a suitable portion of the street for the location of the sound sources and receivers, which represent the performers and listeners respectively. The most exhaustive studies on the locations of the playing stations focus on the second half of the sixteenth century (White 1984, 1987 and 2000), allowing a more precise identification of the performance sites used in this period. Although there were nine performances in those years the only extant lists of stations are those corresponding to 1554 and 1569, which were recorded in the Chamberlain's Books and House Books, respectively (White 1984).

In 1554 the York Cycle had two stations in Stonegate. The first one was indicated as being located at Robert Bylbowe's property but unfortunately the location of his house is not known (White 1984). The second station located in Stonegate was at Minster Gates and it was allocated to Anthony Dycconson and Robert Staynburne; it was identified as being located in the corner of Stonegate, opposite the Minster Gates and on the left hand side of the pageant route (White 1984). In 1569 two stations are recorded, one at Christopher Willoughby's house, which is thought to have been located on the right hand side of the pageant route approximately where Mulberry Hall stands today (White 1984). A location in the same area was also utilised for the performance of the Pater Noster Play in 1572 (White 1984). The second station was, as in 1554, Minster Gates but since no stationholders were allocated to this playing place the site cannot be precisely located (White 1984).

The most appropriate of these sites for acoustic measurements is at Christopher Willoughby's property. The suitability of this site is due to two main reasons. Firstly, its identification provides a specific landmark, Mulberry Hall, which aids its location. Secondly, it is situated in a portion of the street that includes several buildings of medieval origins on the right-hand side of the pageant route. The 1554 station at Minster Gates may have been suitable due to the precise identification of its location but the area of the station has been greatly modified through the years, and what is now the street called Minster Gates used to be the site of one of the gateways into the Minster precincts. Such change would have had a significant impact on the acoustics of the space, making it a less suitable location for acoustic measurements. Furthermore, its proximity to the York Minster might have resulted in further challenges for impulse response measurements since, as it was observed in section 4.4.3, the York Minster bells have been shown to affect the reverberation time results from 250Hz to 1kHz.

As a consequence of the findings recorded in the experiment conducted in the Black Box Theatre, the IR measurements in Stonegate were carried out using the ESS method with a 90-second exponential sine sweep. The frequency range of the sine sweep was 22-22000Hz and it was followed by 10s of silence to allow the high frequencies to decay completely. The sound source utilised was a Genelec 8040A Monitoring System and two receivers were used, a Soundfield SPS422B microphone and a Kemar dummy head. The latter was incorporated to the setup to allow the recording of binaural impulse response measurements, which can be used to calculate the IACC parameters ($IACC_E$ and $IACC_L$). The soundcard used was a Fireface 800 while Pro Tools 9 was employed for loop playback and recording.

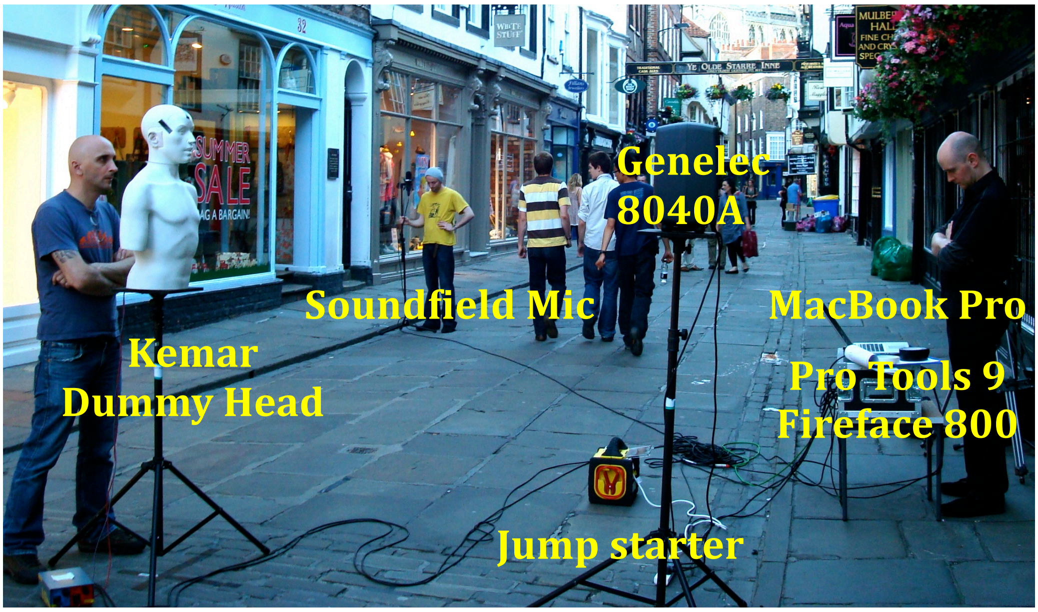


Figure 4.17 – Setup for Acoustic Measurements in Stonegate as part of a pilot study (June 2011).

Figure 4.18 – Setup for Acoustic Measurements in Stonegate (February 2012).

The selection of the source and receiver positions was challenging since the space studied is not a typical performance space with a clear delimitation between performers' and audience area. The measurements were conducted without including the presence of a wagon but instead considering the performance as carried out at street level. Therefore, source and receivers were positioned at a person's ear height (1.65m). The effects of the presence of a wagon will be studied at a later stage using virtual models of the sixteenth-century urban space (see chapter 5). The setup used for the measurements consisted of one source position, which represented a performer at the centre of a hypothetical performance area. This performance area was delineated by taking the breadth of Mulberry Hall at Nos. 15-19 (19.11m) and the approximate depth of a medieval wagon plus some additional backstage space (2.5m)(McKinnell 2000) as a guideline for setting the boundaries of the performance area at street level. The source was positioned towards Mulberry Hall, simulating a side-on oriented performance. Three receiver positions facing the speaker were selected following suggestions made for measurements of the main floor of concert halls (Gade 1989) (see Figure 4.19). The receiver positions also followed the recommendations of ISO 3382 (1997) by positioning the microphones more than half a wavelength from each other and at least a quarter of a wavelength from any reflecting surfaces.

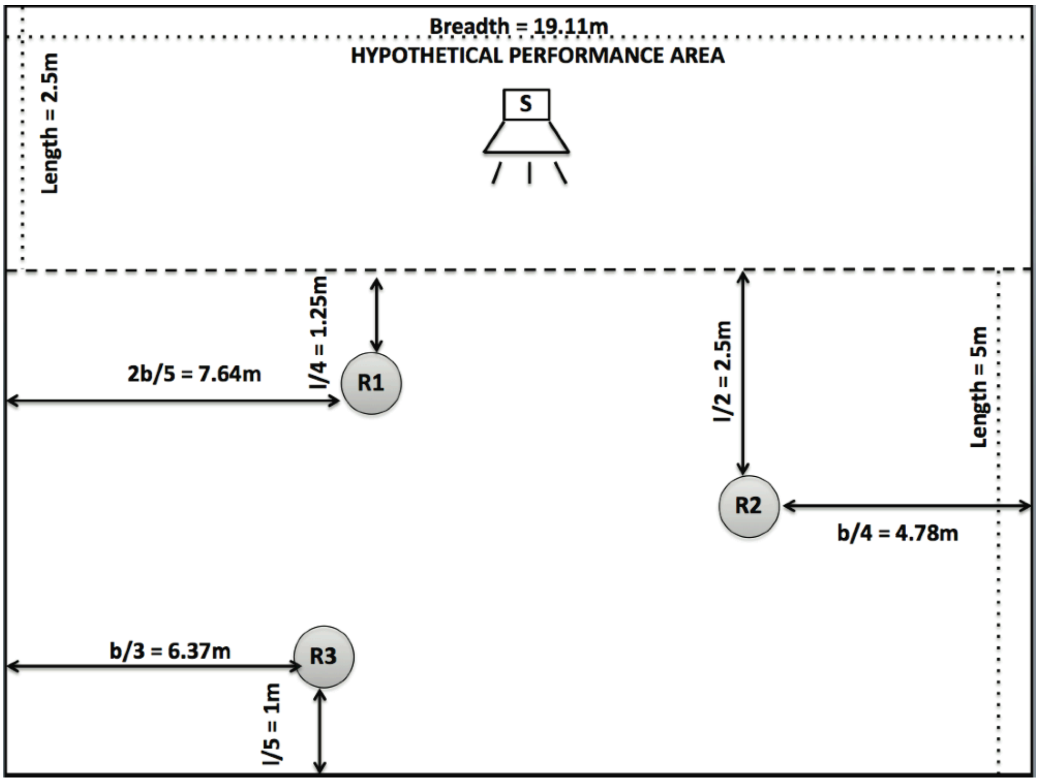


Figure 4.19 - Positions of source and receivers in Stonegate.

A determining factor of the choices on source and receiver positions explained above was that the setup had to allow the capture of data in the time window between 8-9am on a Sunday morning, since 8am is the earliest time at which the York City Council allows the placement of loudspeakers in the street and at 9am the Minster bells start ringing and the street gets busier. Sunday mornings present the best opportunity for the measurements due to the fact that there are fewer passers-by in the area when compared to weekdays and Saturdays. However, during that short time window noise levels increase as time progresses mainly due to the increase in the presence of visitors and of people working in the shops in the area (see Figure 4.20) consequently measurements taken closer to 9am are more likely to present low SNR and be affected by passers-by. Another complicating factor is that during this time window the street is open to traffic, which meant that the setup had to be dismounted to allow cars to pass on several occasions. Such limitations suggest that the best approach is the concentration on a limited number of measurements. Therefore, only one source position was utilised, although the use of at least two source positions is recommended in ISO 3382 (2009). Furthermore, although it would have been of interest to position source and receivers considering the possibility of actors performing in both a side-on and a front-on orientation, only the former was selected for the measurements.

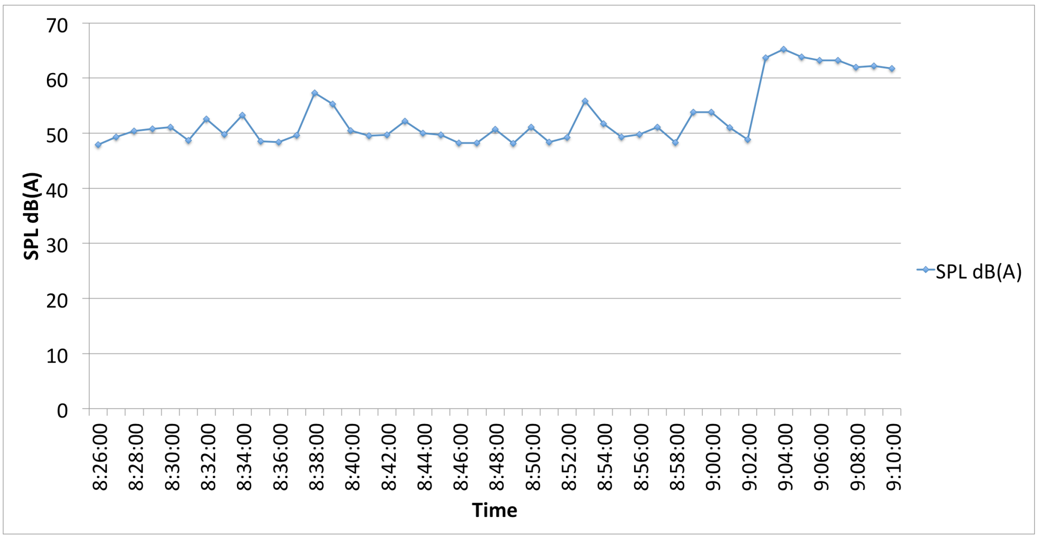


Figure 4.20 - Measurements of SPL dB(A) taken in Stonegate on the morning of July 15th, 2012.

The reference output level for the excitation signal was recorded using pink noise and it was 88dB(A) at 1m from the source. The background noise was measured as 58dB(A) at that same position. The York City Council does not determine a maximum SPL at street spaces and leaves it to the discretion of the individual, therefore the playback level was determined by the maximum level that could be played before the activation of the loudspeaker's internal protection circuit. The aim was to repeat the measurement at each S-R combination three times to check repeatability and the possible effects on the measurements of time variance. This was not possible in all cases since the number of measurements had to be modified to avoid conducting them in the presence of passers-by (see Table 4.5). Deconvolution was implemented using a Voxengo Deconvolver and the IRs were analysed using the Aurora plug-ins.

Measurement (S-R)	Nº of Takes
S1 – R1 (Soundfield)	3
S1 – R1 (Kemar)	1
S1 – R2 (Soundfield)	2
S1 – R2 (Kemar)	3
S1 – R3 (Soundfield)	1
S1 – R3 (Kemar)	2*

Table 4.5 - Number of takes at each S-R combination.
* One of these takes had to be discarded due to wind distortion.

The energy decay curves for the three receiver positions at 1kHz (see Figures 4.21-4.23) indicate the higher SNR achieved in the acoustic measurements for receivers 1 and 2 in comparison to receiver 3. The significant difference is related to the increase in the noise floor at the time in which the measurement at receiver 3 was conducted. This acoustic measurement was carried out closer to 9am and as shown in Figure 4.23 the background noise tends to increase with the passage of time which can affect the calculation of reverberation time parameters, in particular T_{30}.

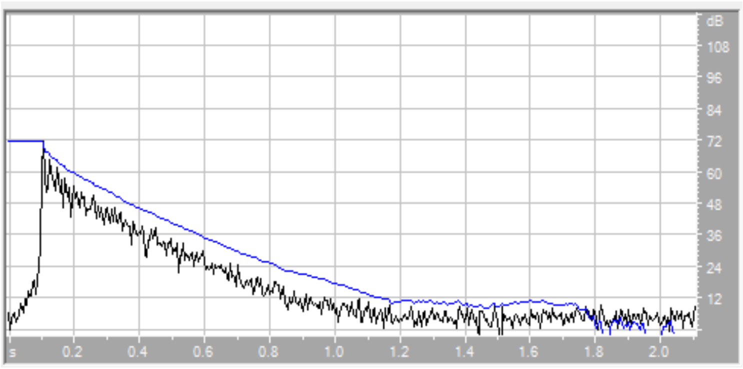


Figure 4.21 - Energy decay curve corresponding to S1-R1 at 1kHz.

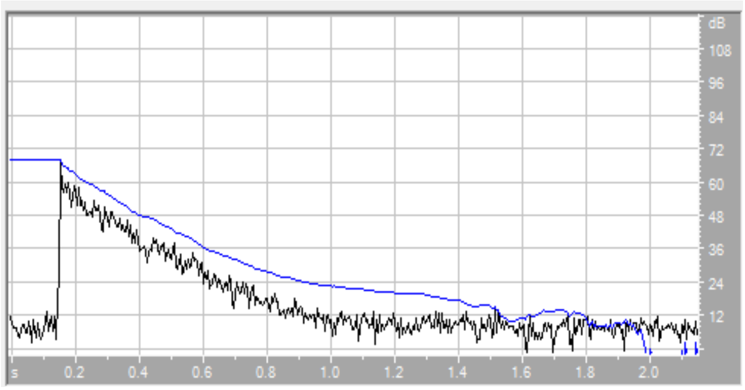


Figure 4.22 - Energy decay curve corresponding to S1-R2 at 1kHz.

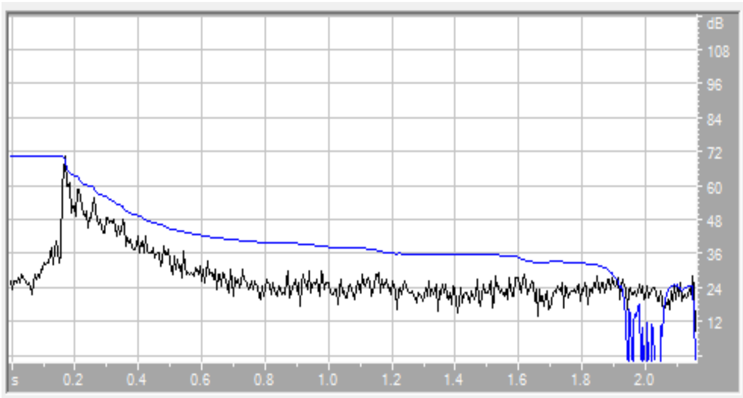


Figure 4.23 - Energy decay curve corresponding to S1-R3 at 1kHz.

The measurements in Stonegate were analysed through the parameters related to reverberation time, clarity and spatial impression introduced in chapter 3. Both T_{20} and T_{30} were calculated in order to analyse the way in which background noise affected the measurements, and to determine whether it is possible to calculate T_{30} in this particular site and with the limitations mentioned; the EDT was also calculated due to the fact that it is more closely related to the perception of reverberation. Clarity was measured through the C_{50} and C_{80} parameters. C_{50} was chosen due to the relevance of speech intelligibility in the plays, whereas C_{80} was chosen for the analysis of clarity in relation to the music elements included in the performances. The reverberation time and clarity parameters were calculated through the analysis of the impulse responses recorded with the W-channel of the Soundfield microphone. Spatial impression was determined through the calculation of $IACC_E$ and LF, which are parameters related to the perceptual broadening of the sound source. The former was measured using the KEMAR dummy head and torso, whereas the latter was calculated using the W- and Y-channels of the Soundfield microphone. Listener envelopment was studied through the calculation of $IACC_L$, which was also recorded through the KEMAR dummy head.

The analysis of the mean reverberation time (T_{20} and T_{30}) values across source-receiver combinations indicates that at 125Hz–4kHz the values range between 0.67-1.01s and 0.71-1.12s for T_{20} and T_{30} respectively (see Figures 4.24-4.25, Appendix Table 4.2). These values are mostly within the range found in theatres and considered suitable for speech intelligibility (0.7-1.2s) (Barron 1993), the only exception being the T_{20} at 4kHz, which is below 0.7s (see Figure 4.24 and Appendix Table 4.2). A drop in reverberation time can be observed at 8 and 16kHz, which is a consequence of air absorption at higher frequencies. Besides the inclusion of speech in the plays it should be noted that plainchant and polyphonic pieces were also performed. Plainchant items were performed at the time of the York Mystery Plays in cathedrals with long reverberation times, such as the York Minster, which has a T_{30} of 6.1s at 1kHz calculated by placing the sound source under the centre tower and the receiver in the nave area at a distance of 23.5m (Murphy 2006). Musical pieces in the same style would have also been performed in parish churches. Acoustical data from St. Patrick's, Patrington (East Yorkshire) in the fifteenth century indicates a T_{30} of 3.5s at 1kHz when sound emanates from the High Altar (Masinton 2006), which although significantly lower than the reverberation time recorded for the York Minster is still much higher than the values recorded in Stonegate. The short reverberation time of Stonegate in comparison to the York Minster and St. Patrick's, taken as an example of a late medieval English parish church, is significant when interpreting the perception of the musical items by the audience as well as when taking into account the singers' performance.

Plainchant items are slow, monophonic and sung at unison, and were composed to suit the long reverberation time of the religious spaces for which they were composed (Barron 1993). Furthermore, although they are monophonic pieces, when performed in reverberant spaces they benefit from the harmony produced when a note is sung which overlaps with the reverberant decay of the previous note (Forsyth 1985). This effect is lost when performed in a space such as Stonegate. Beranek (1996b) also comments that the musical pieces lose their impact when performed in spaces with low reverberation times. Some of the singers performing in the York Mystery Plays would have been trained singers and might have been part of the York Minster choir (Rastall 1984, 1996); they would have been used to performing the same items in a very different acoustical setting and might have had to modify their performance to suit the characteristics of Stonegate. Audiences accustomed to hearing plainchant items performed in the York Minster or in their parish churches would have surely remembered what they sounded like in these contexts and would have been aware of the differences of performing these chants in a very different acoustical setting.

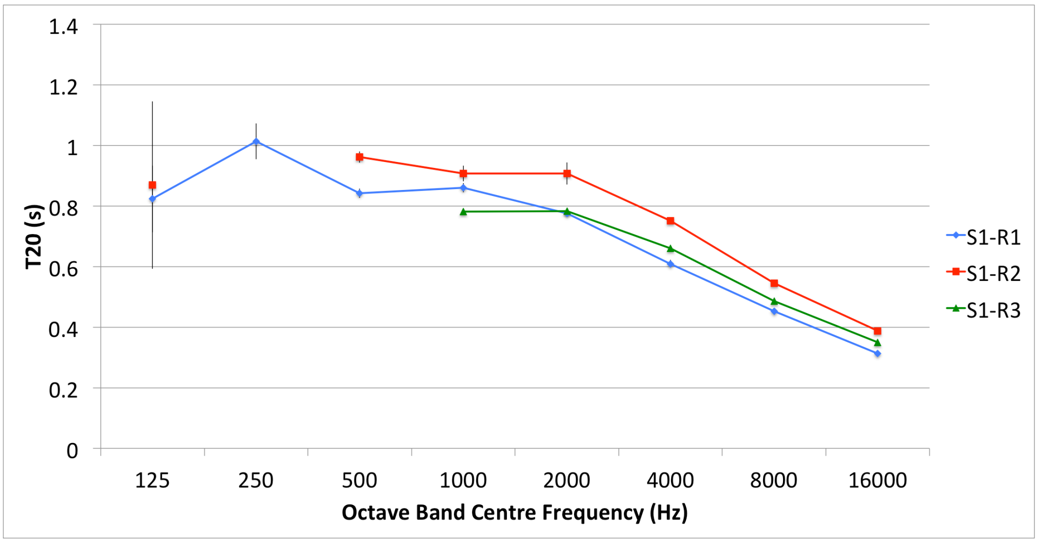


Figure 4.24 - Mean T20 across takes and standard deviation. Missing data indicates that values for T20 could not be calculated due to the background noise.

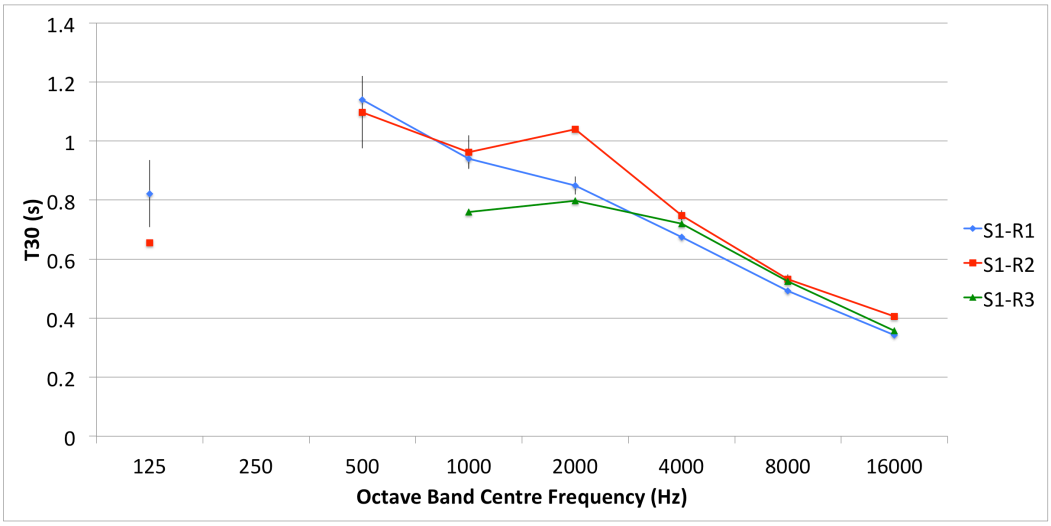


Figure 4.25 - Mean T30 across takes and standard deviation. Missing data indicates that values for T30 could not be calculated due to the background noise.

EDT values have been studied per source-receiver combination, without the calculation of mean values due to EDT results being more susceptible to changes depending on the listener position. Results range between 0.53-0.93s for receiver 1, 0.57-0.8s for receiver 2 and 0.49-0.78s for receiver 3, showing a lower range that is below the values recommended for theatres and in the case of receiver 3 with values below 0.5s, which have been proven to be uncomfortable to listeners (Barron 1993) (see Figure 4.26 and Appendix Table 4.3).

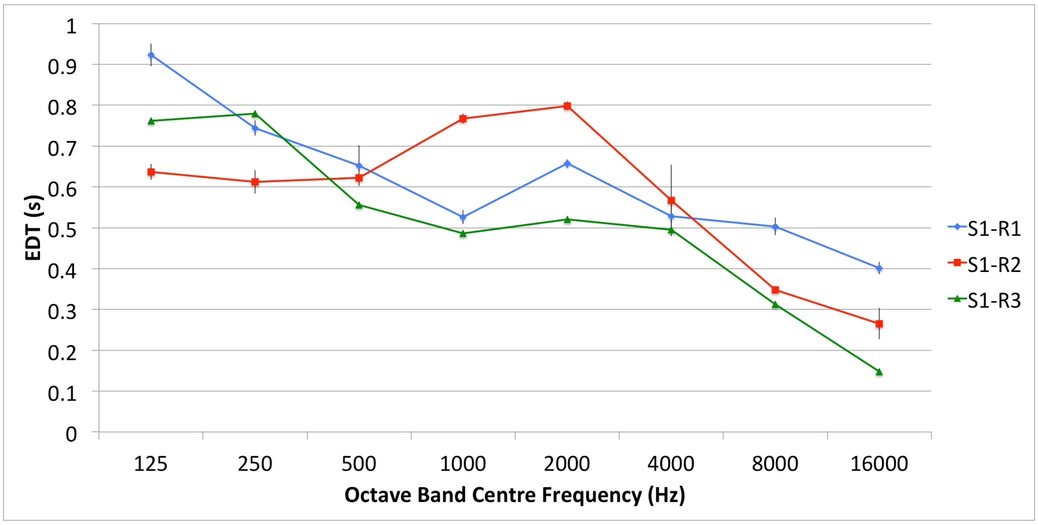


Figure 4.26 – Mean EDT across takes and standard deviation.

The mean C_{50} and C_{80} values across all source-receiver combinations show results extending from 3.03-11.35dB for C_{50} and 6.24-17.14dB for C_{80}, results that are a lot higher than the optimum clarity values for concert halls, which are -2dB to +2dB (Barron 1993) (see Figures 4.27-4.28 and Appendix Table 4.4). Such high clarity was expected due to the greater amount of early energy in comparison to late energy as a consequence of the space being semi-open, sound dispersing quickly and the reverberation times short. The highest clarity values correspond to the higher frequency bands (8-16kHz), which also presented the lowest reverberation time. Moreover, receiver 1 has higher values due to its proximity to the sound source, which results in the predominance of direct sound. Although high clarity is preferable for spaces with speech applications, when investigating the performance of plainchant items this poses a problem, as the items were composed for spaces with low clarity values. The York Minster has a C_{50} of -3.44dB and C_{80} of -2.77dB at 1kHz, measured at a distance of 23.69m with the source position under the tower and the receiver at the centre of the nave (Murphy and Shelley, n.d.). The parish church of St. Patrick's has a mean C_{80} of -8dB at 1kHz, when sounds are emitted at the High Altar but this mean value includes extremes such as -3.1dB under the roodloft and -13.5dB at the back of the nave (Masinton 2006). The high values of C_{80} recorded for Stonegate indicate that musical notes and rhythms will be defined. This may be of benefit for the performance of the "B versions" of the polyphonic pieces from *The Assumption of the Virgin*, which have complex rhythms that would be perceived as defined when performed in Stonegate. In the case of plainchant items this high definition of musical detail is a disadvantage as its simpler rhythms and its contemplative performance style requires low levels of clarity to retain their impact.

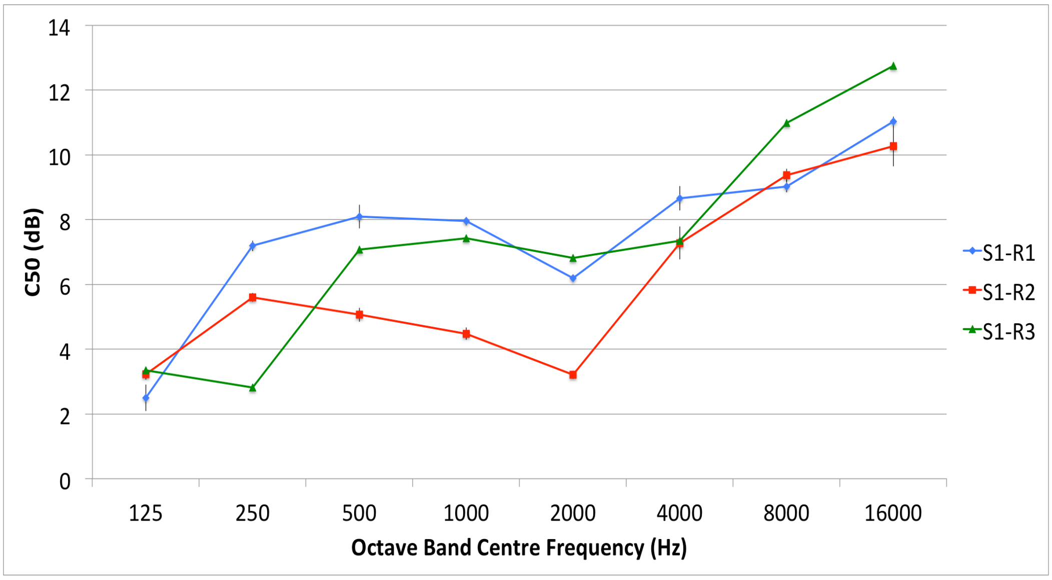


Figure 4.27 – Mean C_{50} across takes and standard deviation.

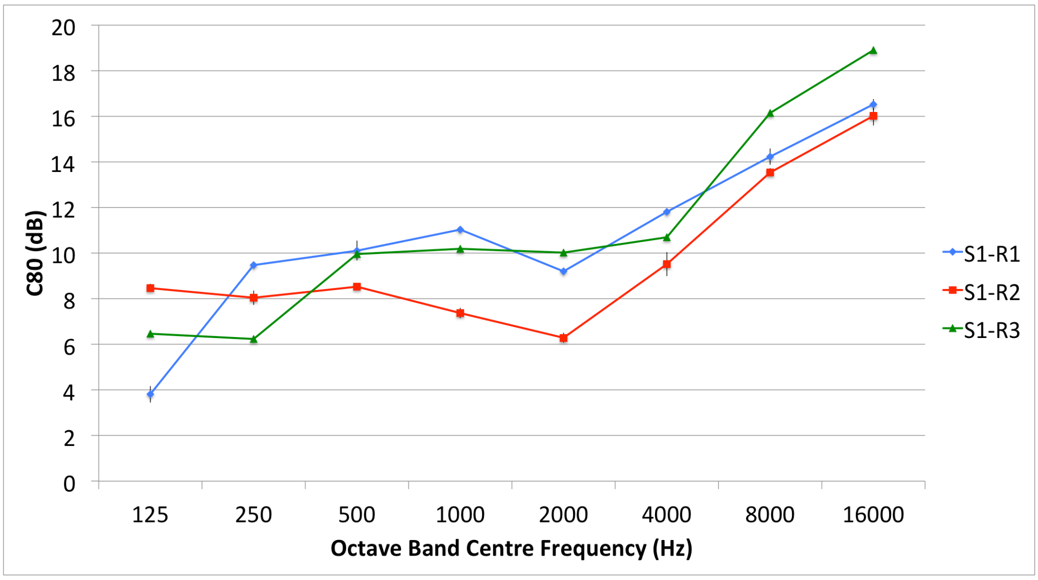


Figure 4.28 – Mean C80 across takes and standard deviation.

The study of spatial impression in Stonegate was divided into the study of the ASW and LEV. The former was analysed through the calculation of $IACC_{E3}$ and LF_{E4}, whereas the latter was investigated using the $IACC_{L4}$ parameter.

Values of $IACC_{E3}$ were recorded as 0.48 for receiver 1, 0.43 for receiver 2 and 0.59 for receiver 3 (see Figure 4.29 and Appendix Table 4.5-4.6). Such values match the ranges indicated for "good" concert halls in the case of receiver 3, "good to excellent" concert halls for receiver 1 and "excellent to superior" for the value recorded at receiver 2 (Okano, Beranek and Hidaka 1998). Furthermore, the $IACC_{E3}$ values are within the range of 0.15-0.78 recorded for churches with a gothic architecture (Cirillo and Martellotta 2006), the style used for the York Minster. The characteristics of Stonegate seem to indicate a suitable space for musical performances, which might even compensate for its very short reverberation time.

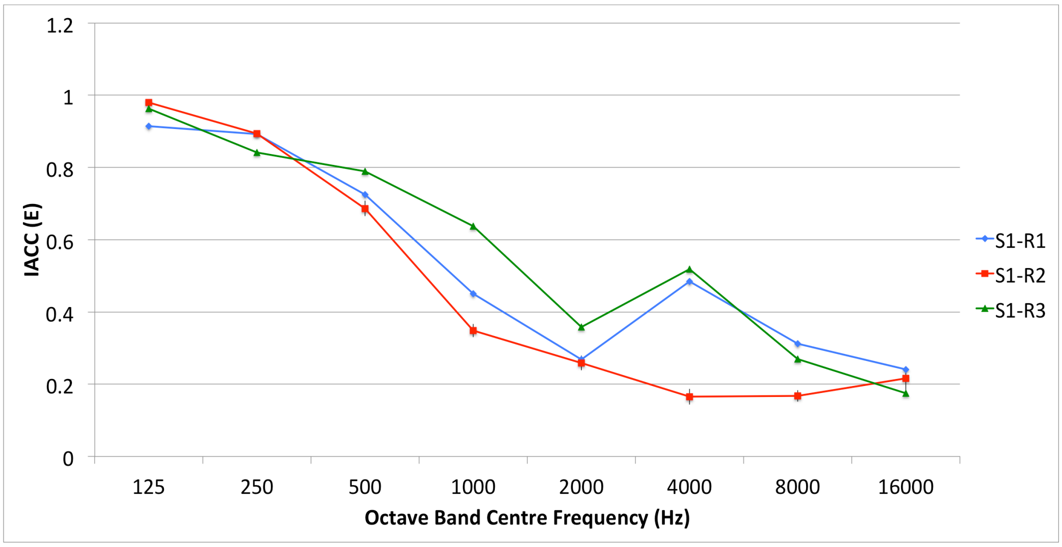


Figure 4.29 – Mean $IACC_E$ across takes and standard deviation.

The results for the LF_{E4} parameter indicate that receivers 2 and 3, which present values of 0.12 and 0.13 respectively, have values matching the characteristics of "good" concert halls, whereas receiver 1, with a value of 0.07 presents a result below the range, possibly due to its proximity to the sound source and the consequent predominance of direct sound (see Figure 4.30 and Appendix Tables 4.7-4.8). The values recorded in Stonegate for receivers 1-3 are within the lower range of the values recorded in gothic churches, which extend from 0.05-0.42 (Cirillo and Martellotta 2006).

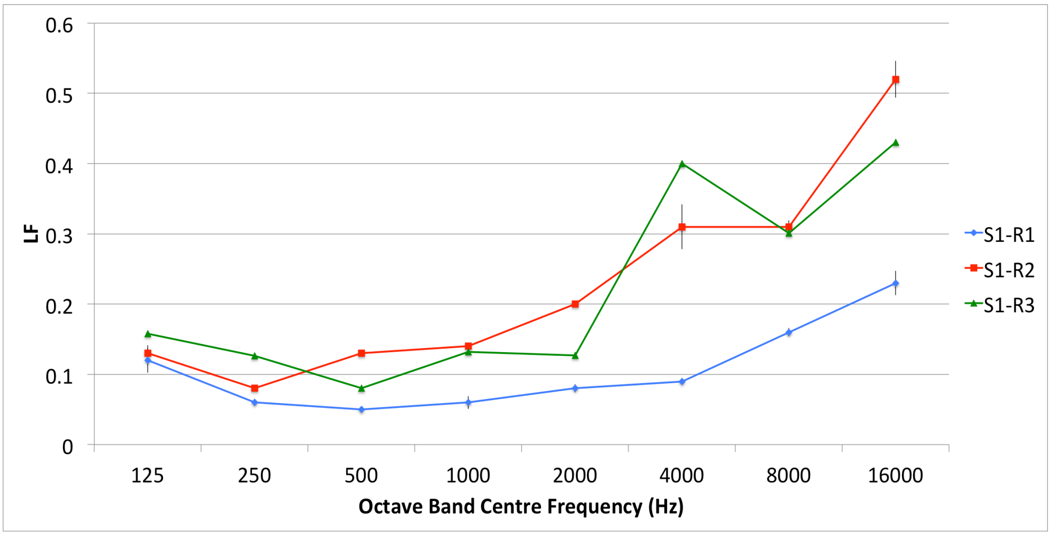


Figure 4.30 – Mean LF across takes and standard deviation.

The $IACC_{L3}$ values calculated show that for receivers 1 and 3 the values are of 0.15 and 0.18 respectively and correspond to values recorded for concert halls ranked from "fair" to "superior". Receiver 2 has an $IACC_{L3}$ of 0.27, a value associated with less diffuse spaces (Beranek 1996) (see Figure 4.31 and Appendix Tables 4.9-4.10). However, it is worth noting that, as discussed in chapter 3, this parameter has to be approached with caution as it does not seem to be able to differentiate among spaces with different rankings (Beranek 1996).

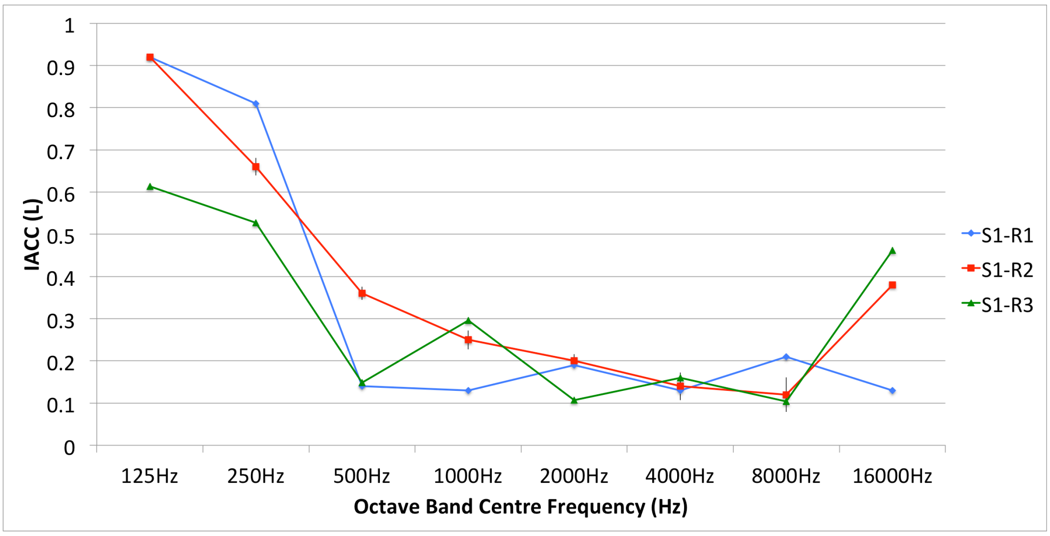


Figure 4.31 – Mean $IACC_L$ across takes and standard deviation.

The results presented in this section indicate that Stonegate exhibits a reverberation time and clarity beneficial for intelligibility and as a result appropriate for the spoken sections of the York Cycle. However, those same characteristics make it less appropriate for the inclusion of plainchant items, which were composed to be performed in spaces with high reverberation times and low levels of clarity, which suit the characteristics of the chants. The suitability of the acoustics for the performance of polyphonic items will depend on the characteristics of the piece but it is possible that the higher levels of clarity were more beneficial to the performance of the 'B versions' of *The Assumption of the Virgin*. The acoustic measurements revealed that Stonegate does possess an important characteristic for the perception of music, which is the perceptual broadening of the sound source. Furthermore, levels of envelopment have been found to be comparable to those recorded in concert halls. However, these results for the envelopment parameter seem unusual in a space with a low reverberation time and it is possible that they give further indication of the unreliability of the parameter.

4.4.5 A Virtual Model of Modern Stonegate

A. Objective Evaluation

The acoustic measurements conducted in Stonegate provided an insight into the characteristics of the space as it stands today, which is of great value due to the state of preservation of some of its medieval features. However, the aim of this project is to arrive at a deeper understanding of the acoustics of the space in the sixteenth century and its impact on the performance of the plays. An analysis of this kind requires the use of computer simulations. However, this virtualisation process first needs to be validated, that is, it is key to ensure that the virtual models replicate the acoustics of the space as closely as possible and awareness should be raised regarding any limitations of the simulation process. With this aim in mind, a virtual model of modern Stonegate was created using CATT-A and calibrated so as to be comparable to the acoustic characteristics measured on site. It is this virtual model that will be used in a subsequent stage for the simulations of Stonegate in the sixteenth century.

Geometrical data for the construction of the virtual model was gathered using modern photogrammetry techniques. Several photos of each building in the area of interest were taken and uploaded to the application Autodesk 123D Catch. This application allows the user to measure the dimensions of different surfaces as long as a reference distance is entered. For this purpose, reference distances were taken on site for each building using the laser distance meter Leica Disto D2. In order to corroborate that the application was providing accurate measurements further reference distances were taken on site and compared to the values outputted by the computer application.

The virtual model consists of 454 planes and includes both the left and right-hand sides of the pageant route as well as a portion of Little Stonegate (see Figures 4.32-4.33). On the left-hand side of the route the buildings included are Nos. 22-34 and on the right-hand side Nos. 13-25. Structures in Little Stonegate are limited to those that are part of the buildings at the corners of Stonegate and Little Stonegate. A preliminary virtual model that included a much larger portion of the street was employed to determine the section of the street that was of importance for the study of the acoustics at Christopher Willoughby's house. The analysis of this preliminary model through the Image-Source method allowed the study of the reflection paths and the determination of the surfaces that had an impact on the results. The buildings forming part of the virtual model here discussed include those that were shown to have an impact on the results alongside, as a precaution, additional buildings.

Absorption coefficients were sourced from the Surface Properties Library in CATT-A. The exception to this was the stone surface data used to simulate the pavement. Since stone is not a material commonly used in current construction its absorption coefficients were unavailable. As a consequence, the data was sourced from research on virtual simulations of Greek and Roman theatres in which stone was a key surface material (Chourmouziadou and Kang 2008). The selection of absorption coefficients was carried out through a process of calibration. Such calibration process entailed the comparison between the results of the virtual model and the on-site measurements for each acoustical parameter considered individually. Such comparison was carried out every time a change was applied to the absorption coefficients of the virtual model. Moreover, results were considered per source-receiver combination and frequency band, that is, no averaging was applied to the numerical values. The aim of the calibration process was to arrive at objective values for the virtual model comparable to those recorded on site.

Figure 4.32 - Screenshot of virtual model showing the frontage of the left-hand side of the pageant route and Little Stonegate.

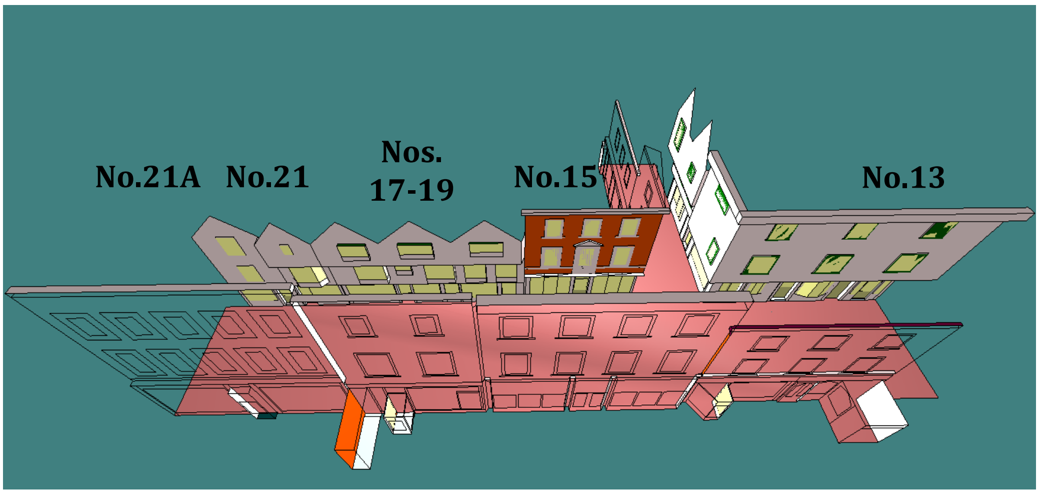


Figure 4.33 - Screenshot of virtual model showing the frontage of the right-hand side of the pageant route and Little Stonegate.

The determination of scattering coefficients can rarely be done through the use of surface property libraries, since the values for most surface materials are not included. In the case of the library included in CATT-A the scattering coefficients are only included for the audience, occupied and unoccupied seats and diffusors. Although the scattering coefficients of different surface materials can be measured, when required for several materials within a computer model the process itself can be impractical, as it involves the use of a reverberation chamber as well as samples of the materials in question (ISO 17497-1, 2004). A preferred approach has often been to resource to practical experience and experts' suggestions (Zeng *et al.* 2006). Scattering coefficients for the model of Stonegate were determined following recommendations found in the literature as well as applying the process of calibration described for the absorption coefficients. CATT-A guidelines support this approach by suggesting the use of both low and high values alternatively to check for the sensitivity of the results to the changes (CATT-A 2007).

The default surface scattering coefficient in CATT-A is 10% and the software developer recommends this value for larger flat smooth surfaces (CATT-A 2007). This recommendation was followed and rougher surfaces were given higher scattering coefficients, with the highest value being applied to the road to simulate an uneven surface. A full list of absorption and scattering coefficients can be found in the Appendix Table 4.11.

Edge scattering was also applied to some of the planes within the virtual model. The application of edge scattering in acoustic modelling has been considered essential to the recreation of sound fields (Torres *et al.* 2001). Guidelines for its application suggest its use to simulate the propagation of sound around corners (Torres *et al.* 2001), as well as its application to reflectors, windows and furniture (if modelling interior spaces) (CATT-A 2007). Edge scattering in CATT-A is done automatically and is dependent on the size of the surface and varies across frequency bands (CATT-A 2007; Zeng *et al.* 2006). In the virtual model of Stonegate edge scattering was applied to simulate the irregularities of the street façade (columns, passages) and pavement level (irregularities, steps). It was also applied to overhanging windows (bay and bow windows), jetties and overhanging cornices. It was also used at the corners of Stonegate and Little Stonegate. The process of calibration demonstrated that closer values to the real-world measurements were obtained when edge scattering was implemented.

The source and receivers added to the virtual model replicated the positions and head direction of those used for the on-site measurements. In the case of the sound source, the directivity of the Genelec 8040A was simulated.

The completion of aspects in relation to geometry, surface materials, source and receivers was followed by the computation of the acoustic predictions. These predictions were conducted using algorithm number three in TUCT and with the number of rays/cones set to Auto, as recommended by the software developer (TUCT 2010), which resulted in 83,145 rays. The accuracy of the virtual model was then tested by comparing the results of the different objective parameters derived from the acoustic measurements on site to the results of those same parameters derived from the virtual model; all impulse responses, both measured on-site and simulated, were analysed with the Aurora plug-ins.

Differences in the accuracy of acoustic simulations can be dependent on the modelling software utilised with differences between the results on site and those from a virtual model varying across different applications (Bork 2005; Vorländer 1995). Previous studies have deemed acceptable for differences between values derived from real and simulated impulse responses to be of up to 3JNDs for T_{30}, 4JNDs for EDT, 1.5JNDs for Clarity, 2.5JNDs for LF and 0.5JNDs for IACC (Bork 2005). Although these different levels of variation might occur, in the present project acceptable results were proposed to be within 2JNDs (Galindo *et al.* 2009, Vorländer 1995, Vorländer 2008) and in any cases in which the differences are larger than this value it is necessary to exercise caution when arriving at conclusions (Vorländer 1995).

A JND value of 5% for T_{20}, T_{30} and EDT (ISO 3382, 2009) was used for values larger than 0.6s and a fixed value of 0.03s was assumed for reverberation times shorter than 0.6s (Niaounakis and Davies 2002). JND values for C_{50} and C_{80} were 1.1dB and 1dB respectively (Bradley, Reich and Norcross 1999; ISO 3382: 2009). The JND for both IACC parameters Early and Late was taken to be 0.075 (ISO 3382-1 2009), whereas for LF it was considered as 0.05 (Cox 1993).

The comparison between the results of the reverberation time parameters from the on-site measurements and the computer simulation indicates that when analysing the results across source and receiver combinations and frequency bands the T_{30} parameter presents the highest levels of accuracy (see Appendix Table 4.12), with 74% of the results within 2JNDs. The T_{20} parameter presents 65% of acceptable results whereas the EDT presents lower values of accuracy with only 50% of the results within the 2JND limit (see Appendix Table 4.12). Additionally, examination of the source-receiver combinations independently reveals that the results for T_{20} and T_{30} are most accurate for S1-R3. In contrast, it is the EDT values resulting from S1-R1 and S1-R2 combinations with shorter distances between source and receiver, which present the most accurate results (see Appendix Table 4.12 and Figures 4.36). These results seem to correspond to the explanation given by Vorländer (1995) who indicated that the differences in the results of EDT between measurements and simulations tended to increase with source-receiver distance.

Furthermore, T_{20} and T_{30} are found to deviate the most from the on-site measurement results at frequencies from 125-500Hz (see Appendix Table 4.12 and Figures 4.34-4.35). Moreover, the results of the acoustic measurements present higher values than the results of the virtual model, this being in accordance to the tendencies in virtual models reported by San Martin and Arana (2006).

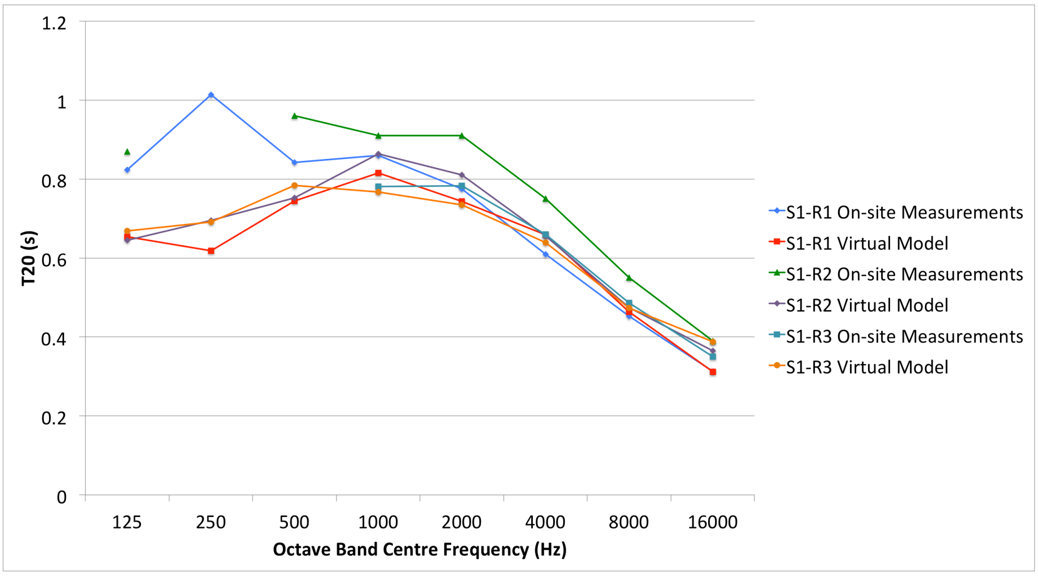


Figure 4.34 - Comparison of T_{20} results between the on-site acoustic measurements and the virtual model.

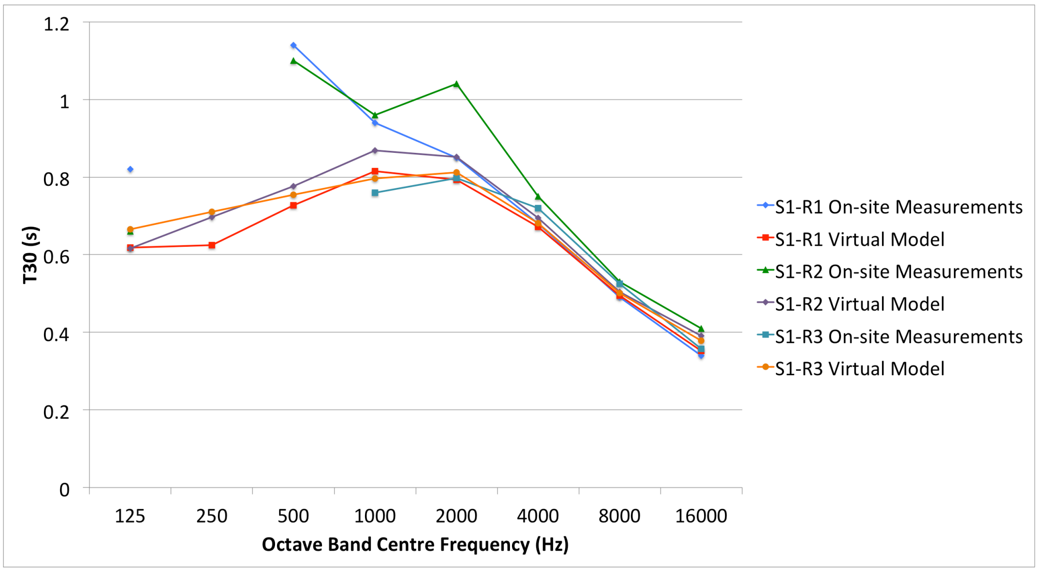


Figure 4.35 - Comparison of T_{30} results between the on-site acoustic measurements and the virtual model.

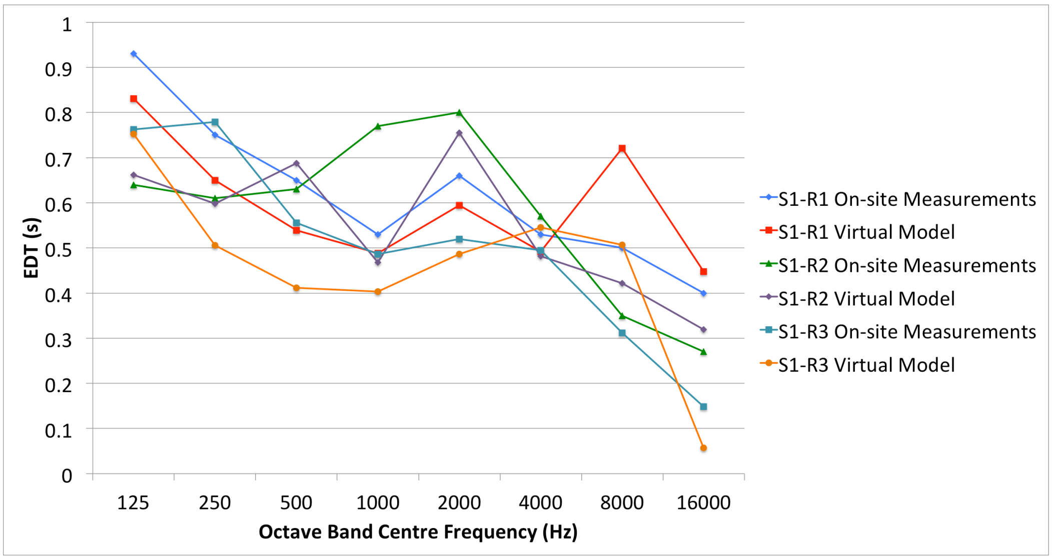


Figure 4.36 - Comparison of EDT results between the on-site acoustic measurements and the virtual model.

The results for the clarity parameters demonstrate high levels of accuracy with 75% of results within 2JNDs for C_{80} and 66.5% for C_{50} (see Appendix Table 4.13). Furthermore, both parameters present values closer to the acoustic measurements in the S1-R2 combination (see Appendix Table 4.13 and Figures 4.37-4.38).

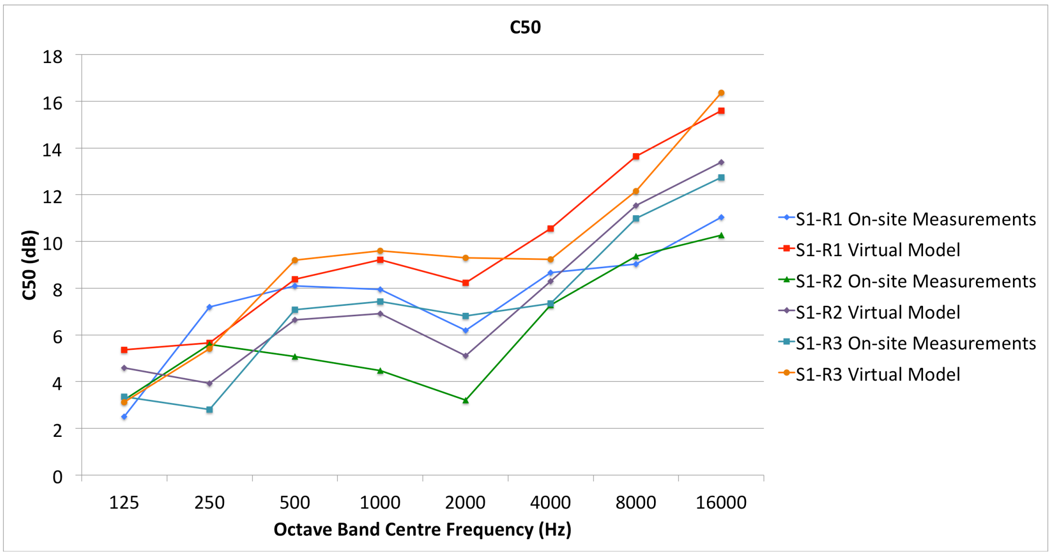


Figure 4.37 - Comparison of C_{50} results between the on-site acoustic measurements and the virtual model.

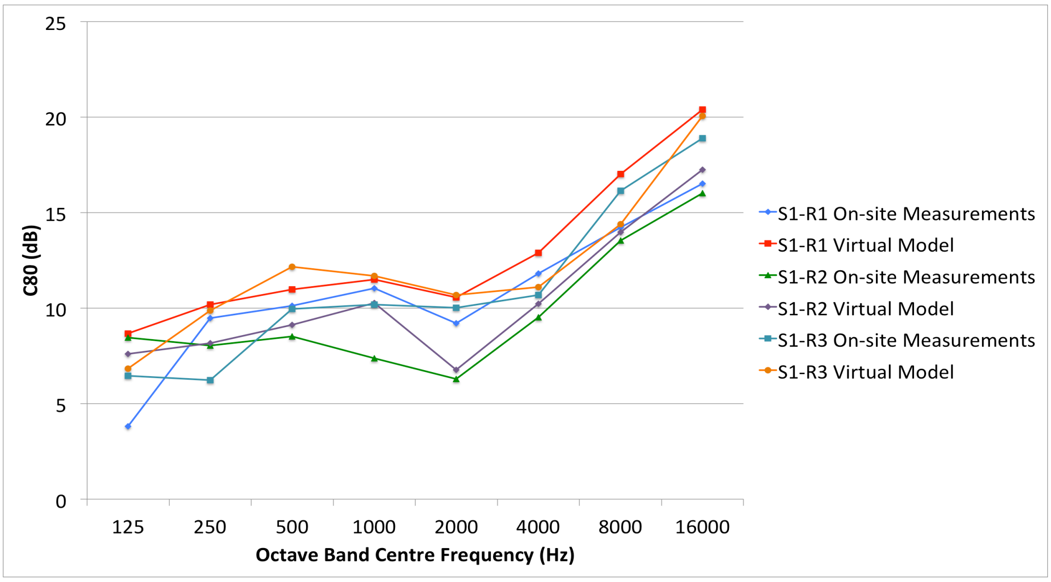


Figure 4.38 - Comparison of C80 results between the on-site acoustic measurements and the virtual model.

The results of $IACC_E$ and LF indicate high levels of accuracy, the former presenting 79% of the results within 2JNDs and the latter 66% (see Appendix Table 4.14). Additionally, $IACC_E$ presents its lowest deviations from the acoustic measurements in the S1-R2 combination whereas LF presents its best results for S1-R1 (see Appendix Table 4.14 and Figures 4.39-4.40).

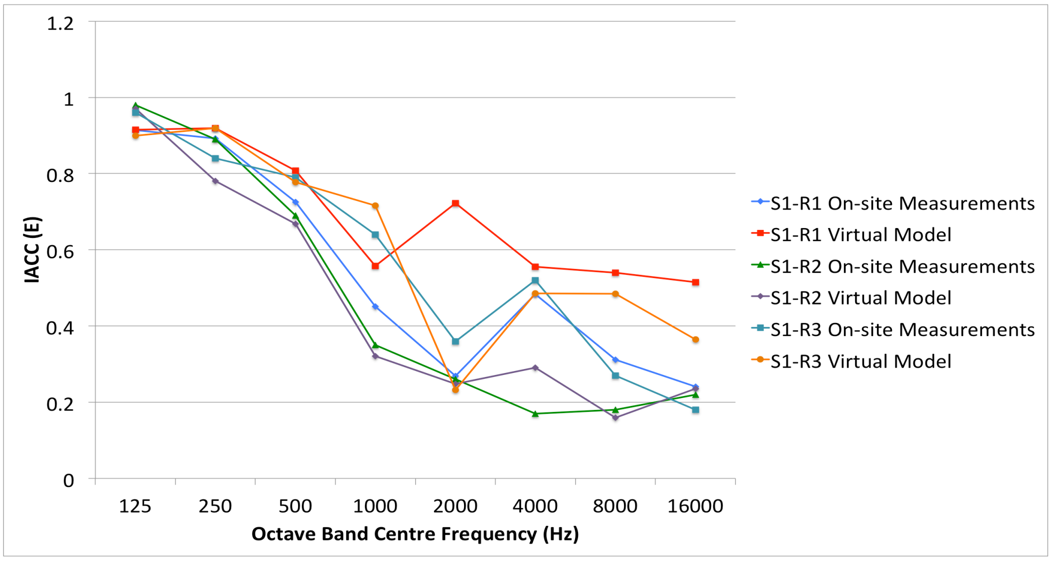


Figure 4.39 - Comparison of $IACC_E$ results between the on-site acoustic measurements and the virtual model.

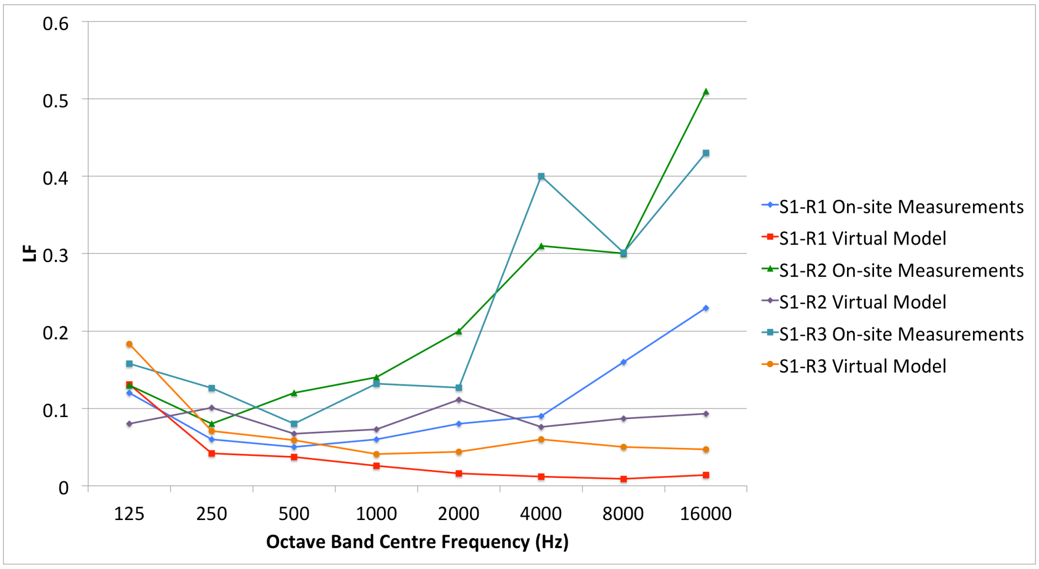


Figure 4.40 - Comparison of LF results between the on-site acoustic measurements and the virtual model.

The analysis of the results of $IACC_L$ for the virtual model compared to the acoustic measurements demonstrates high levels of deviation from the measurements with only 17.5% of the results within 2JNDs (see Appendix Table 4.14 and Figure 4.41). These results seem to indicate that the virtual model cannot be fully relied on when considering late lateral reflections and should be removed from any subsequent analysis. However, such significant differences between the values from the acoustic measurements and those from the virtual model might also be an indication of an issue related to the measurement of late reflections on site. As was indicated above, the high levels of envelopment recorded for the on-site measurements seem surprising since spaces with high levels of envelopment tend to also have long reverberation times. Therefore, it is possible that the presence of noise during the measurements influenced negatively the calculations of $IACC_L$ and this is the reason for such a notable dissimilarity between the real-world measurements and the simulations.

The study of the differences between the acoustic measurements and the computer simulation across several objective parameters demonstrated the overall accuracy of the model (see Appendix Table 4.15). Nevertheless, it should be noted that different parameters presented different levels of accuracy, with results ranging from 17.5% for $IACC_L$ to 79% for $IACC_E$.

Furthermore, when comparing the results across frequency bands and acoustical parameters, it is the simulation of S1-R2 that presents the lowest discrepancies in relation to the acoustic measurements.

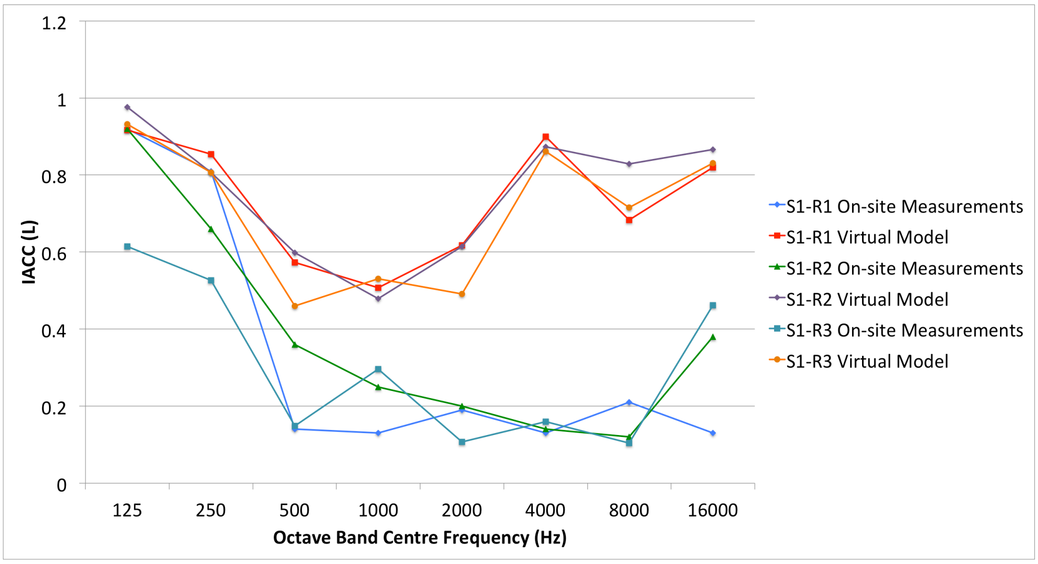


Figure 4.41 - Comparison of $IACC_L$ results between the on-site acoustic measurements and the virtual model.

The following section introduces a listening test that was conducted with the objective of studying how the overall differences between the acoustic measurements and the virtual simulation are perceived through the auralization of extracts from the York Mystery Plays.

B. Subjective Evaluation

The comparison between the virtual model and the acoustic measurements based on the results obtained through applying different acoustical parameters and analysing them using JNDs, allowed the assessment of the level of accuracy of the virtual model and as a result, its reliability. However, it is also necessary to analyse how the differences between real-world measurements and the virtual model translate to the field of subjective perception. Although the differences in the results for the objective parameters have been calculated on the basis of JNDs, which refer to the minimum perceptible differences, the calculation of such minimum differences as well as the establishment of correlations between objective parameters and subjective perception are the result of laboratory experiments, which in most cases, use expert listeners as test subjects. The relationship between objective parameters and listeners' perception is seldom straightforward and the findings based on an expert audience might not always extend to the entire population. Equations used for the calculation of parameters attempt to reproduce auditory perception by assuming that it is identical in all individuals across cultures (Blesser and Salter 2007). However, assessments on the quality of auditorium acoustics have been shown to vary between musicians and non-musicians. Indeed, even the possession of a recorded version of a musical piece influences the perception of the acoustics of the auditorium when that same piece is performed (Cox and Shield 1999). Furthermore, where acoustical parameters such as $IACC_E$ and LF have been considered, previous studies have shown that values can vary significantly even within the same seating position, which would represent an audience member leaning forwards, backwards or side to side, but this is unlikely to produce a significant change in auditory perception (de Vries, Hulsebos, Baan 2001).

The aforementioned differences between the objective and subjective evaluation of room acoustics resulted in the need to determine the perceived level of discrepancy between the results from the virtual model and those from the on-site acoustic measurements by means of a set of auralized extracts from the York Mystery Plays. With this purpose in mind a listening test was designed to study the differences between the virtual model and the on-site measurements, determine the effects of the source-receiver combinations in the perception of differences as well as analyse the impact of various audio samples in the evaluation of dissimilarities between the real and the simulated space.

The method used for the listening test was the double blind triple-stimulus with hidden reference presented in the ITU-R BS.1116-1 standard (1994-1997). This method has been suggested as appropriate for testing whether the auralizations derived from virtual models and the ones derived from impulse responses measured on site are indistinguishable (Lokki and

Savioja 2005). This method requires three simultaneous signals: A, B and C. A is always the reference signal, in this particular test it is an anechoic excerpt convolved with a binaural impulse response measured on site. B and C are randomly assigned to be either a hidden reference (that is, an audio file identical to A) or an audio sample that presents a difference in comparison to A. In the listening test in question, the sample different from A (this could be either B or C) was the same anechoic recording used for A but convolved using a binaural impulse response derived from the virtual model of Stonegate.

Participants were asked to listen to the samples and compare B to A followed by C to A. The goal was to identify which audio file, B or C, was the hidden reference and which one was different. Subjects were given a scale derived from ITU-R BS.1284 (1997-2003) and used the grade 5.0 to refer to the signal that they thought was the hidden reference. An additional grade from 1.0 to 5.0, using 0.1 steps, had to be assigned to the signal that was identified as being different to the reference, and the grade would be an indication of the level of dissimilarity they perceived between the samples (see Table 4.6). Subjects were instructed to only grade one of the samples in each trial with a 5.0 and if they could not perceive a difference between samples they could award a 4.9 grade to the remaining sample, thus indicating that the difference was imperceptible. The use of a 4.9 grade for such cases forces listeners to make a decision as to which sample is the hidden reference and prevents subjects that are able to perceive very small differences from being overly cautious in their approach to the completion of the test (ITU-R BS.1284 1997-2003).

The experiment was designed using the application QLab (see Figure 4.42). The presentation of the stimuli was randomised for each participant to ensure that the responses were not dependent on the order of presentation. Participants were permitted to listen to the audio samples of a trial as many times as needed before proceeding to the next one and a near instantaneous switch was programmed to allow the smooth transition from one sample to the other (ITU-R-BS.1116-1 1994-1997). The scores for each trial were entered on an online form (see Figure 4.43).

Grade
5.0 – Imperceptible difference
4.0
3.0
2.0
1.0 – Very clear difference

Table 4.6 - Grading Scale for the listening test.

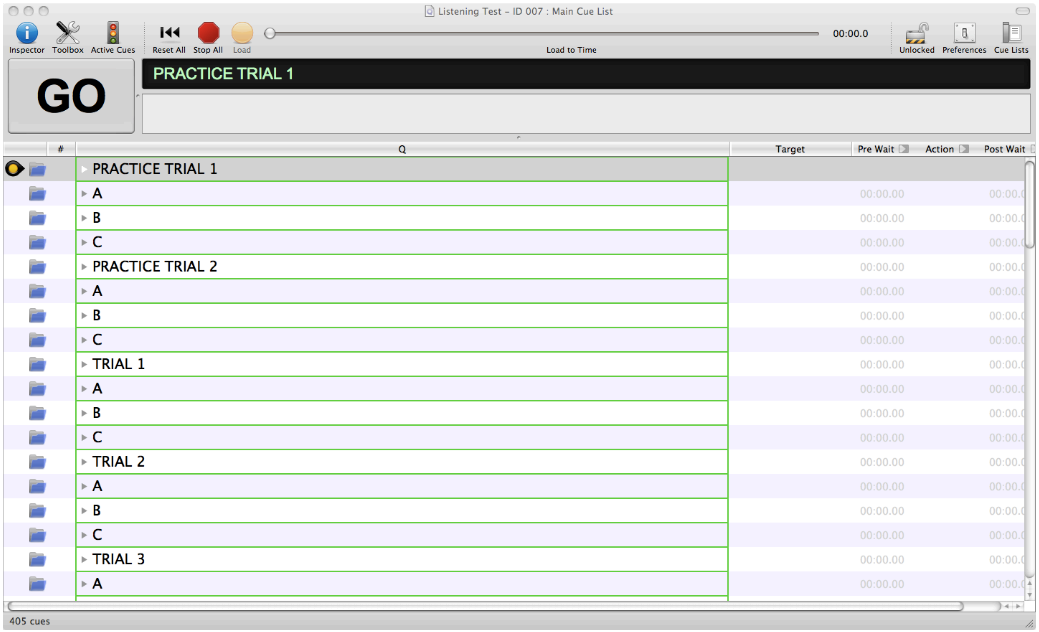


Figure 4.42 - QLab Interface used for the listening test.

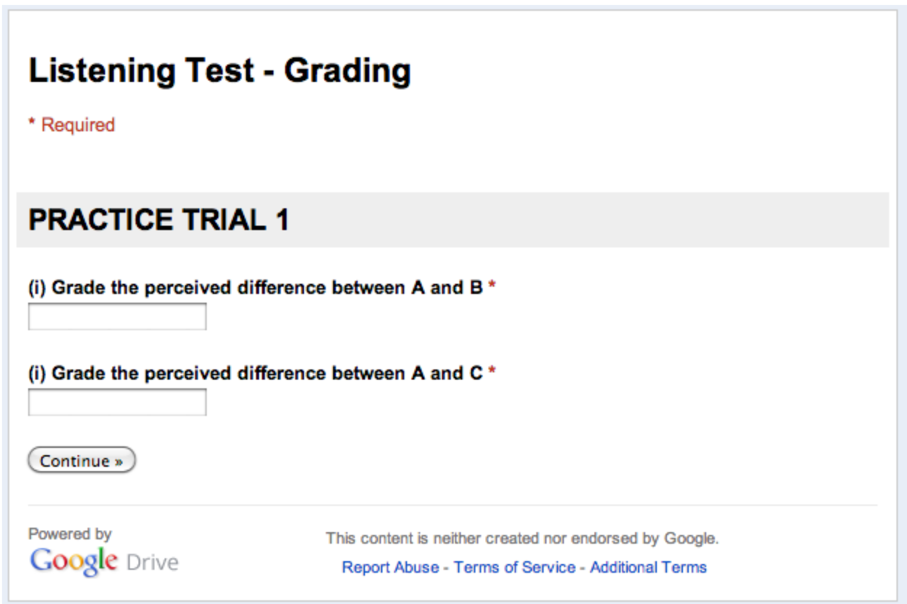


Figure 4.43 - Online form used to enter scores for the listening test.

Time was allowed before beginning the listening test for the subjects to familiarise themselves with the test methodology and the interface (Bech and Zacharov 2007). To help facilitate this, participants were presented with a written introduction to the context of the listening test as well as written instructions on the test itself and the use of the interface. This was followed by verbal instructions and two practice trials.

The objectives of the listening test were to study the level of difference between the auralizations derived from the real and the simulated space as well as to determine the reliability of the auralizations derived from the simulation for their use with the general public. For these reasons, the listening panel was conformed of non-specialist subjects.

The number of subjects recommended by the ITU-R-BS.1116-1 standard (1994-1997) is twenty, but it suggests increasing the number to provide more conclusive results that apply to a larger group and allow for any possible variations in the sensitivity of participants to the differences presented in the test. Following these guidelines twenty-seven subjects were drawn from the student and staff community of the University of York, who were offered no remuneration for their participation. Although a pre-screening process was not carried out, participants were asked to complete an online hearing test designed by the British Society of Hearing Aid Audiologists, which consisted of four tones at 500Hz, 1kHz, 2kHz and 4kHz respectively (BSHAA, n.d.). They were also asked whether they had any hearing problems. All participants passed the hearing test, including two subjects who reported a hearing difficulty. As a consequence no data was discarded on these grounds. Although twenty-seven participants completed the test, the data entered by one of the subjects had to be excluded from the analysis as in seven out of eighteen trials the participant graded both B and C as being different from reference (A).

Participants were aged between 19 and 48 and with varying levels of experience with audio (see Figure 4.44). Furthermore, eleven out of twenty-six reported having experience completing listening tests.

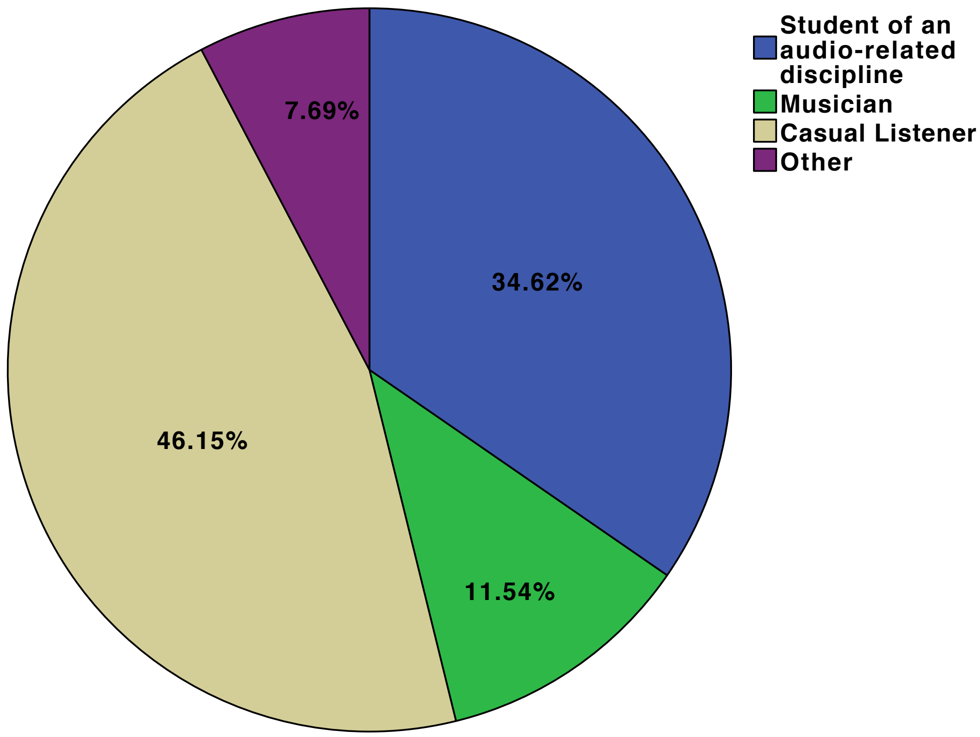


Figure 4.44 – Level of Audio Experience of subjects that participated in the listening test.

The programme material consisted of six anechoic extracts approximately 11 to 27 seconds long, thus following the suggestions included in the ITU-R-BS.1116-1 standard (1994-1997). The selection of the programme material was aimed at determining whether the perceived difference between auralizations with measured IRs and those with IRs from the virtual model presented variations when applied to speech and vocal music.

Two speech extracts in Middle English were used, one from the *Pentecost* play and another one from *The Resurrection* play. The programme material also included three extracts of monophonic vocal music: the Alleluia and Communion *Christus Resurgens* and the *Veni Creator* hymn all according to the Use of Salisbury (Sandon 1990). The monophonic pieces were selected with the objective of studying the effects of the simulations on three different types of plainchant: syllabic, neumatic and melismatic. These types of chant vary in their relationship between music and text. Syllabic chants are characterised by having each syllable of the text set to one note, whereas neumatic chants can have two to ten notes per syllable. Melismatic chants are similar to neumatic ones but with passages with more than ten notes per syllable (Emerson *et al*. 2007). The *Veni Creator* hymn was selected as a syllabic chant and seems to have been performed in the *Pentecost* play and in *The Baptism* (Rastall 2001). The Communion *Christus Resurgens* was selected as a neumatic chant while the Alleluia was chosen as a melismatic example; either of these items could have been performed as part of *The Resurrection* (Rastall 2001). Male actors and singers performed all speech and monophonic vocal music recorded for the listening test in keeping with the traditional Middle Ages practice of using all male casts.

The programme material also included the B version of the two-part polyphonic piece *Veni de Libano, sponsa* from *The Assumption of the Virgin* (see chapter 2). For this project *Veni de Libano, sponsa* was performed by four female singers. Female singers were chosen because the pieces are in the mezzo-soprano range. As the piece contains a four-part chord, four women were required for the performance (Rastall 1984). Moreover, pictorial evidence has suggested that the use of four singers for two-part polyphony might have been a practice of the period (Rastall 1994) (see chapter 2). The choice of the B version as opposed to the A version was due to its greater complexity (see chapter 2) which has been suggested to be inadequate for outdoor performances (Rastall 1996). Its inclusion in the test can help us shed light on the effect on the piece of the acoustics of an outdoor space.

The recordings were conducted in the anechoic chamber of the Electronics Department of the University of York. A Neumann U87 condenser microphone was placed on axis, 30cm away from the performer's mouth and set to a cardioid polar pattern (see Figures 4.45-4.46). The polar pattern was selected due to the need to have minimal spill among microphones when recording the polyphonic piece.

The auralizations used for the listening test were prepared by convolving the anechoic recordings with the binaural impulse responses measured on site using the Kemar dummy head and those derived from the virtual model for each source-receiver combination. As a result, whereas the auralizations based on real-world measurements were affected by Kemar's HRTFs, those derived from the simulation were processed using a binaural setting from the CATT-A library (CATT1_plain_48). The change in HRTFs between the auralizations as well as the fact that those HRTFs would not necessarily match the ones belonging to the listeners means that a further difference is introduced between the samples based on the acoustic measurements and those based on the virtual model. Although such differences could have been avoided by using the monaural impulse responses, in this project it was deemed of importance to study the influence of the IACC on the results, which made the use of binaural impulse responses necessary. It is also worth noting that only the subjective analysis is based on the binaural impulse responses and all objective analyses presented in this thesis are based on the monaural IRs, with the exception of the IRs used to measure $IACC_E$ and $IACC_L$.

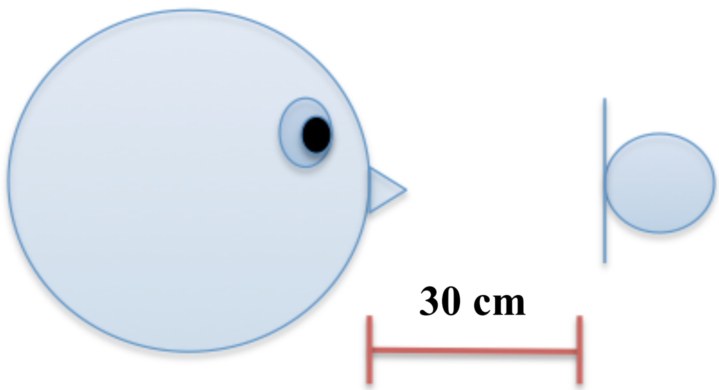


Figure 4.45 – Diagram of microphone setup in the anechoic chamber.

Figure 4.46 - Pierre-Philippe Dechant, Anechoic chamber, University of York, September 2011.

The listening test was carried out using a MacBook Pro and an additional computer screen (see Figure 4.47). On the laptop screen participants had access to the online form in which they entered the grades for each trial while on the additional screen they could interact with the QLab interface. Sound was reproduced using a Fireface 400 soundcard and beyerdynamic DT150 headphones.

The listening test was conducted through headphones in order to minimise the effect of the acoustics of the listening space on the results (Bech and Zacharov 2006). Coloration of sound, in-head localisation and front-back confusion are problems that have been associated with the use of headphones for listening experiments on auralization techniques (Lokki and Savioja 2005, Lokki 2005, Martellotta 2008). However, these have been considered problems when the listening tests had the aim of assessing the quality of auditoria, study particular attributes or analyse preferred listening conditions. Since these aspects are not studied in this project reproduction through headphones was deemed the best option.

The system was calibrated by using pink noise at -18dBFS. The pink noise was played through a loudspeaker and measured 76.94dB at 1m from the source. This value was chosen because it is the average SPL measured in Stonegate, where levels at 1m were recorded individually for an actor reading an extract from the York Mystery Plays and a singer singing an A440. The level of reproduction over headphones was set to be equivalent to the output of the loudspeaker by alternating listening to pink noise through the loudspeaker and headphones and modifying the headphones output to achieve as close a match as possible. The reproduction level remained constant throughout the test and for all participants. Room background noise measured at the listener position was 27dB(A) and a consequence of the ventilation system and the computer fan.

Prior to the statistical analysis, the results of each subject were normalised with the objective of reducing the differences related to the use of the grading scale among subjects. Normalisation was conducted by using the equation suggested in ITU-R-BS.1116-1 (1994-1997):

$$Z_i = \frac{(x_i - x_{si})}{s_{si}} . s_s + x_s \tag{4.1}$$

where Z_i is the normalised result, x_i the score of subject i, x_{si} the mean score for subject i in session s, x_s the mean score of all subjects in session s, s_s the standard deviation for all subjects in session s and s_{si} the standard deviation for the subject in session s.

Figure 4.47 - Listening Test Setup, March 2013.

The Kolmogorov-Smirnov test and Q-Q plots were used to determine if the data was normally distributed. The Kolmogorov-Smirnov test compares the data being analysed with a second data set that is normally distributed and has the same mean and standard deviation (Field 2005). It calculates the probability of the results having been obtained by chance (p) and if $p<.05$ then we can refer to a statistically significant result (Field 2005). Significant values indicate that the data is not normal whereas non-significant results $p>.05$ indicate that the data is normally distributed (Field 2005). Q-Q plots indicate with a straight line the values corresponding to normally distributed data and with dots the distribution of the scores being analysed. If the dots present deviations from the straight line the data can be interpreted as departing from normal distribution.

When studying the scores corresponding to the auralizations derived from the acoustic measurements the scores for most of the samples were constant, that is, all participants recognised the hidden reference and gave a particular sample the score of 5.0. In these cases the results were omitted from the Kilmogorov-Smirnov test. Those cases in which some participants graded the hidden reference as different from A, resulted in the test having significant results, indicating that the data is not normally distributed (see Appendix Table 4.16).

The results based on the auralizations derived from the virtual model presented a mix of significant and non-significant results (see Appendix Table 4.16). However, when the results indicated as normal with the Kolmogorov-Smirnov test where studied using Q-Q plots the outcome indicated a clear departure from normality (see Figures 4.48-4.49). Consequently, the results were considered as non-normally distributed and non-parametric tests were used.

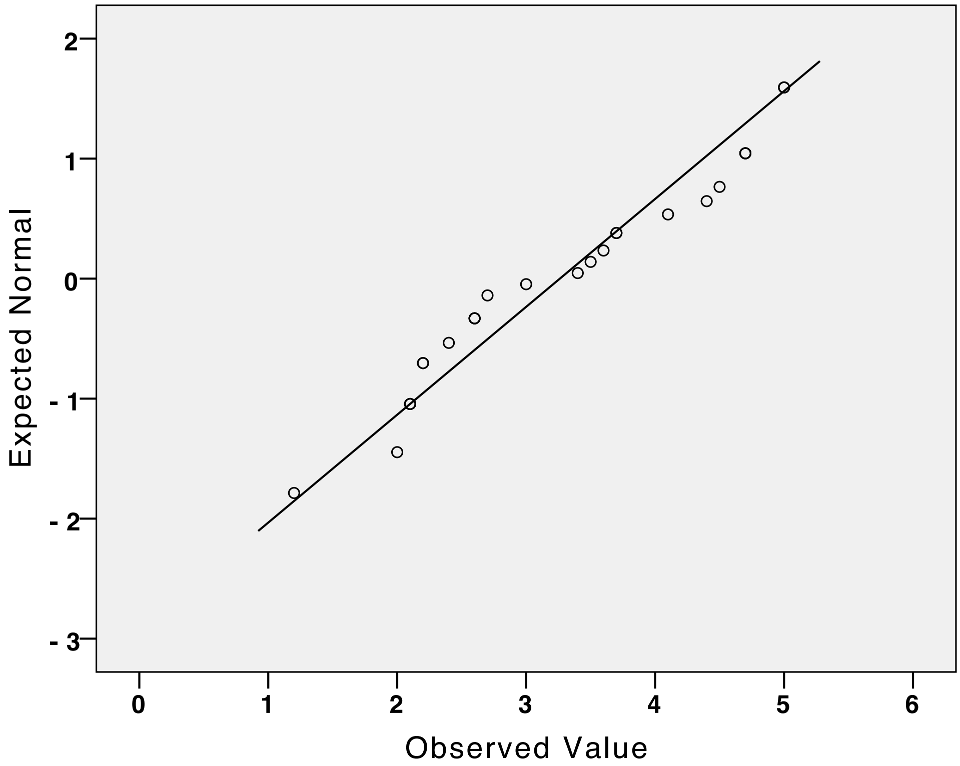


Figure 4.48 - Normal Q-Q plot for Pentecost play Receiver 2 Virtual Model

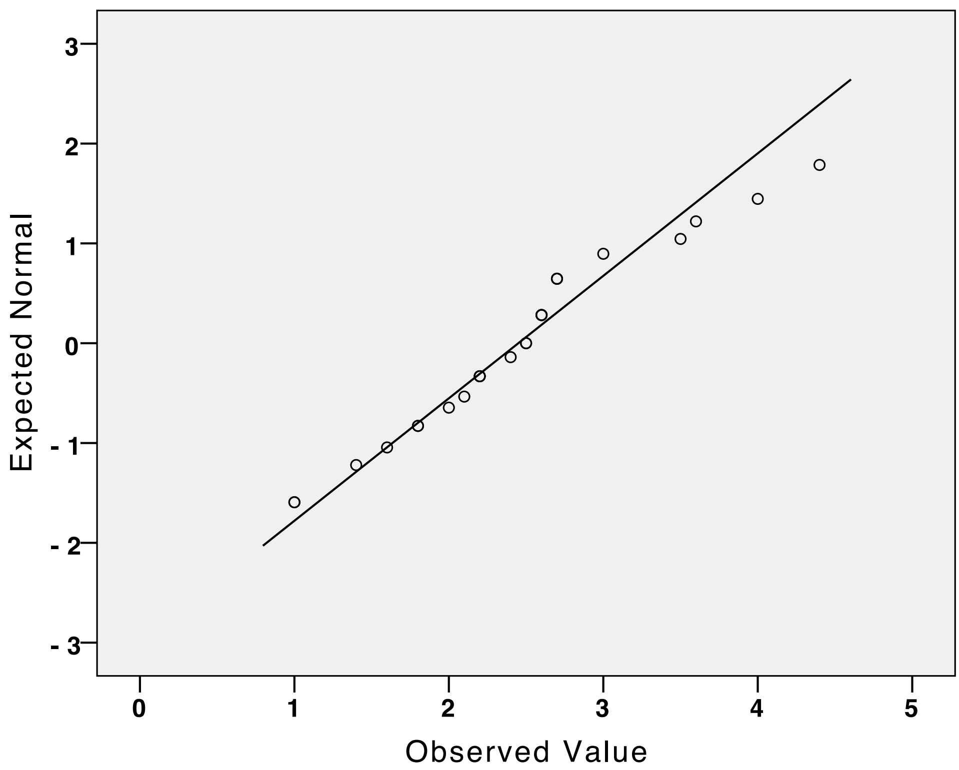


Figure 4.49 - Normal Q-Q plot for Christus Resurgens Receiver 3 Virtual Model

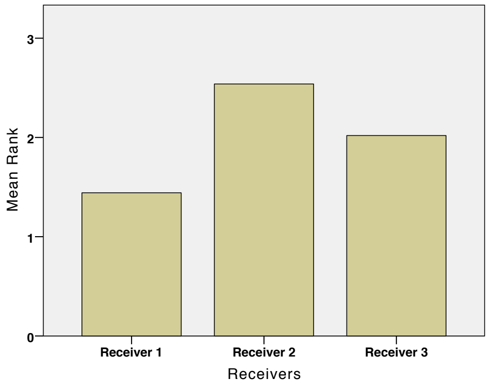
The results from the listening test were analysed through descriptive statistics to calculate the mean score for each sample included in the test. Of particular interest were the values of the samples derived from the virtual model as these reveal the level of perceived difference between the real and the simulated Stonegate. The mean results indicate that no audio samples were rated from 1-2, 44% were rated from 2-3, 44% were given a score of 3-4 and 11% a score of 4-5. Although a greater percentage of scores were located in the upper half of the scale (from 3-5) the difference is only of 11% and does not seem to indicate a clear tendency towards high levels of similarity between sets of results (see Appendix Table 4.17). Consequently, these results seem to indicate that caution should be exercised when using auralizations derived from the virtual model.

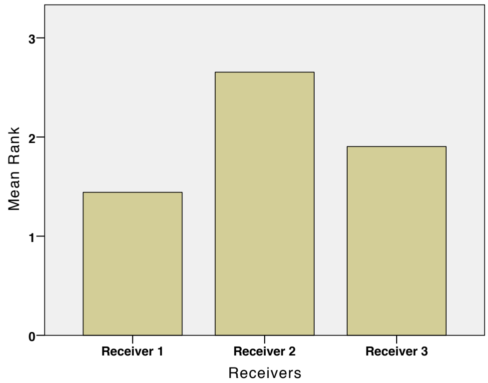
The scores were also analysed using the Wilcoxon Signed-Rank test which enables the comparison of two sets of scores given under two experimental conditions by the same group of participants (Field 2005). The test calculates and ranks the differences between scores by assigning a number one to the smallest difference, a number two to the next highest value and so on. The differences are then classified as positive or negative. The test statistic, which is based on the smaller value of the two summed ranks – positive or negative -, gives us an indication on how representative the results are of the general population (z-score) (Field 2005). The significance is also calculated.

The Wilcoxon Signed-Rank test was employed to compare the results given to the hidden reference with the results that should have been given (5.0, imperceptible difference). The results demonstrate that the differences are non significant for all samples ($p>.05$) allowing us to conclude that the hidden reference was clearly recognisable (see Appendix Tables 4.18).

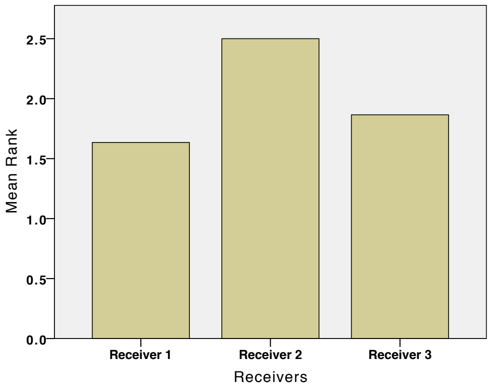
The Wilcoxon Signed-Rank test was also used to analyse the differences between the scores given to the audio samples derived from the acoustic measurements and those derived from the virtual model (see Appendix Tables 4.19). All results are significant at $p<.05$ and the effect size (r), which calculates the magnitude of the effect observed and can be considered as small at 0.10, medium at 0.30 and large at 0.50 (Field 2005), ranged from 0.46 to 0.62. Therefore, it can be concluded that there is a perceptible difference between on site measurements and the simulated space.

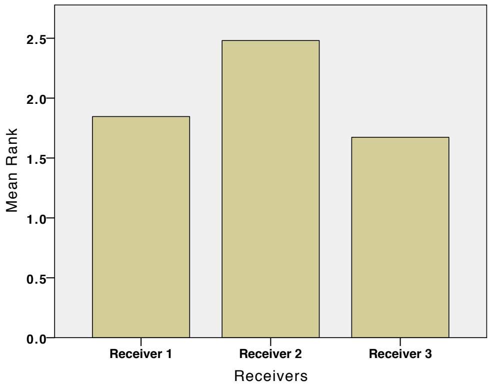
A subsequent analysis of the scores aimed to verify whether the variations found in the objective analysis of the virtual model among source-receiver combinations (see section 4.4.5.1), were also perceptible through the auralizations. With this objective the scores given to the samples derived from the virtual model were analysed using Friedman's ANOVA. This test allows comparisons among groups of experimental conditions (the different receivers) when the same participants were asked to provide scores for all conditions (Field 2005). The test works by ranking the scores per participant and calculating the mean rank per condition, in this case per receiver (Field 2005). The analysis was conducted for each extract of programme material and the results show a significant difference at $p<.05$ (see Appendix Table 4.20). Receiver 2 scored the highest mean ranks in all cases, suggesting that the difference perceived between the real and the simulated space is smaller for this receiver than for receivers 1 and 3 (see Figures 4.50-4.55).



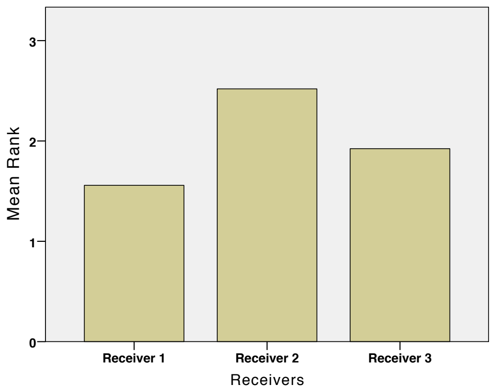


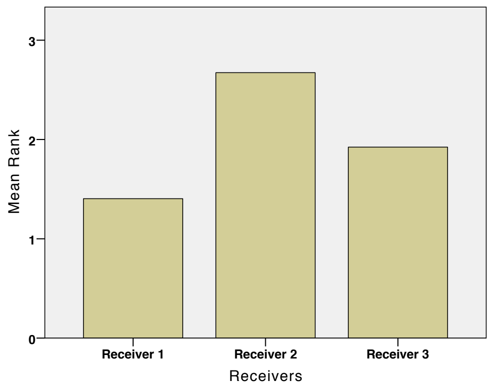
Figures 4.50 and 4.51– Mean Ranks for auralizations based on the virtual model for the *Pentecost* extract (left) and *The Resurrection* extract (right).





Figures 4.52 and 4.53 – Mean Ranks for auralizations based on the virtual model for the *Veni Creator* hymn (left) and the *Christus Resurgens* Communion (right).





Figures 4.54 and 4.55 – Mean Ranks for auralizations based on the virtual model for the Alleluia *Christus Resurgens* (left) and *Veni de Libano* (right).

A Wilcoxon Signed-Rank test was also used to provide a clearer insight on the differences among receivers by comparing them in pairs (receiver 1-receiver 2, receiver 1-receiver 3 and receiver 2-receiver 3). This is a post-hoc test and as a result the Bonferroni correction was applied to modify the p value by calculating α (.05)/nº of comparisons (3) (Field 2005). Consequently, findings are considered significant if $p<.0167$.

When comparing receivers 1 and 2 the results show significant differences for all programme material ($p<.0167$ and $r = 0.34$ to 0.58) (see Appendix Table 4.21). For receivers 1 and 3 results are significant ($p<.0167$ and $r = 0.34$) only when analysing the speech extracts (see Appendix Table 4.21). The comparison between receivers 2 and 3 shows significant results for all programme material ($p<.0167$ and $r = 0.33$ to 0.45) with the exception of the extract from the *Pentecost* play (see Appendix Table 4.21). These results support both the objective results and the results from Friedman's ANOVA by demonstrating that receiver 2 presents both objectively and subjectively a smaller difference in relation to the acoustic measurements than the other receivers. It also confirmed that the differences found in the objective analysis between receivers 1 and 3 are considered significant in the subjective analysis only when speech extracts are employed and in such cases receiver 3 has significantly higher scores than receiver 1. The reason for this difference might be related to the higher accuracy in receiver 3 of the reverberation parameters (T_{20} and T_{30}) as reported in the objective analysis (see section 4.4.5.1).

Results were also evaluated in order to determine whether differences perceived between the virtual model and acoustic measurements were related to the programme material. This analysis was conducted using Friedman's ANOVA and considering each receiver individually. The results for all the receivers are significant, allowing us to conclude that there is a connection between the perception of difference and the programme material utilised (see Appendix Table 4.22). Moreover, in all receivers the *Veni Creator* hymn had the highest mean rank, indicating differences between the real and the simulated space were smaller when using this extract (see Figures 4.56-4.58).

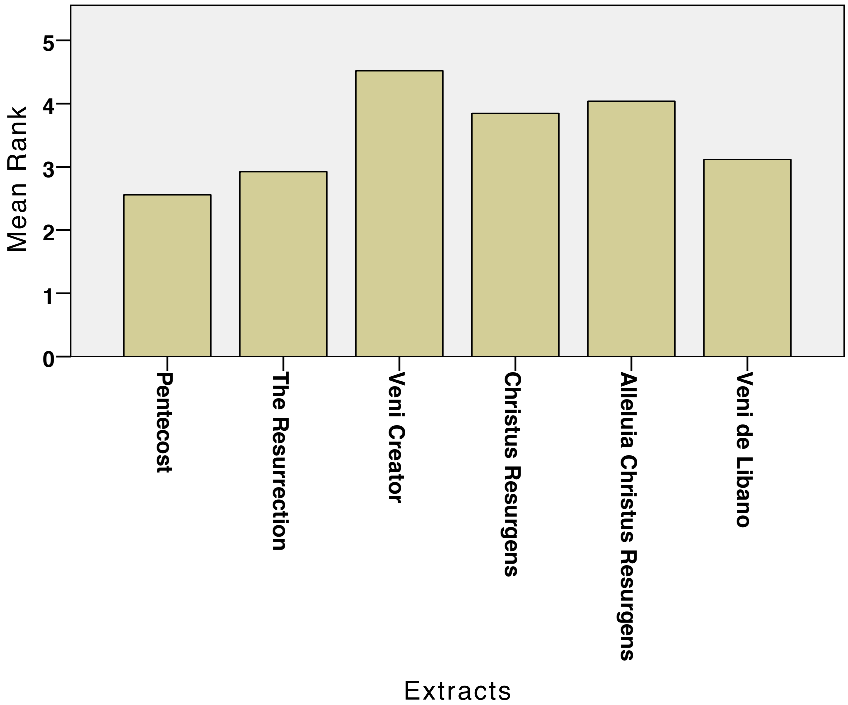


Figure 4.56 - Comparison of auralizations corresponding to receiver 1 using IR from virtual model.

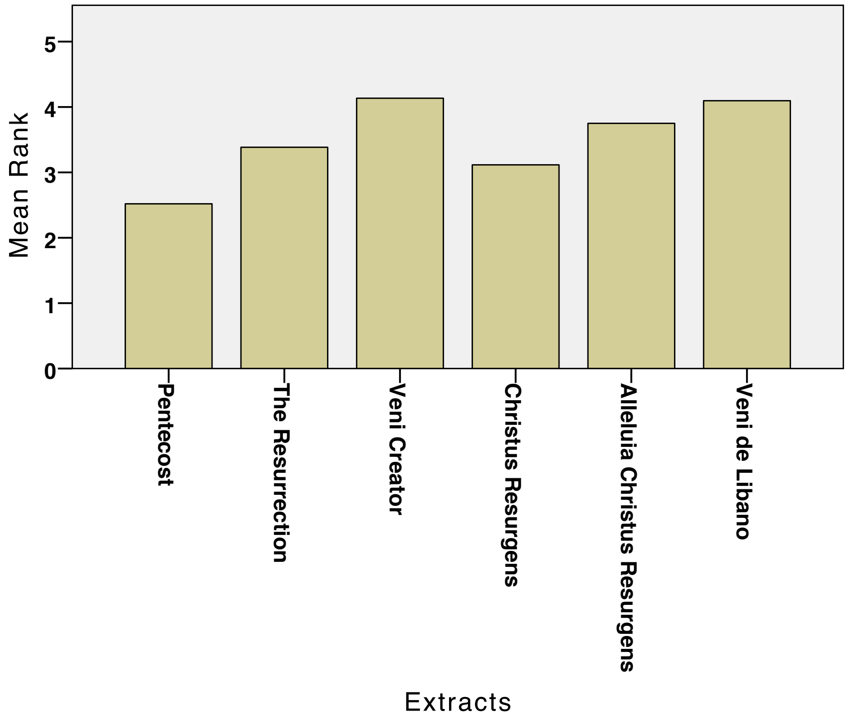


Figure 4.57 - Comparison of auralizations corresponding to receiver 2 using IR from virtual model.

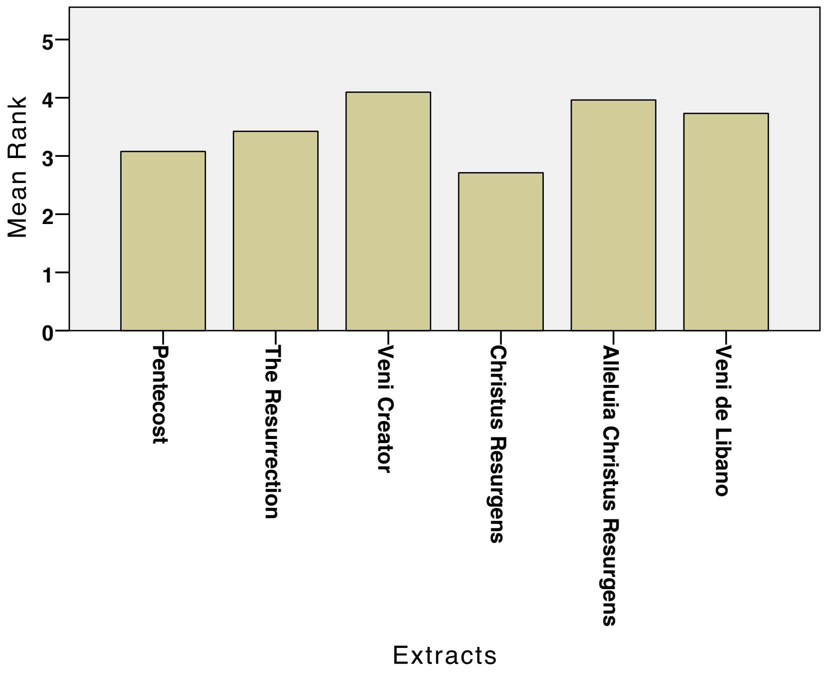


Figure 4.58 - Comparison of auralizations corresponding to receiver 3 using IR from virtual model.

This analysis was followed up by a Wilcoxon Signed-Rank test that considered all possible pairings of programme material and analysed the results per receiver, focussing on the comparison between speech and music auralizations. Differences between music and speech extracts resulted in significant findings only in connection to some of the combinations and this was not consistent across all receivers (see Appendix Tables 4.23-4.25). Receiver 3 did not present any significant results when comparing individual speech extracts to individual music samples. Receiver 1 presented significant differences ($p<.05$ $r = 0.12$ to 0.44) for all comparisons between music and speech extracts, with the exception of the comparison between speech and the polyphonic item. Furthermore, scores were higher for the music samples indicating less pronounced differences between reality and simulation were perceived when music samples were used. Receiver 2 presented scores that were significantly higher for the musical extracts when compared to the speech extract ($p<.05$ $r = 0.28$ to 0.40) when considering the sample from the *Pentecost*. The only exception was the comparison between this speech extract and the neumatic chant, which had non-significant results. No significant results were found when examining the extract from *The Resurrection*.

Due to the inconclusive nature of the results obtained from comparing each musical extract to each speech extract further analysis was pursued. The new analysis compared the combined results for the two speech samples to the results of all possible pairings of music samples. For example, the results for receiver 1 *Pentecost* and receiver 1 *The Resurrection* where compared to the results of receiver 1 *Veni Creator* and receiver 1 *Christus Resurgens*. In all the results the scores assigned to the musical extracts were significantly higher than those given to the speech samples ($p<.05$ $r = 0.21$ to 0.55), the only exception was found in receiver 1 in relation to the comparison between the speech samples and the combination of Alleluia *Christus Resurgens* and *Veni de Libano* at $p=.056$ (see Appendix Tables 4.26-4.43).

A further study investigated whether the perception of difference between real and simulated acoustics was impacted by the changes in the relationship between music and text, or the differences between monophonic and polyphonic music.

A measure of the impact of the text-music relationship is revealed by the significant differences found between the syllabic and the neumatic chant ($p<.05$ and $r = 0.18$ to 22.73) in receivers 1 and 2. These differences indicate significantly higher results assigned to the syllabic chant. A significant difference between the neumatic and melismatic chant for receiver 3 ($p<.05$ and $r = 0.35$) was also observed and it indicates that differences were perceived as less pronounced when the melismatic chant was used. No significant differences were found between the syllabic and melismatic chants.

To further explore this impact of text-music relationships on the perception of differences in acoustics an additional test was conducted. This test combined the scores given to all receivers and through a Wilcoxon Signed-Rank test the scores for syllabic vs. neumatic, syllabic vs. melismatic and neumatic vs. melistmatic were compared (see Appendix Table 4.45). The results are only significant when comparing syllabic to neumatic ($p<.05$

and r = 0.30) and neumatic to melismatic ($p<.05$ and r = 0.19), corroborating the results reported with the previous analysis. Syllabic chants received significantly higher scores than neumatic chants and melismatic chants received significantly higher scores than neumatic chants.

Significant differences between monophonic and polyphonic pieces were found for all receivers although in receiver 1 this significance refers to the comparison of the polyphonic piece to the syllabic chant ($p<.05$ and r = 0.27) and for receivers 2 and 3 the comparison is with the neumatic chant ($p<.05$ and r = 0.54 and 0.31). In receiver 1 the monophonic piece received significantly higher scores than the polyphonic piece whereas the opposite proved true for receivers 2 and 3.

The examination of the data collected through the listening test made it possible to reach a better understanding of the perceptual differences between auralizations derived from acoustic measurements and those derived from the virtual model. The analysis demonstrated that the differences were noticeable since the participants recognised the hidden reference. Likewise, significant differences were found between the scores for the real and the simulated space. Furthermore, the differences recorded by the participants between the results from the real and the simulated measurements indicate that 44% of the results are in the lower half of the scale (1-3) and 55% in the upper half of the scale (3-5), indicating only a slight tendency towards the rating of differences as imperceptible (5.0). These results seem to indicate the limitations of the virtual model in the production of accurate auralizations.

However, the comparison of the results among receivers indicate that the auralizations that were a product of receiver position 2 were perceived as presenting significantly smaller differences to the acoustic measurements than the auralizations resulting from receivers 1 and 3, with mean grades ranging between 3.26-4.08. These results correspond to those observed for the objective analysis, which also demonstrated that the results for this receiver are closer to the values from the acoustic measurements. Therefore, the objective results are corroborated in the subjective domain.

This also seems to point towards the relevance of the accuracy of certain parameters over others. When examining the mean differences between the virtual model and the acoustic measurements the results for receiver 2 were only within 2JNDs for parameters C_{50}, C_{80} and $IACC_{E}$, which were greatly influential in the auralizations. On the other hand parameters related to reverberation time for which the mean results of receiver 2 were above 2JNDs had less relevance in producing auralizations perceived as accurate.

The scores given to the virtual model were also dependent on the programme material. Significant results were calculated when comparing speech to music extracts and they indicated that the scores given to music samples were significantly higher than those given to speech samples. This finding might be related to the higher level of accuracy achieved for C_{80} and $IACC_{E}$, two parameters associated with music perception.

Music samples were also examined to determine whether different relationships between text and music in monophonic chants affected the perception of the auralizations using the simulated space. Significant differences were found between syllabic and neumatic chants, with the former receiving higher scores, and between neumatic and melismatic chants, with the use of the latter resulting in smaller perceptible differences.

Finally, the difference between monophony and polyphony was evaluated and significant differences were found in all receivers, albeit only when compared to the syllabic chant in the case of receiver 1 and the neumatic chant when considering receivers 2 and 3. Furthermore, the results for receiver 1 indicate that the monophonic pieces result in smaller perceptible differences whereas with receivers 2 and 3 the use of the polyphonic piece presents higher scores.

The data collected indicates that although a general consideration of the results of the listening tests indicates that only 55% of the perceived differences are in the upper half of the grading scale when looking at the results more closely finer distinctions can be made. It was observed that the auralizations derived from the virtual model and corresponding to receiver 2 presented the smallest perceived differences, owing to the accurate prediction of C_{50}, C_{80} and $IACC_E$. Furthermore, musical examples resulted in the perceived differences between the real and the simulated space becoming smaller, in particular when combined with monophonic syllabic and melismatic chants.

4.5 The Acoustics of Sixteenth-Century Stonegate

The objective analysis of the virtual model of modern Stonegate indicated its overall accuracy in comparison to the acoustic measurements conducted on site, while also drawing attention to the discrepancies recorded for the EDT and $IACC_L$ parameters, the former counting with only 50% of its results within 2JNDs and the latter with just 17.5%. The subsequent listening test highlighted that although differences between the auralizations derived from the acoustic measurements and those derived from the virtual model can be perceived, these are dependent on the source position and the programme material.

The validation of the virtual model of modern Stonegate through both the objective and subjective analyses, accompanied by a gained awareness of its strengths and limitations, made it possible to employ this model as a starting point for the study of the acoustics of the space in the sixteenth century. This was achieved through alterations and refinements made to the geometry and surface materials of the virtual model.

The information on streets and buildings in medieval and Tudor York presented in this chapter (see sections 4.3 and 4.3.1) was used as a basis for the design of eight different computer models that attempt to arrive at an approximation of the acoustics of Stonegate in the sixteenth century. Since it is not possible to arrive at the definite acoustics of the space due to the incompleteness of the surviving information, the use of different models allows reflection on the impact different variations in the street space might have had on its acoustics. The decision to simulate several models stems from the importance of avoiding inaccurate conclusions that take a reductionist approach to the space and its acoustics, based on the limited evidence available. Scholars in the field of archaeology have discussed this matter in relation to the use of visualisations of heritage sites for the communication of knowledge. They have examined how the use of only one computer model as a representation of a space tends to obscure the areas of uncertainty involved in the study of historical sites and can be mistakenly interpreted as a reality (Denard 2009; Giles, Masinton and Arnott 2012; Miller and Richards 1995). The present project translates such considerations into the field of virtual acoustics by using a multiplicity of simulations and, as a consequence, presenting more transparent results.

All models were completed using the simulation of modern Stonegate as the starting point and included the same source and receivers positions as well as their characteristics (head direction, directivity). The section of the street modelled as well as its width were the same in both modern and sixteenth-century versions, as literature indicates that Stonegate has retained its medieval dimensions (White 1987). Research also indicated that cobbles were a common paving material in the area (Dean 2008; Hartshorne 2004). Such a material is similar to the one present nowadays on Stonegate, allowing the use of the same absorption coefficient in both the modern and the sixteenth-century versions. Furthermore, the unevenness of the current surface, which was simulated in the model of modern Stonegate by using a 35% scattering coefficient across all frequency bands, was now changed to 38% to simulate the effects of the greater unevenness of the cobblestones.

The façades of the buildings were modified to match the characteristics of buildings in the sixteenth century and the different virtual models reflect the alternative features that the buildings might have possessed and that might have been relevant to both the performance of the plays and the acoustics of the space. The scarcity of information regarding the buildings on the left-hand side of the pageant route during the period of interest meant that the best approach was to model the street frontage following the general characteristics of urban secular buildings of the period. The greater amount of information in relation to the right-hand side of the route allowed the virtual models to incorporate the general characteristics alongside the specific features of Stonegate documented as dating from the fourteenth and fifteenth centuries (RCHM, V, 1962-81).

Due to the importance of medieval Stonegate as a street accommodating businesses related to the church, the ground floor of the buildings were modelled following the features of medieval shops. Furthermore, all buildings were simulated as timber-framed houses with brick infill and jetties with a projection of 0.6m, considered by Harris (1993) to be standard. The absorption and scattering coefficients that were used in the computer model of modern Stonegate to simulate the extant timber-framed structures were utilised for all buildings included in the models. The coefficients used for the remaining surfaces, with the exception of the cobble stones, where also the same that were used for the modern version of Stonegate (see Appendix Table 4.46). The virtual models also reflected possible differences in the number of storeys by creating models with both two and three storeys in the cases in which the information for specific buildings was not available. As mentioned in section 4.3 buildings in this period could have presented windows in line with the wall as well as projecting windows. Furthermore, although glass started being used at around this time (Harris 1993), it is likely that during the performance of the plays windows would have been opened to allow viewing the performance from inside. Since these details are not known the virtual models included windows both in line and projecting as well as open or closed (with glass on the upper elevations and wooden shutters on the ground floor). The names given to the different virtual models as well as their characteristics are included in Table 4.7.

Sixteenth-Century Model Version Nº	Pageant Route Side	General Features	Fenestration
1	Left	Two-storey jettied buildings	Glass on upper storeys. Wooden shutters on ground floor.
	Right	Two-storey jettied buildings with the exception of the building on Nº13 which was modelled as a three-storey jettied building	
	Little Stonegate	All two-storey jettied buildings	
2	Left	Same as Version 1	No glass on upper storeys. No wooden shutters on ground floor.
	Right		
	Little Stonegate		
3	Left	Three-storey jettied buildings.	Same as Version 1
	Right	Three-storey jettied buildings with the exception of the building corresponding to 21A	
	Little Stonegate	Three-storey jettied buildings with the exception of Nº13	
4	Left	Same as Version 3	Same as Version 2
	Right		
	Little Stonegate		
5	Left	Same as Version 1	Projecting windows on upper storeys. Glass on upper storeys. Wooden shutters on ground floor.
	Right		
	Little Stonegate		
6	Left	Same as Version 1	Projecting windows on upper storeys. No glass on upper storeys. No wooden shutters on ground floor.
	Right		
	Little Stonegate		
7	Left	Same as Version 3	Same as Version 5
	Right		
	Little Stonegate		
8	Left	Same as Version 3	Same as Version 6
	Right		
	Little Stonegate		

Table 4.7 –Virtual Models of sixteenth-century Stonegate.

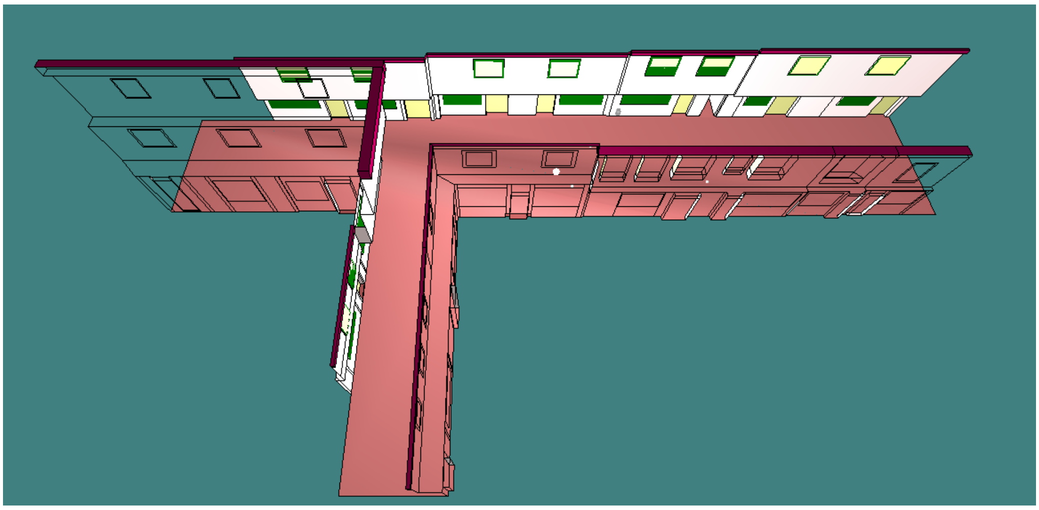


Figure 4.59 – Stonegate 1 – Left-hand side of the pageant route.

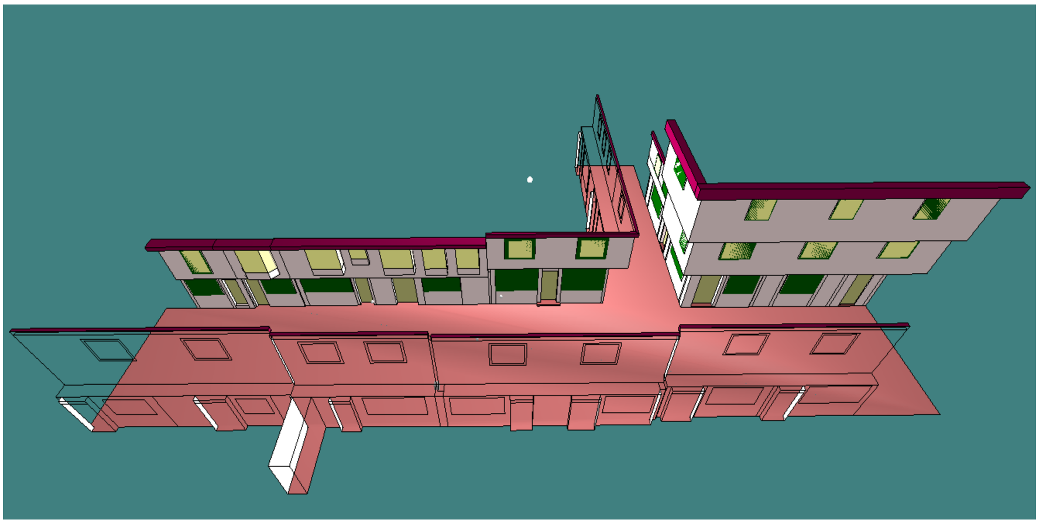


Figure 4.60 – Stonegate 1 – Right-hand side of the pageant route.

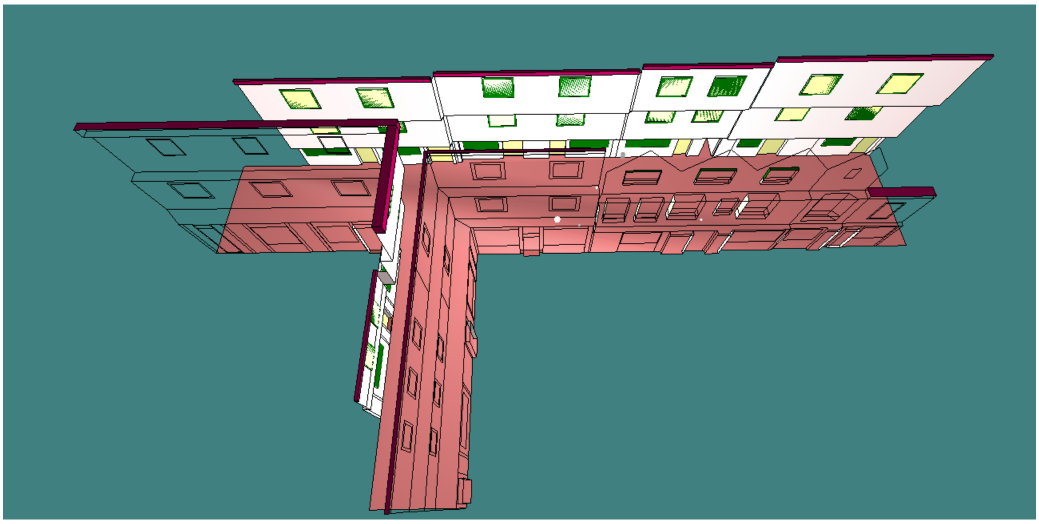


Figure 4.61 – Stonegate 3 – Left-hand side of the pageant route.

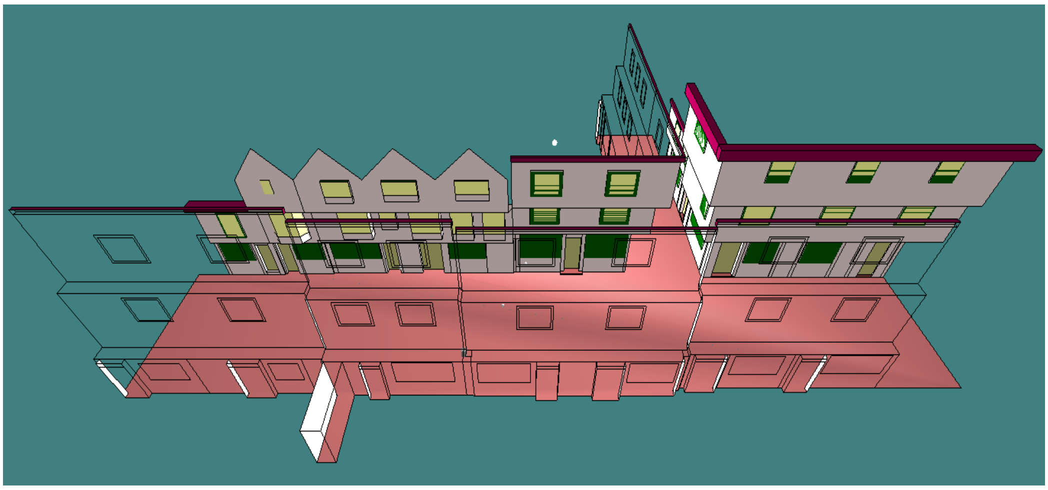


Figure 4.62 – Stonegate 3 – Right-hand side of the pageant route.

The analysis of the acoustic predictions from the eight medieval models were analysed with respect to reverberation time (T_{20} and T_{30}), clarity (C_{50} and C_{80}) and spatial impression ($IACC_E$, $IACC_{E3}$, and LF); all calculated with the Aurora plug-ins. Due to the low level of accuracy achieved for EDT and $IACC_L$ when working on the modern simulation of Stonegate, these parameters have not been considered sufficiently reliable to be applied to the study of the results of the sixteenth-century simulations; consequently both parameters have been excluded from the analysis.

The study of the results is focussed on four sets of comparisons. Firstly, the results of the virtual models simulated as having all windows closed (versions 1, 3, 5 and 7, referred to as "closed" models) are compared to those of the models simulated as having open windows (versions 2, 4, 6 and 8, referred to as "open" models). Secondly, models that present the majority of buildings as two-storeyed (versions 1, 2, 5 and 6) are compared to their three-storeyed counterparts (versions 3, 4, 7 and 8). Thirdly, the effects of changing windows in-line with the wall (versions 1-4) for projecting windows (versions 5-8) are also studied. Finally, the differences between the modern models and the sixteenth-century versions are considered.

Reverberation time values for the closed models, that is, with closed windows on the upper storeys and shutters on the ground floor, have T_{20} and T_{30} values that extend from 0.33-0.88s (see Appendix Table 4.47). The open models, without glass on the upper storeys or wooden shutters on the ground floor, have reverberation times that range between 0.28-0.62s for T_{20} and 0.28-0.6s for T_{30} (see Appendix Table 4.47). In both closed and open models the lowest values are a result of air absorption at high frequencies (8-16kHz). When comparing the closed and open models in terms of JNDs, the mean JND was calculated as 5.16 and 5.47 for T_{20} and T_{30} respectively (see Appendix Table 4.48), indicating significant drops in the reverberation time as a consequence of the removal of glass and wooden shutters from the windows. Although, both closed and open models indicate acoustics that will ensure speech intelligible, the latter present decay times below 0.5s at low and mid frequencies, which might produce discomfort to listeners (Barron 1993) and would prove particularly unsuitable for plainchant performances.

The comparison between virtual models with a majority of two-storey structures and those with a greater number of three-storey buildings demonstrated that the increase in the height of the street façades results in a notable increase in reverberation time. The simulations with a greater preponderance of two-storeyed buildings resulted in reverberation times ranging between 0.28-0.76s and 0.28-0.78s for T_{20} and T_{30} respectively, whereas simulations with taller façades recorded values between 0.31-0.88s for T_{20} and 0.3-0.88s for T_{30} (see Appendix Table 4.47). Differences amounted to a mean JND of 2.47 for T_{20} and 2.26 for T_{30}, which indicates significant changes in the reverberation time as a result of changes in the height of the buildings' frontages (see Appendix Table 4.48).

The simulation of different window types did not produce any notable effects, with a mean JND below 1 for both T_{20} and T_{30} (see Appendix Table 4.48). This finding suggests that considerations on window projections in relation to reverberation time may be disregarded when studying the acoustics of other similar sites, such as other playing stations from the York Mystery Plays.

The differences between the medieval and the modern simulations were also calculated. When compared to the closed versions of the sixteenth-century models mean differences were calculated as 1.65JNDs for

T_{20} and 1.59JNDs for T_{30}, whereas when compared to the open models variations were of 5.21JNDs for T_{20} and 5.38JNDs for T_{30} (see Appendix Table 4.48). The larger dissimilarity between the modern model and the open simulations is due to the lack of reflective surfaces represented by windows in the open models, which results in a decrease in reverberation time. Differences between the modern simulation and the closed versions are much smaller. In most cases it is the modern simulation that presents the higher values with the exception of versions 3 and 7 of the medieval simulations, which present significantly higher values at low and mid frequencies, and versions 1 and 5 that present higher values at low frequencies.

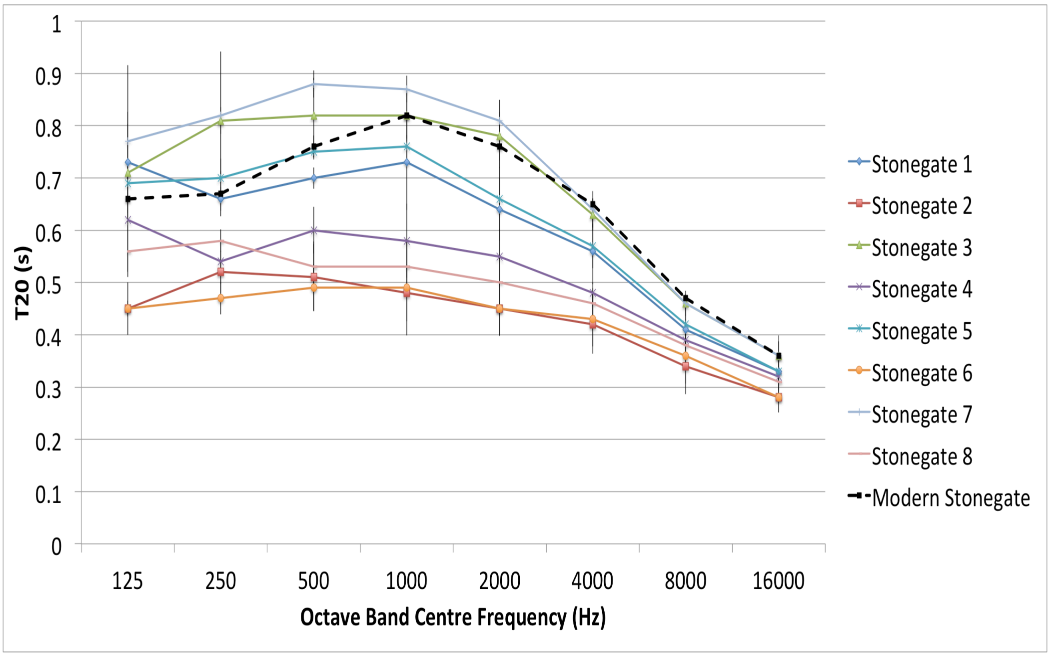


Figure 4.63 – T_{20} across all source-receiver combinations.

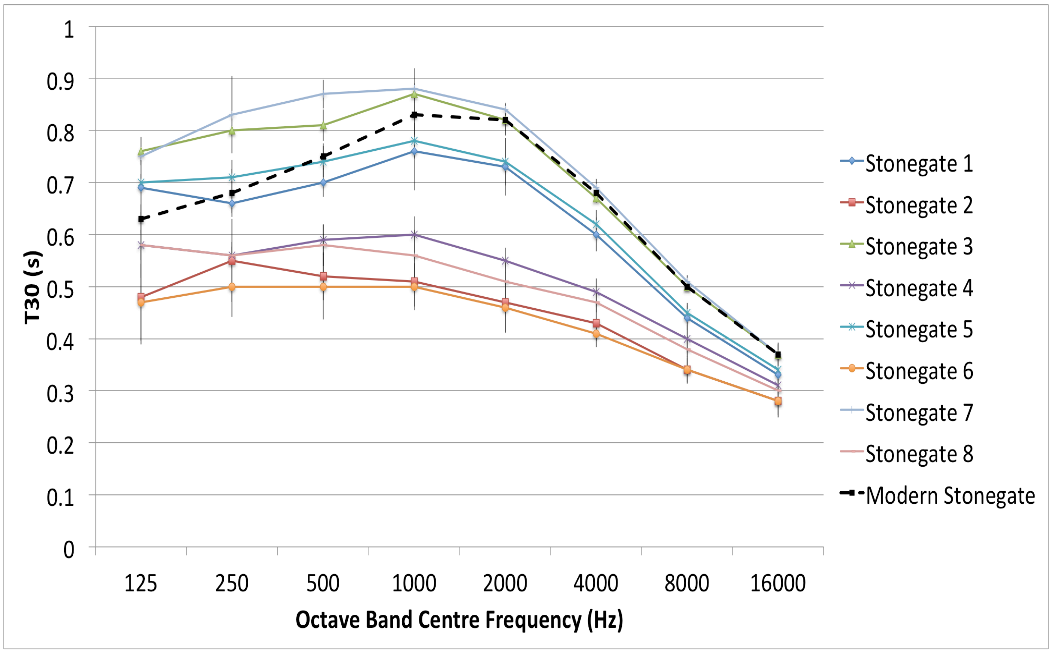


Figure 4.64 – T_{30} across all source-receiver combinations.

Clarity values (C_{50} and C_{80}) were greatly affected by the simulation of the space as closed or open, with the latter presenting the highest values (see Figures 4.65-4.66 and Appendix Table 4.49). This result is due to the fact that in the open models sound is absorbed at a quicker rate as a result of the application of a 99% absorption coefficient to all windows. The differences between the two types of simulations are of 3.47JNDs for C_{50} and 4.79JNDs for C_{80} (see Appendix Table 4.50). Values for the closed models range between 2.91-13.13dB and 5.17-18.43dB for C_{50} and C_{80} respectively, whereas for the open simulations the results extend from 4.45-17.28dB for C_{50} and 7.4-24.11dB for C_{80}. The results for C_{50} indicate very high clarity, which will ensure speech intelligibility, but this high clarity is detrimental to the reverberation time and might result in listeners' discomfort. Moreover, such high clarity values are not optimum for the performance of plainchant items and their suitability for polyphonic pieces might depend on their complexity and the effect on the ability of the singers' to listen to themselves and their fellow performers when sound is so quickly dispersed.

Buildings' heights also affected clarity, mean differences being of 1.75JNDs for C_{50} and 2.31JNDs for C_{80} (see Appendix Table 4.52) and signalling a drop in clarity with an increase in height. Clarity values for versions with lower façades ranged between 4.87-17.28dB for C_{50} and 7.81-24.11dB for C_{80}, whereas the increase in height resulted in C_{50} ranging between 2.24-15.49dB and C_{80} from 5.17-21.6dB.

Changes in the projection of the windows were of little consequence to the clarity of the space, with mean differences being below 1JND (see Appendix Table 4.52). The comparison of the modern simulation of Stonegate to the closed medieval versions indicated small differences of 1.43JNDs for C_{50} and 1.35JNDs for C_{80}, whereas when comparing the modern version to the open models differences recorded were of 2.36JNDs for C_{50} and 3.81JNDs for C_{80} (see Appendix Table 4.52). All open models present higher clarity values when compared to the modern simulations. When considering the closed models modern Stonegate has higher clarity values than versions 3 and 7, whereas when analysing versions 1 and 5 values for the modern simulation are higher only at some frequency bands, 1-2kHz and 16kHz.

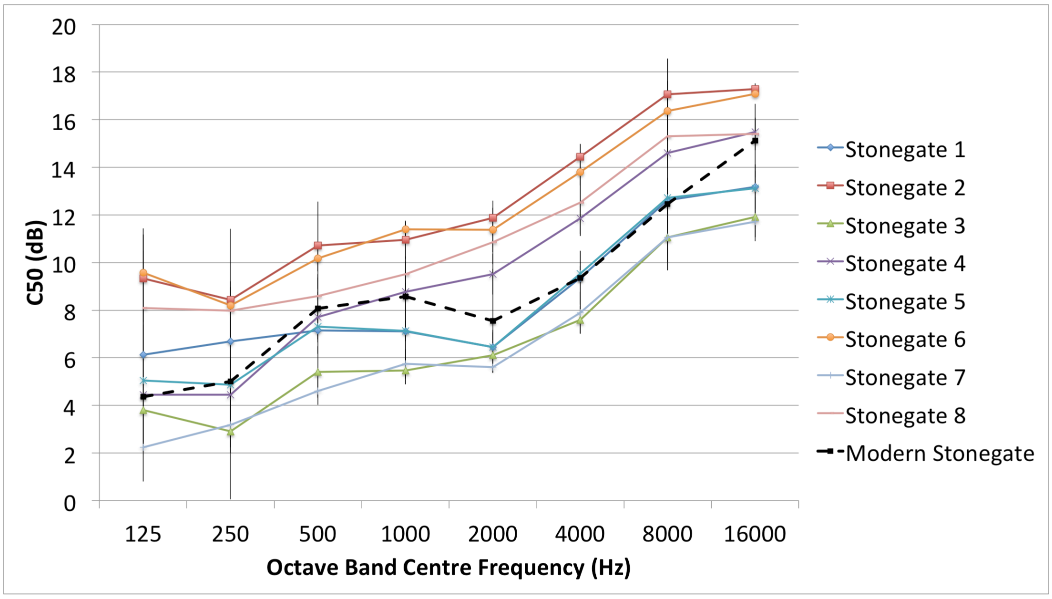


Figure 4.65 – C_{50} across all source-receiver combinations.

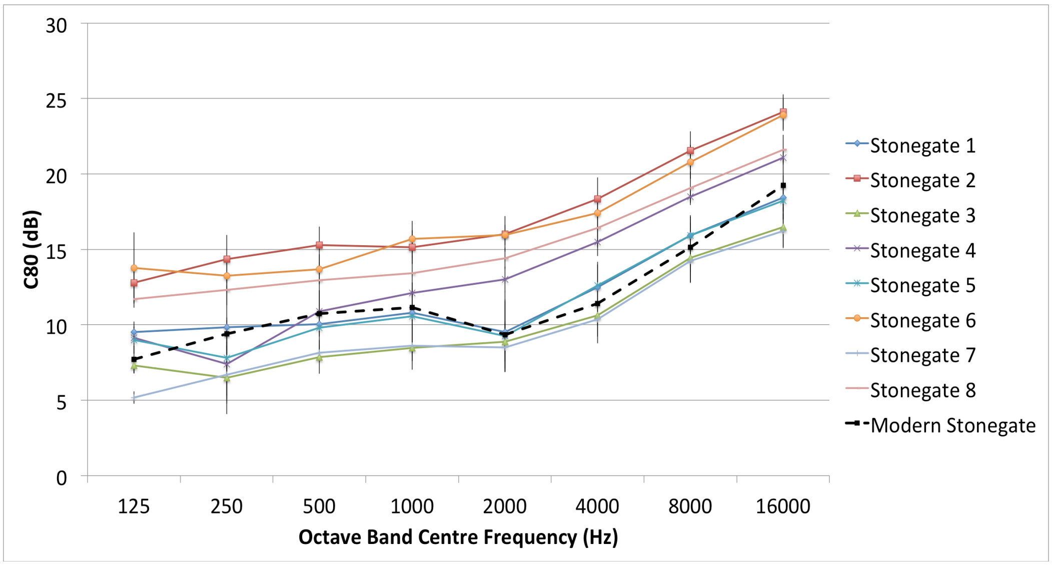


Figure 4.66 – C_{80} across all source-receiver combinations.

The analysis of the data from $IACC_{E3}$ helps establish that very small differences were produced by the changes made across simulations, suggesting that such changes did not affect the early lateral reflections. When comparing values between the closed and open simulations, the former presented results in the range of 0.37-0.64 and the latter between 0.41-0.83. These values show a tendency towards higher levels of spaciousness when closed models are used. However the analysis of the mean differences indicates that the dissimilarities are small, with mean differences amounting to 0.97 JNDs for receiver 1, 0.64 for receiver 2 and 2JNDs for receiver 3 (see Appendix Table 4.53).

Changes in the height of the structures resulted in very small changes of $IACC_{E3.}$ Mean differences were below 1JND for receivers 1 and 2, whereas for receiver 3 the difference was of 1.8JNDs. Variations caused by changes in window types are negligible being below 1JND for all receiver positions.

The comparison between the modern and medieval models suggested minimal variations. Mean differences below 1JND were observed for all receiver positions when taking into account the closed models. When considering the open models differences were below 1JND for receivers 1 and 2, whereas the difference for receiver 3 was of 1.73JNDs.

The analysis of the results for the LF parameter corroborated the findings reported for $IACC_{E3}$, the behaviour of early lateral reflections seems to have been unaffected by the changes in the virtual model. LF values for the closed models range between 0.03-0.14, whereas those for the open models range between 0.02-0.20. A study of the mean differences between closed and open models revealed that although there are differences between the results these are below 1JND for all receivers. Differences as a consequence of the changes in the height of street frontages as well as changes in the type of windows modelled also proved minimal, with the highest variation being of 1JND when considering receiver 3 and the effects of changes in fenestration. Mean differences between modern and medieval simulations were also demonstrated to be negligible with all variations below 1JND (see Appendix Table 4.56).

The analysis of the results derived from the simulations of Stonegate in the sixteenth century showed that significant changes in reverberation time and clarity parameters were the consequence of the inclusion or exclusion of reflecting surfaces at the windows. Open models presented lower reverberation times and higher clarity values which would correspond to the effect produced if all windows of the properties in the area of the playing station were open to allow watching the plays from the inside. Notable effects in the reverberation time and clarity parameters were also a result of the difference in the height of the street facades, with higher structures resulting in higher reverberation times and lower clarity values. No significant differences were caused by changes in the window types from windows in-line with the wall to projecting windows.

When comparing the results for the reverberation time and clarity resulting from the modern model of Stonegate to the results of the sixteenth-century versions, it was observed that the differences were more pronounced when considering the open models, whereas when just taking into account the closed models differences were below 2JNDs.

The analysis of the results also demonstrated that changes across the virtual models only had a very limited impact on the spatial impression parameters analysed ($IACC_{E3}$ and LF_{E4}), indicating that such variations did not influence the early lateral reflections.

4.6 Conclusions

The present chapter presented a study of the acoustics of one of the playing stations of the York Mystery Plays, the station situated at Christopher Willoughby's house in Stonegate. Research into the relevance of this street as well as its characteristics was set within the context of changes in the topography of York from its Roman foundation up to the Tudor era. The focus was placed on the characteristics of the space in the later period of the performance of the plays, in the sixteenth century, on which a greater amount of information survives. The fact that Stonegate has preserved its medieval dimensions and includes several buildings dating from the fourteenth and fifteenth century enabled the study of the acoustics of the playing station through measurements conducted on site. The challenge posed for the successful completion of impulse response measurements in outdoors spaces, which are also tourist attractions, were explored. Through an experiment in a controlled environment the ESS method using a 90-second exponential sine sweep was established as the most dependable method for measurements in Stonegate.

The subsequent acoustic measurements in Stonegate demonstrated that the space as it stands today has reverberation time and clarity values beneficial for speech intelligibility as well as for the perception of musical detail present in complex polyphonic items. However, these characteristics are less appropriate for the performance of plainchant items, which were usually performed in spaces with very different acoustic characteristics such as the York Minster and parish churches. Although reverberation time and clarity in Stonegate seem detrimental to the plainchant items, the high levels of spaciousness recorded include values associated with concert halls as well as gothic cathedrals. This characteristic implies that the quick sound decay time and high clarity might have been compensated for by high levels of spaciousness, in particular related to the increase of the ASW.

The design of a computer model of modern Stonegate, which was calibrated to better resemble the acoustics on site, was also discussed. This virtual model was validated objectively by comparing the results for different acoustical parameters obtained on site with those derived from the virtual model. This comparison showed a high level of accuracy for all parameters with the exception of EDT and $IACC_L$, which as a result were excluded from any future analyses of the space based on the computer simulation. The objective comparison was followed by a subjective evaluation of the results conducted through a listening test and followed by statistical analysis. The subjective evaluation demonstrated that there was a perceptible difference between auralizations derived from the impulse responses measured on site and those derived from the impulse responses of the virtual model. However, these differences were perceived as smaller when music was listened to, in particular, syllabic and melismatic monophonic pieces. These results are a consequence of the higher accuracy achieved in the virtual model for acoustical parameters related to the perception of music, such as C_{80} and $IACC_E$. Furthermore, the results indicated that differences between real-world measurements and the virtual model were perceived as smaller when auralizations combining the source with receiver 2 were used; this corroborates the objective analysis which proved that receiver 2 had small deviations from the acoustic measurements.

The validation of the virtual model of modern Stonegate was followed by the design of eight simulations that used the modern model as a starting point and modified it in relation to its geometry and its surface materials to attempt to replicate different characteristics associated with the space in the sixteenth century. The design of the models as well as their analysis attempted to investigate the effects on the acoustics of the space caused by changing between open and closed windows both on the ground floor and upper storeys, changes in the height of the buildings and modifications in relation to the window types. The results showed that the simulation of the windows as open resulted in a significant drop of reverberation time values as well as an increase in clarity. An increase in the height of the buildings resulted in a higher reverberation time and lower clarity. Alterations to the window types had a minimal impact on all the acoustic parameters analysed. Furthermore, the study of $IACC_{E3}$ and LF_{E4}

parameters proved that the impact of the variations across the virtual models on these parameters was negligible.

A comparison between the different sixteenth century models and modern Stonegate demonstrated prominent differences only when the open models were used. When considering the closed models differences were below 2JNDs for all parameters, suggesting that the acoustic characteristics of Stonegate might have not varied markedly since the sixteenth century.

Chapter 5 will examine an essential aspect of the use of Stonegate as a performance space, which is the incorporation of wagons and audiences and their effects on the acoustics. With this purpose in mind different wagon configurations will be added alternately to the sixteenth century models. The analysis will concentrate on the repercussions for the acoustics resulting from the inclusion of different wagon structures, wagon orientations and performers' positions. As a result of the analysis presented in this section, which demonstrated the minimal differences caused by the changes in window type, the models with the added projecting windows will be excluded from the next modelling phase, whereas the rest of the simulated versions will be included.

Chapter 5

Wagons and Audiences in the York Mystery Plays

5.1 Introduction

The aim of this chapter is to study how the acoustics of Stonegate are affected by some of the fundamental staging hypotheses put forward by scholars and explained in chapter 2. With this in mind thirty-two virtual models were generated, which are the result of the combination of the four virtual models of sixteenth-century Stonegate that presented significant differences, referred to as Stonegate 1-4 (see chapter 4), and eight different staging configurations. The staging configurations modelled were designed to address five main questions. The first analyses whether the addition of a wagon structure had any repercussions on the acoustics of the space. The second issue addressed whether the use of a wagon closed on three sides or a wagon open on all four sides had an impact on the acoustics of the performance area. Thirdly, the significance of using wagons positioned side-on or front-on was explored. Finally, the effects of varying the performer's position were studied. In addition, audience areas were simulated to analyse the impact on the acoustics of audiences standing at the sides of the wagons as well as those sitting at a wooden scaffold at one side of the street.

The results are analysed in terms of reverberation time (T_{20} and T_{30}), clarity (C_{50} and C_{80}) and spatial impression ($IACC_{E3}$ and LF_{E4}). When reading the analysis of the results of the spatial impression parameters it should be acknowledged that both $IACC_{E3}$ and LF_{E4} are related to the perception of the ASW. However, whereas higher values of LF_{E4} indicate an increase in the ASW, $IACC_{E3}$ has a negative correlation with the ASW, meaning that an increase in $IACC_{E3}$ corresponds to a decrease in ASW and vice versa.

Differences between the results derived from the various virtual models studied are reported in JNDs and considered significant when measuring 1JND or above. When the ranges of differences between virtual models are reported in the body of the text, only significant fluctuations will be considered. Differences below 1JND are not analysed as they represent changes that are not perceived by listeners. However, the full results (including changes smaller than 1JND) can be consulted in the tables provided in the Appendix. Moreover, the sections of this chapter and their corresponding Appendix tables are noted at the start of the relevant sections.

Due to the complexity and the volume of the results presented in this chapter the lengthier sections that include analyses on acoustics are followed by a summary of the results reported as well as remarks on the effects of the acoustics on speech and vocal music.

5.2 Wagon Structures

Two contrasting examples of wagon structures were simulated and the resulting effects on the acoustics of sixteenth-century Stonegate were measured with respect to a side-on and front-on orientation for each wagon. The first type of wagon studied is a multi-level design with its lower section, which represented Earth, closed on three sides. This structure is based on some of the features described in chapter 2 for the 1433 Mercers' wagon of *The Last Judgement* (see Figures 5.1-5.2). The base of the wagon structure was modelled through the simulation of curtains covering the wheels. The main deck has a wooden surface and the sides consist of wooden frames with curtains. The upper deck, which represents Heaven, has a wooden base and a wooden surface is included at the back, but it is open on the left- and right-hand sides.

Work by McKinnell (2000) was used as the basis for determining the dimensions of the wagon structure. The wagon has a depth of 1.83m and a length of 3.66m. The height of the wagon from the street level to the topmost part of the structure is 6.7m. This height is achieved through a deck that is 1.83m, a lower structure that is 2.44m, the base of heaven which is 0.25m and the upper part of the structure that measures 2.18m. A "backstage" area was also included but its depth was varied depending on which model of sixteenth-century Stonegate was being used; when the wagon was combined with versions 1 and 2 it was 0.91m deep and when it was combined with versions 3 and 4 the depth was 3.66m. These variations in the backstage area are due to the changes in the height of the buildings' façades. Versions 1 and 2 present a majority of buildings that are only two storeys high and therefore only include a jetty on the first floor, the increase in height in versions 3 and 4 of the virtual model incorporates jetties both on the first and second floors and results in a reduction of the width of Stonegate at the height of the upper level of the wagon. As a consequence, it was necessary to move the wagon towards the opposite side of the street, to avoid interference with the street façade on the left-hand side of the pageant route.

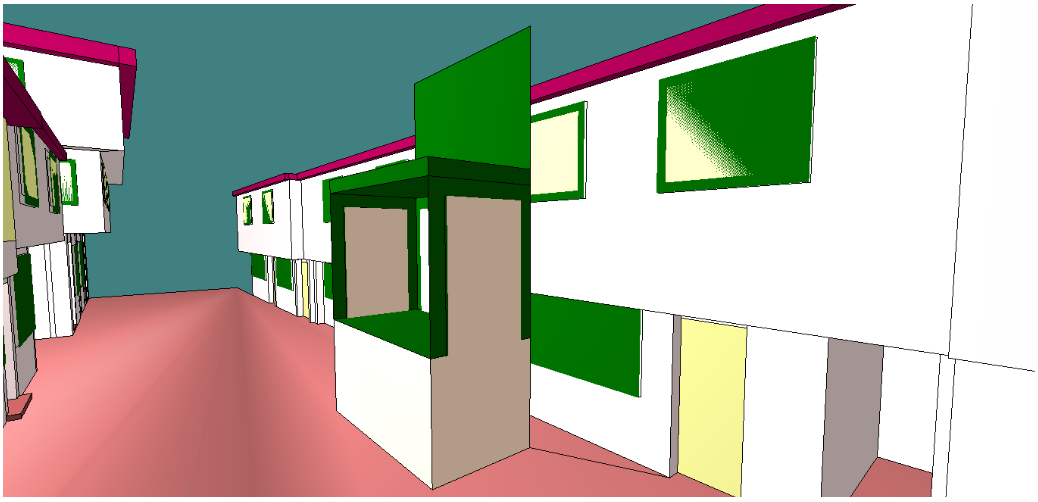


Figure 5.1 – Wagon structure closed on three sides with a side-on orientation and incorporated to Version 1 of the sixteenth-century simulations. Light-coloured surfaces indicate curtains whereas green surfaces indicate wood.

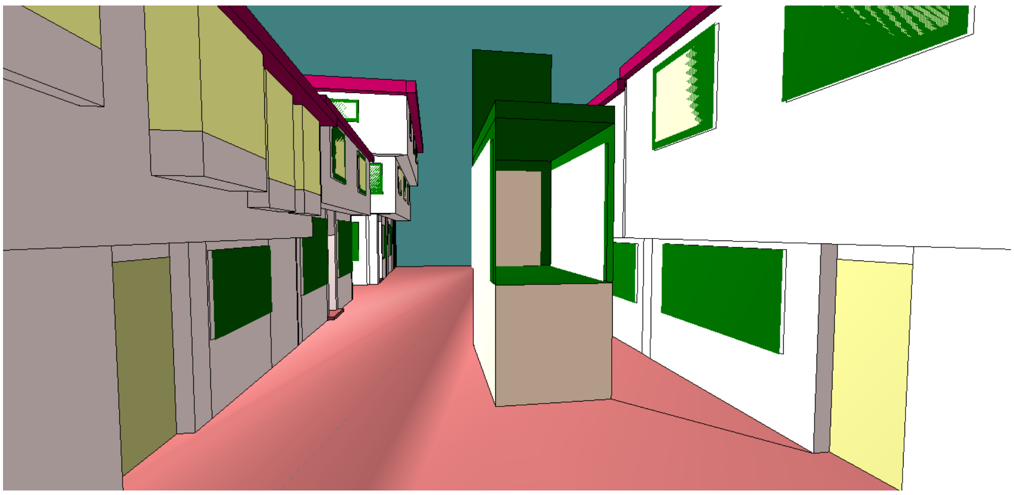


Figure 5.2 – Wagon structure closed on three sides in a front-on configuration and incorporated to version 1 of Stonegate.

The second type of wagon studied is based on The Nativity wagon in van Alsloot's painting *The Triumph of Archduchess Isabella* (1615) (see chapter 2). It consists of a wooden wagon deck that is covered with curtains, and a wooden pitched roof supported by four wooden columns (see Figure 5.3). The dimensions are the same as the closed wagon with the exception of the height from street level to the top of the roof, which is 6.17m, with the roof accounting for 1.9m of the total height. The absorption and scattering coefficients used for both wagon types can be found in the Appendix Table 5.1 and were sourced from the Surface Properties Library in CATT-A.

The design of the virtual pageant wagons evolved from the primary characteristics of the structure as well as their orientation. The choice of materials, which are in the majority of the cases wooden surfaces, reflects the importance of timber in the construction of medieval vehicles (Munby 2008). Details pertaining to the undercarriage and the tongues were disregarded, as they are not essential to the study of the acoustics of the space. Other features that were excluded from the models are those relating to practical aspects such as machinery employed for theatrical effects; in the case of the multi-level wagon this would have been used to simulate the ascent of God to heaven. Practicalities concerning the ascent and descent of actors and singers to the acting decks, which might have been through the use of ladders, were also omitted.

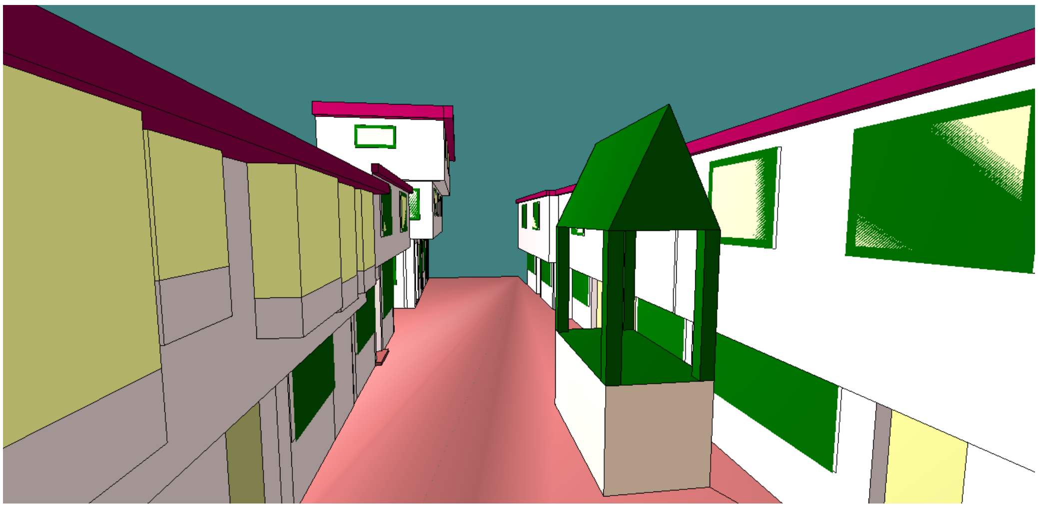


Figure 5.3 – Wagon structure open on all sides and with a side-on/front-on orientation and incorporated to version 1 of the street model. Light-coloured surfaces indicate curtains whereas green surfaces indicate wood.

5.3 Sound Sources

The use of the wagon closed on three sides was accompanied by the inclusion of five different sound sources (see Figures 5.4-5.5), which represent performers standing at various positions in relation to the wagon structure. Two sound sources were located atop the wagon deck, one of them towards the back of the structure (B0) and the other one towards the front (B1). Another source was located at street level in front of the wagon (B2) and two more sources were located atop the upper deck, one of them towards the back of the structure (B3) and the other one towards the front (B4). The virtual models that include the wagon open on all sides only incorporated sources B0-B3 as sources B3-B4 correspond to the upper deck, which is not present in the open wagon (see Figures 5.6-5.7). All sound sources are orientated towards the receivers with their directivity matching the sound source representations used in the street simulations discussed in chapter 4.

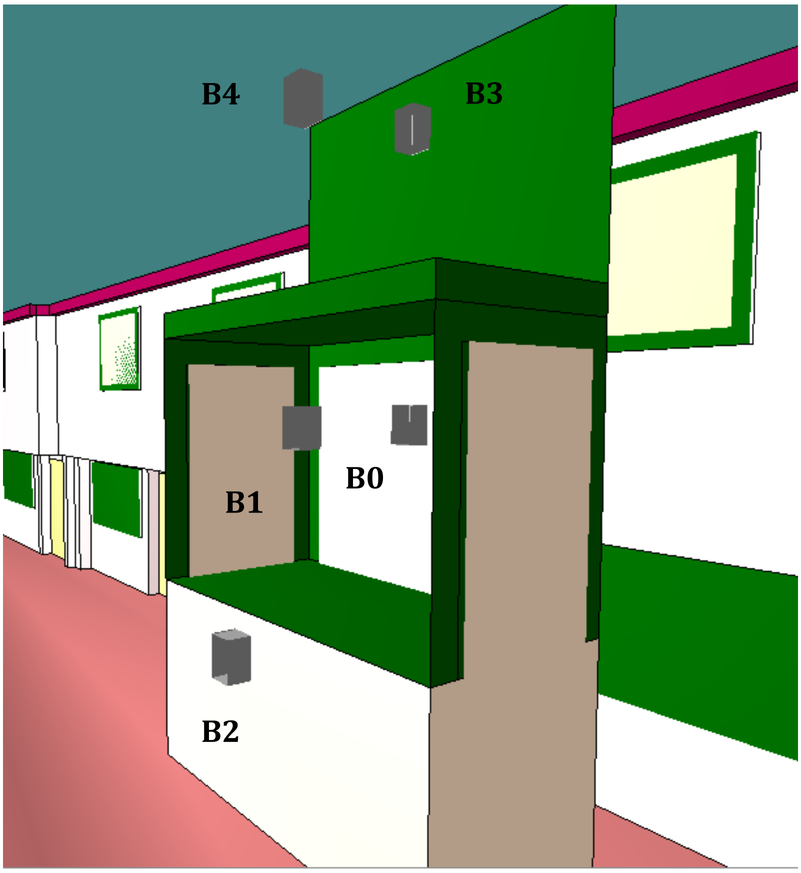


Figure 5.4 – Sound source positions for the closed wagon with a side-on orientation.

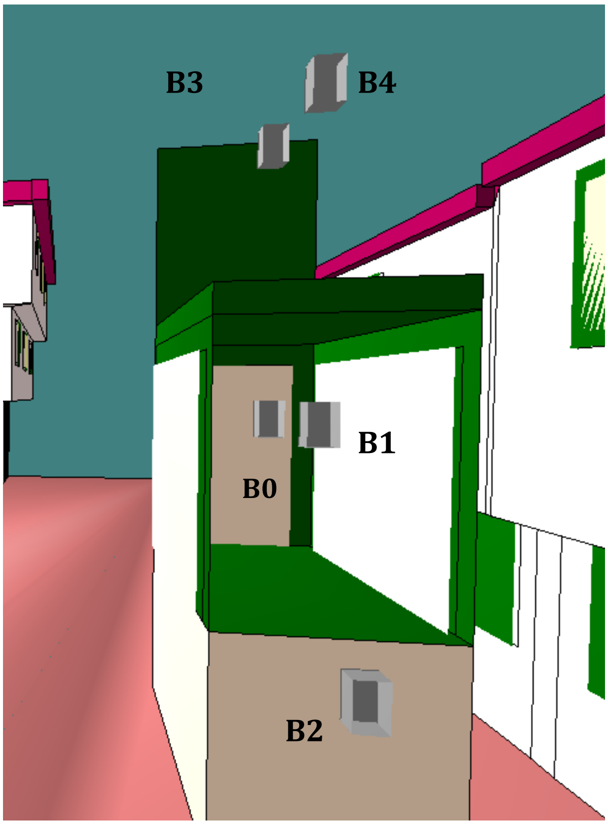


Figure 5.5 – Sound source positions for the closed wagon with a front-on orientation.

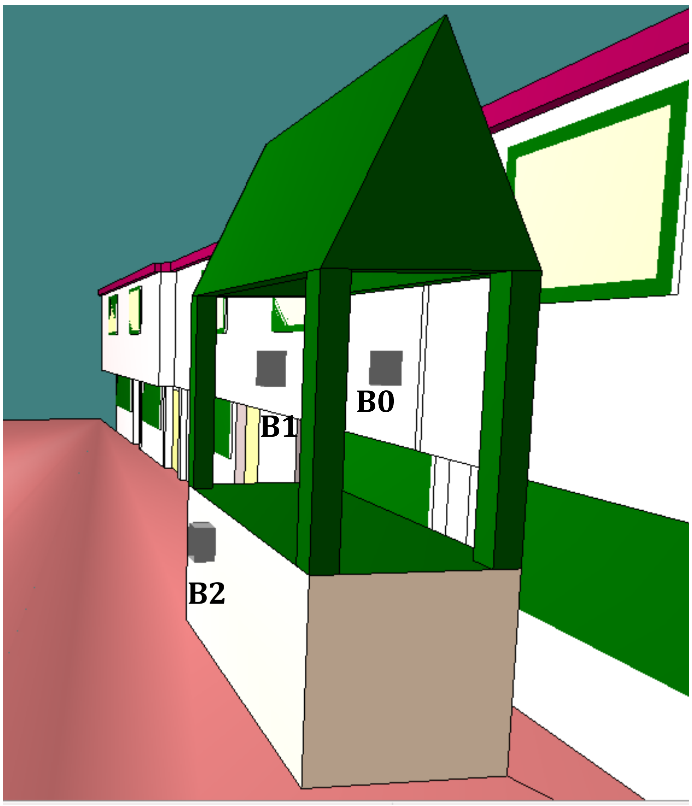


Figure 5.6 – Sound source positions for the open wagon with a side-on orientation.

Figure 5.7 – Sound source positions for the open wagon with a front-on orientation.

5.4 Audience Area and Receivers

The three receiver positions used for the acoustic measurements in Stonegate and the subsequent virtual models were maintained for the side-on simulations. These receiver positions were modified for the front-on simulations but they maintained the same relative location with respect to the street and the wagon. The direction in which the head faced for all receivers was set to be straight ahead.

The effects that variations in the audience area had on the acoustics of the space were investigated through additional virtual models. These models included three different areas: two simulating a standing audience (one at each side of the wagon) and a scaffold area set up against one of the sides of the street, representing the possible use of scaffolds for paying audiences (see Figures 5.10-5.11). These audience areas remained the same in all the virtual models, irrespective of the change in wagon orientation.

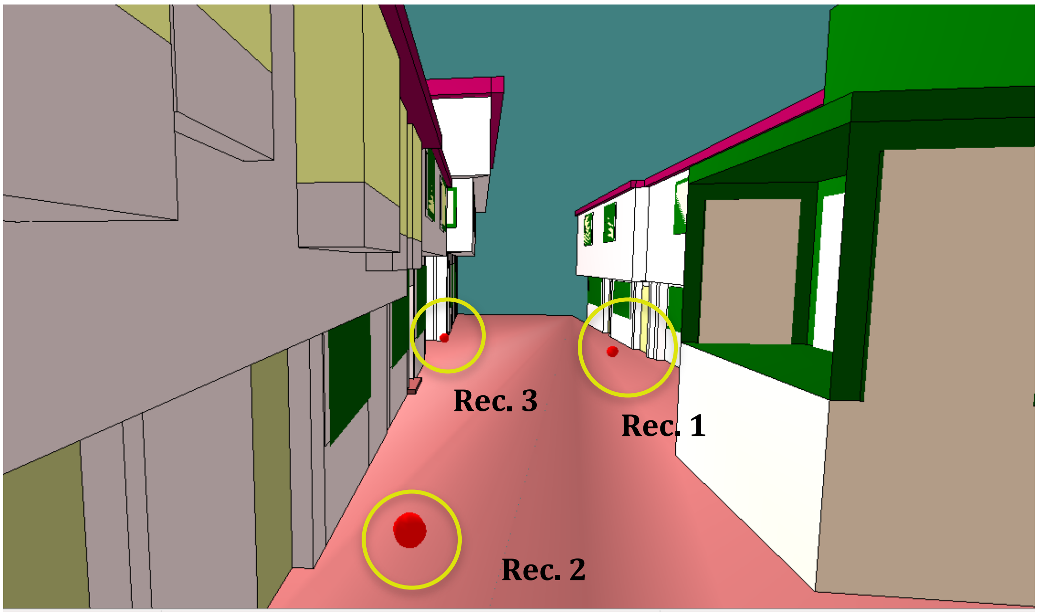


Figure 5.8 – Receiver positions with a side-on orientation.

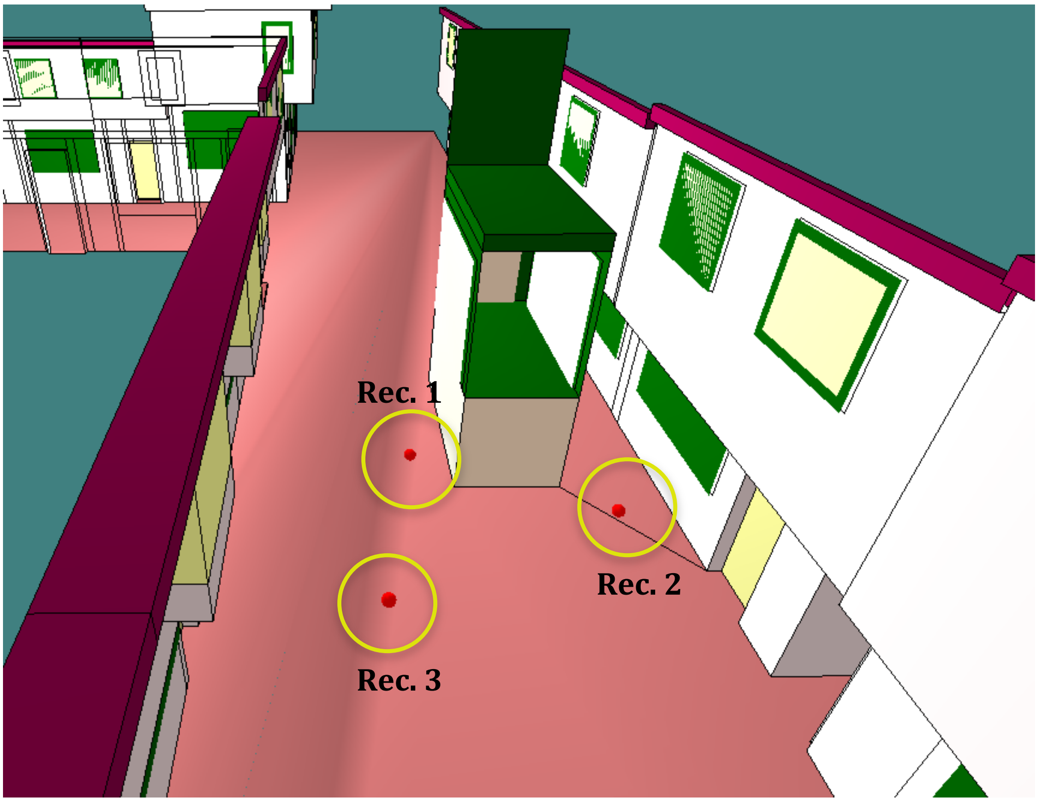


Figure 5.9 – Receiver positions with a front-on orientation.

Scaffolds were modelled to comprise of three different levels and including absorption and scattering coefficients for wooden surfaces as well as audiences sat on wooden chairs (see Appendix Table 5.2). The whole structure was simulated as being 6m high, 2m deep and 3.66m long (the same length as the wagon structures). It should be noted that, due to the very sparse evidence on the appearance and use of scaffolds for the York Mystery Plays, the manner in which this was modelled represents only one out of many possible interpretations of their design and implementation. The idea of having audiences at different levels was drawn from the painting *The Martyrdom of St. Apollonia* by Jean Fouquet (see chapter 2). Southern's (1975) analysis of Fouquet's painting only identifies audiences at two levels and suggests that the scaffolds were built using supporting frames and covered by curtains on the sides, top and back (see chapter 2). The virtual models here presented were only partially based on Southern's analysis as the intention was to determine the effect on the acoustics of Stonegate resulting from a structure that consisted of surfaces with low absorption coefficients. The objective of this decision was to arrive at an understanding of what might have been the highest reverberation times achievable through a modification of the audience area, whilst still using a plausible design.

These audience areas were populated with thirty-eight receivers. Ten were located in each standing audience area and six receivers were positioned at each scaffold level, resulting in eighteen seating positions.

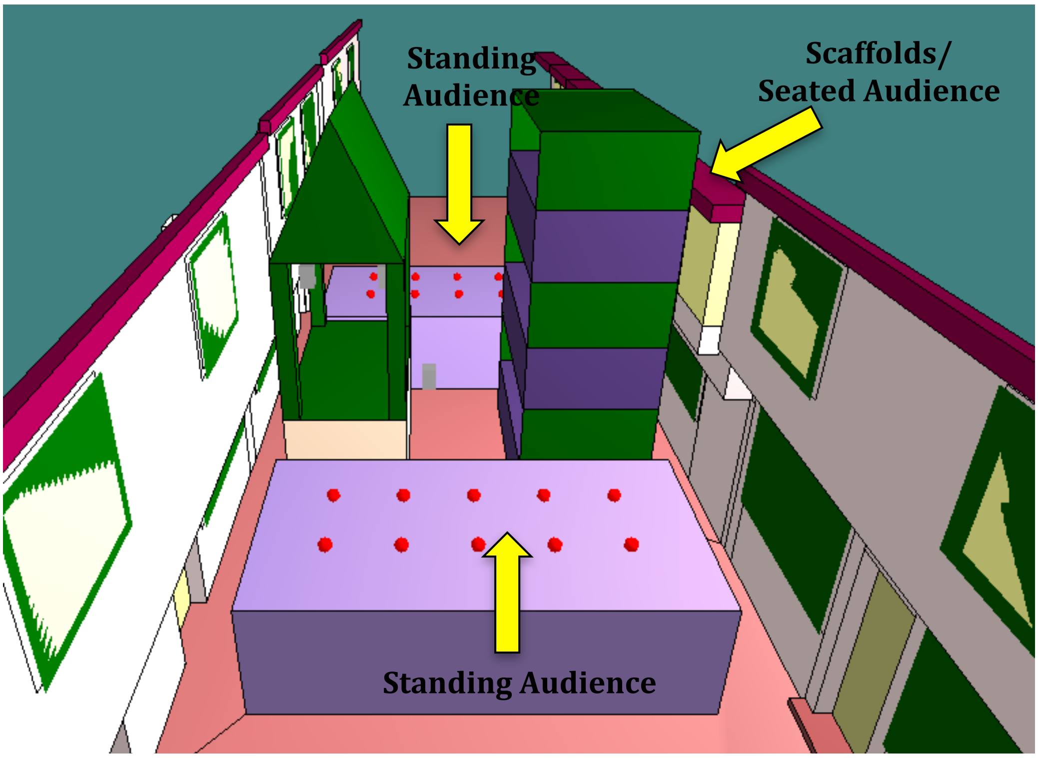


Figure 5.10 – Simulation of audience areas. The surfaces in different purple shades indicate absorption and scattering values associated with the presence of an audience whereas the green surfaces indicate a wooden structure. The red spheres represent the receivers.

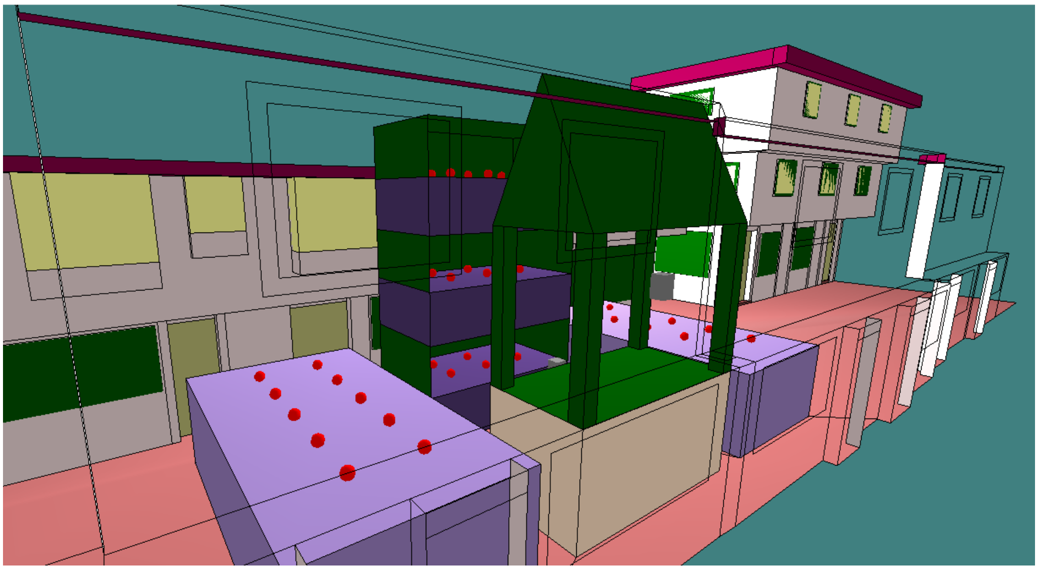


Figure 5.11 – Simulation of audience areas.

5.5 Virtual Models

Thirty-two virtual models were simulated with the objective of studying the effects of the inclusion of wagons and audiences to the street space. Tables 5.1-5.2 summarise the characteristics of each simulation and the nomenclature that will be used when referencing them.

<table>
<tr><th>Wagon CL-SI</th><th>Wagon CL-FR</th><th>Wagon CL-SI-Aud.</th><th>Wagon CL-FR-Aud.</th></tr>
<tr><td colspan="4">Source</td></tr>
<tr><td colspan="4">Mercers' 1433 wagon</td></tr>
<tr><td colspan="4">Features</td></tr>
<tr><td colspan="4">Multilevel wagon, closed on three sides, sides and wheels covered with cloth, main wooden structure</td></tr>
<tr><td colspan="4">Orientation</td></tr>
<tr><td>Side-on</td><td>Front-on</td><td>Side-on</td><td>Front-on</td></tr>
<tr><td colspan="4">Performance Area</td></tr>
<tr><td colspan="4">Atop the wagon and at street level (five sound sources)</td></tr>
<tr><td colspan="4">Audience Area</td></tr>
<tr><td colspan="2">Three receiver positions</td><td colspan="2">Wooden scaffold at the side of the street, standing audience area at the sides of the wagon. Thirty-eight receiver positions.</td></tr>
</table>

Table 5.1 - Characteristics of simulations incorporating a closed wagon.

<table>
<tr><th>Wagon OP-SI</th><th>Wagon OP-FR</th><th>Wagon OP-SI-Aud.</th><th>Wagon OP-FR-Aud.</th></tr>
<tr><td colspan="4">Source</td></tr>
<tr><td colspan="4">Flemish Ommegangen – Nativity wagon (van Alsloot painting)</td></tr>
<tr><td colspan="4">Features</td></tr>
<tr><td colspan="4">Base covered with cloth, one level open structure with columns supporting a pitched roof</td></tr>
<tr><td colspan="4">Orientation</td></tr>
<tr><td>Side-on</td><td>Front-on</td><td>Side-on</td><td>Front-on</td></tr>
<tr><td colspan="4">Performance Area</td></tr>
<tr><td colspan="4">Atop the wagon and at street level (three sound sources)</td></tr>
<tr><td colspan="4">Audience Area</td></tr>
<tr><td colspan="2">Three receiver positions</td><td colspan="2">Wooden scaffold at the side of the street, standing audience area at the sides of the wagon. Thirty-eight receiver positions.</td></tr>
</table>

Table 5.2 - Characteristics of simulations incorporating an open wagon.

Each wagon simulation included in the tables was in turn combined with four of the virtual models of sixteenth-century Stonegate. The models of Stonegate that were used were those in which variations in the geometry and the absorption and scattering coefficients resulted in significant changes to the acoustics of the space. These models were referred to in chapter 4 as versions 1-4, where versions 1 and 2 represent a variation between two-storeyed buildings with closed and open windows respectively, and versions 3 and 4, which have a preponderance of three-storeyed buildings and also vary in relation to windows being closed or open.

In the present chapter virtual models are often referenced by the number of their respective street simulation and by the name given to the wagon structure. For example, Stonegate 1-CL-SI refers to a simulation that uses version 1 of the sixteenth-century model of Stonegate while also incorporating a wagon structure closed on three sides and in a side-on orientation.

5.6 Staging: Acoustical Analysis

The acoustical analysis presented in this section concentrates on the virtual models that do not include audience areas. Analysis seeks to determine the effects of the wagon structures on the acoustics of the space without the influence of the absorption and scattering introduced by the audience areas.

This analysis focusses on four main points. Firstly, it studies the impact of the addition of wagon structures on the acoustics of the street space by comparing the results from the acoustic predictions of the space including the wagons to the results derived from the same space but without a wagon included. Secondly, variation in the acoustical properties of the space through the introduction of closed or open wagon structures is explored. Thirdly, variations resulting from different wagon orientations are measured. Finally, acoustical differences derived from the different source positions are analysed.

5.6.1 The impact of the Wagon Structures on the Acoustics of Sixteenth-Century Stonegate

This section explores the data collected from the combination of the different wagons with the various virtual models of Stonegate and compares it to the data collected for the virtual models of the street space without the inclusion of a wagon structure. Results from such a comparison reveal how the acoustics of Stonegate is modified by the presence of a wagon structure.

A. Reverberation Time: T_{20} and T_{30}

Appendix – Tables 5.3-5.11

All versions of Stonegate present fluctuations in the T_{20} and T_{30} values as a consequence of the introduction of a wagon structure. It is possible to observe a clear tendency towards a decrease in reverberation times when a wagon structure is introduced. However, it can also be noted that even in the cases in which a simulation presents a majority of results indicating a drop in reverberation time values, the 125Hz frequency band often reveals an increase in T_{20} and T_{30}. Furthermore, in all versions of Stonegate, with the exception of Stonegate 1, the introduction of a closed side-on wagon results in the majority of the values indicating an increase in reverberation time.

B. Clarity: C_{50} and C_{80}

Appendix – Tables 5.12-5.20

The addition of wagon structures to the street spaces also resulted in significant variations in clarity. Results for Stonegate 1 show a clear tendency towards an increment in C_{50} and C_{80}. The only exception is when it is combined with an open side-on wagon, where a comparable increase and decrease in clarity can be observed. Furthermore, it is in the 125Hz frequency band where drops in clarity are concentrated, which is related to the increase of reverberation time at this frequency band. Contrastingly, when examining the results for Stonegate 2 it is the decrease in clarity values that is predominant, this is the case for the simulations with a CL-SI, CL-FR and OP-SI wagons. In the case of the OP-FR wagon the opposite is true since higher clarity prevails. Results for Stonegate 3 and 4 in combination with CL-FR, OP-SI and OP-FR wagons exhibit an increase in values when compared to the simulation without them. However, the simulation with a CL-SI wagon presents an overall decrease in clarity, which correlates to the increase in reverberation time recorded for these virtual models.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Appendix – Tables 5.21-5.29

The results for the spatial impression parameters $IACC_{E3}$ and LF_{E4} show significant fluctuations as a result of the addition of wagon structures. A close observation of these results shows that there is a clear tendency towards a drop in values of $IACC_{E3}$ and an increase in values of LF_{E4}. These results indicate that a larger ASW is achieved when the wagons are added to the street space. Nevertheless, some of the results of $IACC_{E3}$ and LF_{E4} indicate a decrease in ASW when the wagon structures are used.

Section Summary and Remarks on Results

The results presented in this section indicated that the addition of wagon structures to the street space resulted in variations in reverberation time, clarity and spatial impression. In terms of reverberation time, it was possible to observe a clear tendency towards a decrease in values. The exception to this was the combination of the CL-SI wagon with Stonegate 2-4, which resulted in longer reverberation times. The impact of the addition of a wagon structure on clarity was highly dependent on the simulation of Stonegate. In the case of Stonegate 1 clarity increased when CL-SI, CL-FR. and OP-FR wagons were used but decreased when the OP-SI wagon was included in the street space. Results for Stonegate 3 and 4 also showed higher clarity with the inclusion of a wagon. However, this is only the case with the CL-FR, OP-SI and OP-FR wagons. When considering Stonegate 2, the CL-SI, CL-FR and the OP-SI wagons result in a decrease in clarity, whereas the inclusion of the OP-FR wagon results in an increase. Changes in spatial impression indicated that the inclusion of wagon structures caused an increase in the ASW.

5.6.2 The Impact of Closed and Open Wagon Structures on Sixteenth-Century Stonegate

The following section analyses the differences in the acoustics of Stonegate as a result of the addition of closed and open wagons. Such analysis begins by comparing each orientation, side-on and front-on, separately; this resulted in comparisons of the CL-SI wagon to the OP-SI wagon, and the CL-FR wagon to the OP-FR wagon. This way of pairing the simulations aims to avoid the tainting of comparisons resulting from wagon orientation, an issue that will be explored in section 5.6.3. Only sources B0-B2 were considered as part of the comparisons since these are the sources that are present in simulations for both wagon types. Furthermore, reverberation time and clarity results have been averaged across receiver positions but not across source positions and these results are considered per frequency band in order to calculate the percentage affected by significant differences. The source-position-based results will be explored in detail in section 5.6.4. The results corresponding to $IACC_{E3}$ and LF_{E4} parameters were not averaged in order to determine any possible influences of the receiver positions on the perception of the ASW. Therefore, the percentage of significant differences for these two parameters refers to all values calculated from the virtual models.

Comparison between side-on wagons

A. Reverberation Time: T_{20} and T_{30}

Appendix – Tables 5.30-5.38

The comparison of the side-on structures demonstrated that when combined with the different simulations of Stonegate there were variations in the reverberation time, which were a consequence of changes between an open and a closed wagon structure. However, not all the simulations of Stonegate were affected to the same extent and it was versions 1 and 4 that were affected the most.

When considering Stonegate 1 significant differences as a result of the change in wagon type were found in 38% of the total results. These differences ranged between 1-2.33JNDs and showed a clear tendency towards a higher reverberation time when the open wagon was used. Such tendency is due to the different level of enclosure of the wagons as well as their surface materials. Whereas the open wagon is open on all sides with only four wooden columns supporting a wooden pitched roof, the closed structure is closed on three sides by a wooden frame and curtains. The open structure results in sound reflections either bouncing off the wooden surfaces of the wagon or off the surfaces of the street space, which have values of absorption ranging between 1-19% (see Figures 5.12-5.13). But in the case of the closed wagon, sound reflections are affected by the curtains at the sides of the structure which have absorption values between 5-76% (see Figures 5.12-5.13). The presence of these curtains greatly influences sound reflections and results in shorter reverberation times.

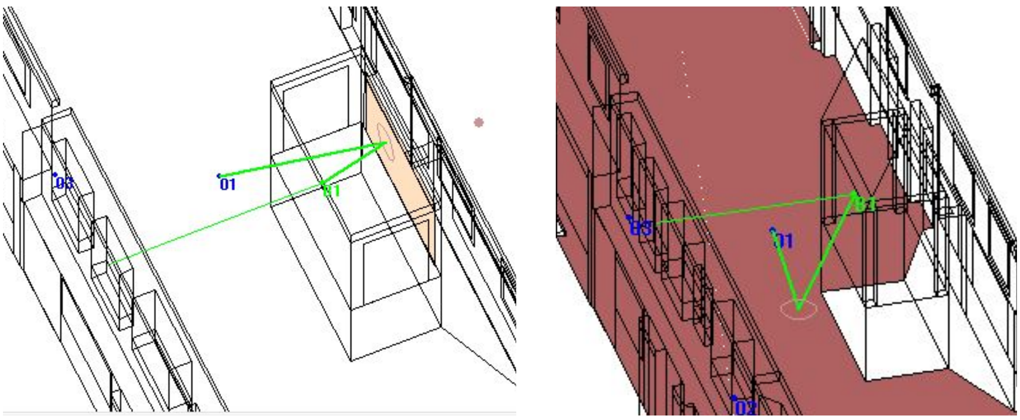


Figure 5.12 – (Left) A first order specular reflection for Stonegate 1-CL-SI (B1xR1) can be seen bouncing off the back of the wagon which is simulated as a curtain. (Right) A first order specular reflection for Stonegate 1-OP-SI (B1xR1) bounces off the floor surface modelled as stone.

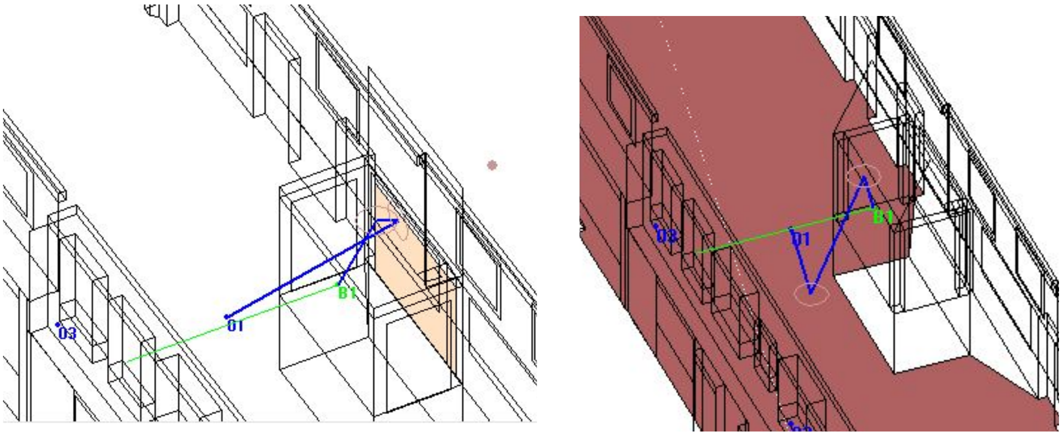


Figure 5.13 – (Left) A second order specular reflection for Stonegate 1-CL-SI (B1xR1) is seen bouncing off the back curtain and the wagon ceiling. (Right) A second order specular reflection for Stonegate 1-OP-SI (B1xR1) is seen reflecting off the wooden wagon frame and the stone floor.

Differences in reverberation time as a consequence of changes in the wagon structure were found to affect Stonegate 4 by showing significant differences in 46% of T_{20} results and 29% of T_{30} results. Moreover, the majority of the differences are concentrated in the frequency range of 125Hz-1kHz and they range between 1-4JNDs. These differences indicate that it is the use of the closed structure that resulted in a higher reverberation time. This result is the opposite of that obtained with Stonegate 1 and is a consequence of the high absorption values (99%) used in Stonegate 4 to simulate open windows in the ground floor and upper storeys. Although both wagon structures are affected by the highly absorbent surfaces found across the street, on the right-hand side of the pageant route, the open wagon was also affected by those surfaces behind the wagon (see Figure 5.14). As was mentioned above, the closed wagon is most influenced by the curtain surfaces at its sides, which in comparison to the open windows have lower absorption coefficients. Therefore, the drop in reverberation is more prominent for the open wagon than it is for the closed wagon. Furthermore, the concentration of differences in the lower frequency bands is related to the fact that at higher frequencies the difference in absorption coefficients between the open windows and the curtained surfaces, which play a key role in simulations using the closed wagon, become smaller.

Versions 2 and 3 of Stonegate also presented significant differences when the type of wagon structure was varied. Stonegate 2 was affected in 21% and 29% of its results when considering T_{20} and T_{30} respectively, whereas Stonegate 3 was impacted in 33% of T_{20} results and 8% of T_{30} results. Results for Stonegate 2 showed similar tendencies to those reported for Stonegate 4 as a higher reverberation time was achieved when a closed wagon was used. Differences also concentrated in the 125Hz-1kHz-frequency range and extended from 1-3.67JNDs.

When analysing the results for Stonegate 3 significant differences between structures extended from 1-2JNDs and were found at all frequency bands with the exception of the 2-4kHz frequency range. However, there is not a clear tendency towards an increase or decrease in values as a result of the addition of one of the wagon types and results seem highly dependent on the frequency band and the source position.

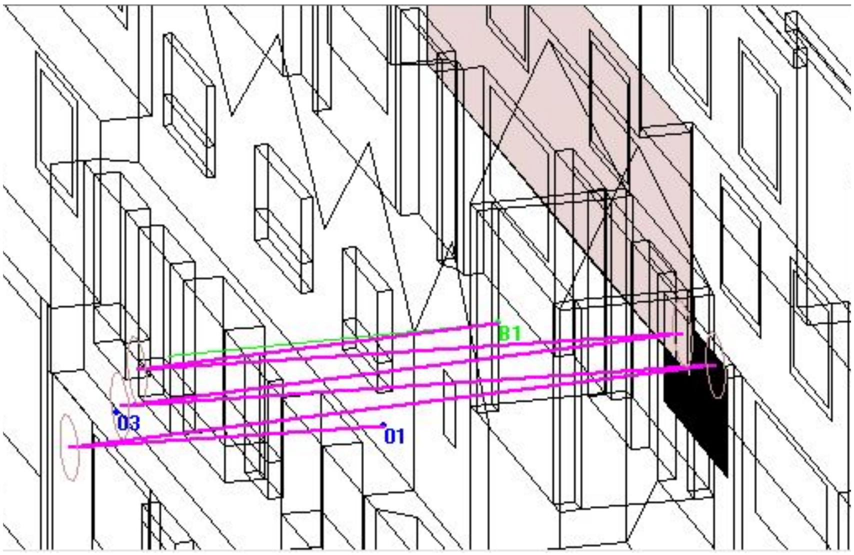


Figure 5.14 – A fifth-order specular reflection in the simulation of Stonegate 4-OP-SI, which is shown reflecting off an open window on the ground floor behind the wagon.

B. Clarity: C_{50} and C_{80}

Appendix – Tables 5.39-5.47

Variations in clarity due to the change in wagon type were measured in terms of C_{50} and C_{80}. Of all the street spaces simulated version 2 was the most affected and significant differences ranged between 1-2.82JNDs. The larger part of the significant differences indicates that higher clarity is achieved when the open wagon is used in the street space. This seems to follow the tendency shown for Stonegate 2 in relation to reverberation time, which was shown to be lower when the open wagon was used. Figures 5.15-5.16 show that a larger concentration of reflections are present within the first 80ms after the arrival of the direct sound when an open wagon is used. Furthermore, clarity is more sensitive to changes in the wagon structure than the reverberation time parameters, with variations over the JND detected in 63% of both C_{50} and C_{80} results.

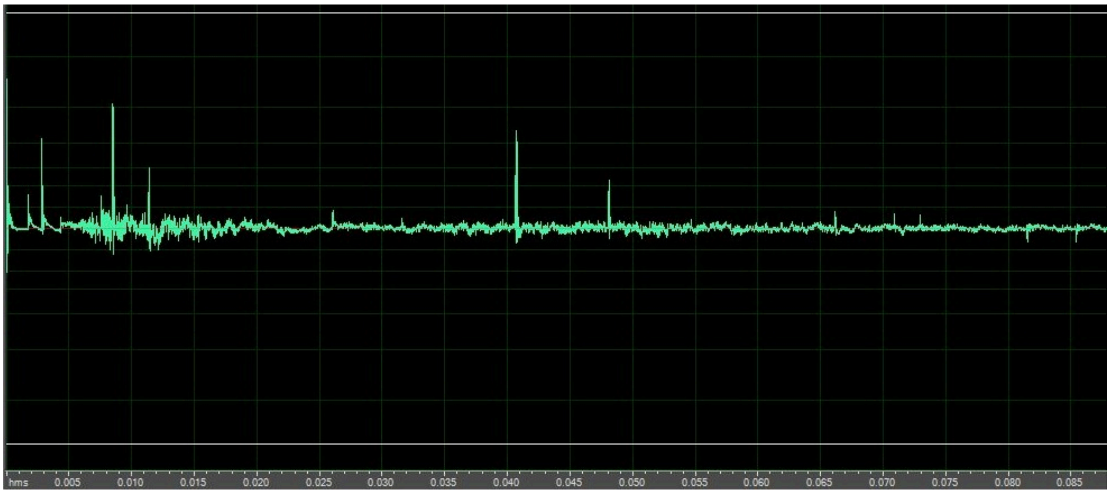


Figure 5.15 – Impulse Response corresponding to Stonegate 2-CL-SI, B2xR2.

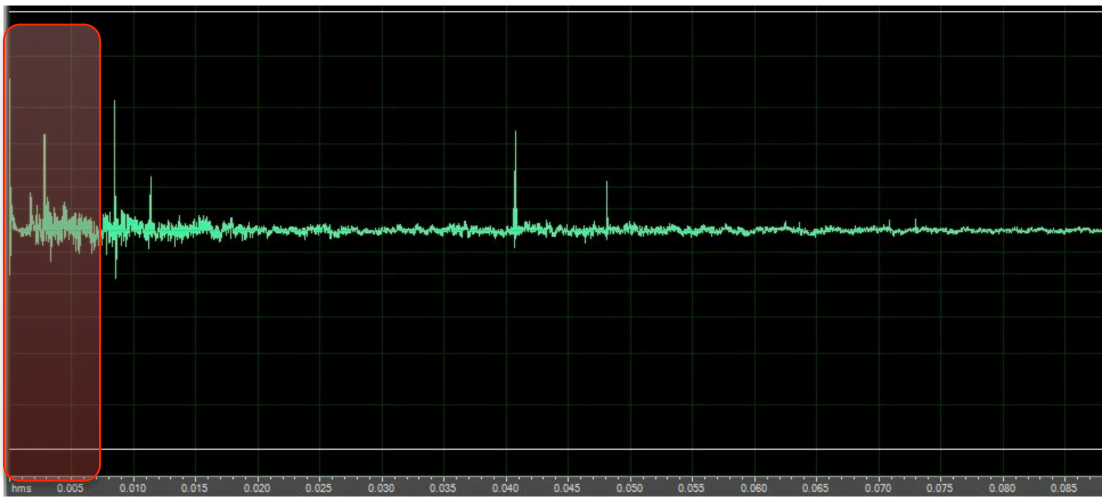


Figure 5.16 – Impulse Response corresponding to Stonegate 2-OP-SI, B2xR2. The red box indicates the larger concentration of early reflections for the OP-SI wagon.

The results for Stonegate 1, 3 and 4 demonstrate higher clarity in relation to the addition of the closed wagon to the street space. When considering Stonegate 1, notable differences are found in 46% of the results for C_{50} and C_{80} and significant differences extend from 1.02-4.26JNDs. The analysis of Stonegate 3 indicates that the results affected amount to 54% and 50% for C_{50} and C_{80} respectively and differences range between 1.09-2.46JNDs. Stonegate 4 showed notable differences in the range of 1.03-3.78JNDs and such differences affected 38% of C_{50} results and 50% of C_{80} values. Although these street spaces present higher clarity when the closed wagon is used, this is mostly applicable to the 1-16kHz-frequency range with results for lower frequency bands (125-500Hz) indicating higher clarity for the open structure.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Appendix – Tables 5.48-5.56

The analysis of the results for $IACC_{E3}$ show that significant differences caused by the change from a closed to an open wagon are found in all the virtual models but it is also evident that a higher percentage of the results are affected by these differences when the street space is modelled as closed, that is the case of Stonegate 1 and 3. LF_{E4} values suffer very little impact with the change of the wagon structure, the maximum percentage of results affected is 33% and corresponds to the use of Stonegate 4.

When studying Stonegate 1 it is possible to observe that 56% of its $IACC_{E3}$ results are affected by significant differences when alternating between wagon structures. However, there is no evident correlation between the use of one of the wagons and the increase/decrease in $IACC_{E3}$ values. Results associated with receiver 3 show that it is the use of the closed wagon that causes an increment in $IACC_{E3}$ by 1.2-1.33JNDs, which can be interpreted as a decrease in ASW. In contrast, when considering the results for B0xR1 and B2xR2 they demonstrate that it is the use of an open wagon that is the cause of higher values by 1.07-1.33JNDs. The results for

LF_{E4} indicate that only 11% of the values were affected by notable differences, the only source-receiver combination affected was B0xR2. The result for this combination indicates that the open wagon has a higher LF_{E4} by 2JNDs, which indicates a larger ASW.

The examination of Stonegate 2 proved that the only significant difference in $IACC_{E3}$ values is recorded for the source-receiver combination B1xR1, where the open wagon presents a higher value. The study of LF_{E4} results shows that there are no significant differences for any of the source-receiver combinations.

The simulation of Stonegate 3 demonstrated that $IACC_{E3}$ values presented a much higher percentage of affected results (67%) when compared to LF_{E4} results (11%). As observed for the results of $IACC_{E3}$ reported for Stonegate 1, those for Stonegate 3, although highly influenced by the change in structure, are also highly dependent on the positions of both the sound source and receiver. Higher values for the closed wagon can be observed for source-receiver combinations B0xR3, B1xR1 and B1xR3 with differences in the range of 1.07-2.67JNDs, whereas an increase in values for the open wagon are found for source-receiver combinations B0xR1, B1xR2 and B2xR2, where variations in results extend from 1.33-3.2JNDs. The LF_{E4} parameter only presents a notable difference of 1JND for source B0xR1, indicating that it is the inclusion of the closed wagon that results in a larger ASW, and therefore reaffirms the result recorded with $IACC_{E3}$.

In the case of Stonegate 4, 33% of the results of both parameters were affected by significant differences. However, there are no clear tendencies in the results as a consequence of the change in wagon structure. When considering $IACC_{E3}$ source-receiver combinations B0xR1 and B1xR2 show higher values for the open wagon by 1.33-1.47JNDs, whereas B2xR2 has a higher $IACC_{E3}$ value for the closed wagon by 1.73JNDs. Results for LF_{E4} show that higher values by 1-1.4JNDs are a consequence of the use of a closed wagon when considering the combinations B0xR1 and B0xR2, but when considering source B2xR3 it is the open wagon that has a higher value by 1.6JNDs.

Section Summary and Remarks on Results

The impact of closed and open wagons on sixteenth-century Stonegate was studied by comparing the two structures in a side-on orientation. Reverberation time results indicate that when considering Stonegate 1 it was the open wagon that had the longest reverberation time, whereas Stonegate 2 and 4 showed opposite results since in these simulations it is the use of the closed wagon that resulted in a longer reverberation time. Stonegate 3 was the least affected of the simulations and the significant differences recorded did not indicate any clear tendencies.

Clarity results showed that Stonegate 2 was the most affected and had higher clarity when the open wagon was used, although at 1-16kHz higher values for the closed wagon could also be observed. Stonegate 1, 3 and 4 exhibit higher clarity at 125-500Hz when the open wagon is used and at 1-16kHz when the closed wagon is used.

The examination of $IACC_{E3}$ and LF_{E4} showed that although both parameters presented variations in their results these did not indicate a clear tendency and were highly dependent on the source and receiver positions.

<u>On Speech</u>: The reverberation time calculated in all simulations is below that considered ideal for theatre (1s) (Barron 1993) but Stonegate 3 combined with either a closed or an open wagon in a side-on orientation are the only simulations with results within the range measured for theatres, 0.7-1.2s (Barron 1993). However, such results are only valid if windows were closed during the performances. If windows were open then it is the combination of Stonegate 4 with a closed wagon that is nearest to the acceptable range. All simulations have adequate results for clarity.

<u>On Vocal Music</u>: The reverberation time in all simulations is below the values found in spaces in which plainchant and polyphonic pieces would have been sung on a regular basis. This would have an impact both on

listeners, unaccustomed to hearing the pieces in a different acoustical setting, and performers who would have had to adapt their singing to a dryer space, which would not provide as much auditory feedback and might result in greater difficulty in maintaining a proper intonation. Such low reverberation times might also result in problems related to "ease of ensemble" (Marshall and Meyer 1985), which would have affected the performance of choral pieces.

Clarity is very high for the performance of plainchant items, although it might benefit the most complex polyphonic pieces whose rhythms would have been perceived more distinctively. Nevertheless, the high clarity is at the expense of the reverberation time and might cause discomfort to singers.

The spatial impression parameter $IACC_{E3}$ indicated that Stonegate 1 and 3 combined with a closed wagon have the lowest values of $IACC_{E3}$, which means that they present a greater perceptual broadening of the sound source. LF_{E4} values demonstrate that Stonegate 1 combined with an open wagon and Stonegate 3 combined with a closed wagon have the highest values. However, both $IACC_{E3}$ and LF_{E4} results are highly dependent on the source-receiver combination, which does not allow the tracing of general tendencies.

Model	**Range**	**Results per Parameter**					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-CL-SI	Min.	0.28s	0.31s	5.66dB	8.83dB	0.28	0.04
	Max.	0.67s	0.68s	14.89dB	21.77dB	0.68	0.12
Stonegate 1-OP-SI	Min.	0.31s	0.32s	2.88dB	5.94dB	0.38	0.05
	Max.	0.68s	0.7s	13.09dB	19.66dB	0.67	0.21
Stonegate 2-CL-SI	Min.	0.23s	0.26s	6.04dB	9.63dB	0.29	0.04
	Max.	0.60s	0.56s	18.63dB	25.5dB	0.73	0.13
Stonegate 2-OP-SI	Min.	0.25s	0.27s	6.94dB	13.05dB	0.32	0.05
	Max.	0.54s	0.52s	16.31dB	23.03dB	0.72	0.11
Stonegate 3-CL-SI	Min.	0.31s	0.35s	3.51dB	6.64dB	0.3	0.05
	Max.	0.81s	0.83s	15.22dB	20.77dB	0.63	0.13
Stonegate 3-OP-SI	Min.	0.33s	0.36s	4.19dB	7.97dB	0.42	0.05
	Max.	0.85s	0.79s	12.51dB	18.94dB	0.68	0.11
Stonegate 4-CL-SI	Min.	0.26s	0.29s	3.28dB	6.25dB	0.3	0.05
	Max.	0.68s	0.68s	17.13dB	23.77dB	0.69	0.14
Stonegate 4-OP-SI	Min.	0.29s	0.31s	5.7dB	10.00dB	0.4	0.05
	Max.	0.61s	0.6s	15.5dB	21.32dB	0.66	0.16

Table 5.3 – Range of values recorded for the CL-SI and OP-SI simulations.

Comparison between front-on wagons

A. Reverberation Time: T_{20} and T_{30}

Appendix – Tables 5.57-5.65

When considering the impact caused by the alternation between wagon structures in a front-on orientation, the percentages of results affected by significant differences are larger than those observed between the side-on structures. The most affected street simulations are Stonegate 1, 3 and 4. The three street spaces indicate that the inclusion of an open wagon results in a longer reverberation time than the addition of a closed wagon, with significant differences ranging between 1-3.33JNDs for Stonegate 1, 1-5.33JNDs for Stonegate 3 and 1-3.67JNDs for Stonegate 4. The same is observed when discussing the side-on orientation, the use of a closed wagon means that there are numerous reflections off the surfaces within the boundaries of the wagon and these are affected by the high absorption coefficients of the curtains used on the sides and back, resulting in a drop in reverberation time (see Figure 5.17). On the other hand the inclusion of an open wagon in the street space causes most reflection paths to be affected by the street façades, which have lower absorption coefficients (see Figure 5.18).

The results for the simulation of Stonegate 2 demonstrate a lesser impact due to changes to the wagon structure, with notable differences extending from 1-2.67JNDs. While reverberation time values that are higher with the use of an open wagon can be observed for sources B0-B1, B2 shows a tendency towards the increase in reverberation time when a closed wagon is included in the street space.

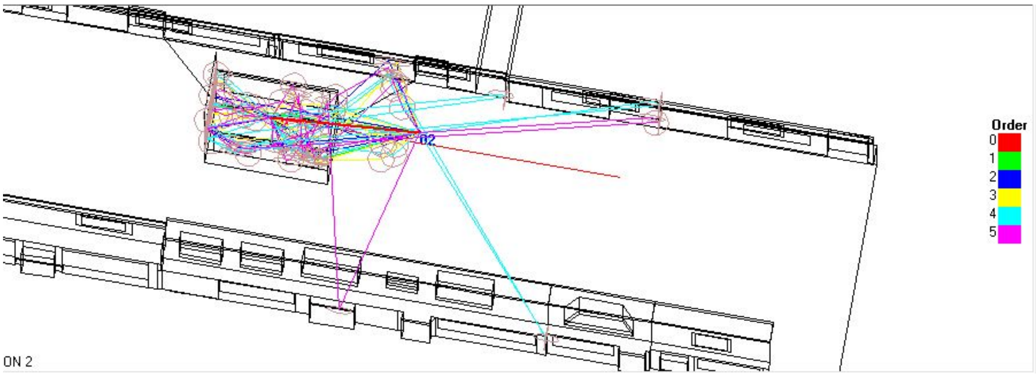


Figure 5.17 – Stonegate 1-CL-FR. All specular paths up to the fifth order for B0xR2.

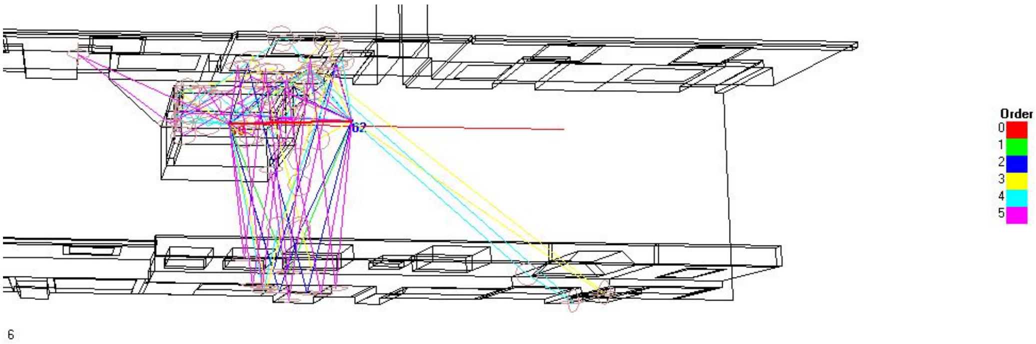


Figure 5.18 – Stonegate 1-OP-FR. All specular paths up to the fifth order for B0xR2.

B. Clarity: C_{50} and C_{80}

Appendix – Tables 5.66-5.74

All street simulations showed significant clarity differences with the change in wagon type and the parameters presented a higher sensitivity to the changes than the T_{20} and T_{30} parameters. Stonegate 2 was the most affected of the street spaces and its analysis showed that 75% of C_{50} and C_{80} results were affected by differences between 1.09-5.18JNDs. Furthermore, this 75% majority indicates higher clarity when an open wagon is used. Although the majority of the results are higher for the open wagon, the closed wagon reveals the highest results at higher frequency bands (2-16kHz).

C_{50} and C_{80} results for Stonegate 1, 3 and 4 also exhibit significant differences with the change in wagon structure but the results for these versions indicate a less clearly defined tendency as to which wagon structure results in higher clarity. Results indicate a propensity towards higher clarity at the 125-500Hz frequency range when the open wagon is added to the street space, whereas an increase in clarity at higher frequency bands (1-16kHz) is, in the majority of the cases, related to the inclusion of the closed wagon.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Appendix – Tables 5.75-5.83

The results of the parameters describing spaciousness also varied as a consequence of the change in structure. Significant differences affected 33-44% of $IACC_{E3}$ and 0-33% of LF_{E4} results. Whereas when comparing the differences between the side-on wagons it was often difficult to determine if there was a correlation between the use of a wagon structure and the results in $IACC_{E3}$ and LF_{E4} values, when comparing the front-on wagons there is a clear propensity towards an increase in $IACC_{E3}$ values, that is, a decrease in spaciousness, when the closed wagon is used. This tendency implies that it is the use of the open wagon that results in higher levels of spaciousness. The results for LF_{E4} show the same tendency but the impact of the differences on the results is less prominent.

The examination of the results for Stonegate 1 determined that higher $IACC_{E3}$ values by 2.93-3.33JNDs are associated with the use of the closed wagon and observed for B0xR2 and B0xR3. In contrast, the combination B2xR1 presents an increase by 1.87JNDs when the open wagon is included in the simulation. The only significant difference in LF_{E4} can be observed at B0xR2 and it is consistent with the result of $IACC_{E3}$ by indicating that it is the open wagon that causes an increase of the ASW.

The analysis of Stonegate 2 and 3 shows that significant differences related to the $IACC_{E3}$ parameter indicate that it is the addition of the closed wagon to the street simulations that results in an increase in values, which are in the 1.73-2JNDs range for Stonegate 2 and 1.47-2.67JNDs for Stonegate 3. These significant differences are found at source B0 combined with all receiver positions and source B2 combined with receiver 3. The LF_{E4} parameter is only affected when the wagons are combined with Stonegate 3. Furthermore, the only notable difference is found at B0xR2 and demonstrates that the open wagon has a higher value by 1JND.

$IACC_{E3}$ results for Stonegate 4 are higher by 1.07-2.27JNDs when the closed wagon is incorporated to the simulation and when considering source B0 combined with all receiver positions. Contrastingly, the open wagon has a higher $IACC_{E3}$ by 1.2JNDs at the source-receiver combination B1xR3. Results for LF_{E4} show that B0xR2 and B1xR3 exhibit an increase connected to the use of the open wagon, which extends from 1.2-1.6JNDs, whereas when B0xR3 is considered it is the closed wagon that has an increase by 1.4JNDs.

Section Summary and Remarks on Results

The comparison between the wagon structures in a front-on orientation proved that the impact of the change is larger when front-on wagons are used instead of side-on wagons. Reverberation time results were affected the most when considering Stonegate 1, 3 and 4 and it was the use of the open wagon that resulted in the longest reverberation time. However, Stonegate 2 exhibited a longer reverberation time for the open wagon only when sources B0 and B1 were used, whereas the use of source B2 resulted in higher values for the closed wagon.

Clarity values were affected the most with the simulation of Stonegate 2. Although the majority of the differences showed that the open wagon resulted in higher clarity, it was also observed that at 2-16kHz there is a predominance of higher results when the closed wagon is included in the street space. The simulations of Stonegate 1, 3 and 4 show that the inclusion of the open wagon results in higher values at 125-500Hz, whereas at 1-16kHz it is the closed wagon that has higher clarity. The analysis of $IACC_{E3}$ and LF_{E4} showed a clear correlation between the use of the open wagon and the increase in ASW.

On Speech: Reverberation time values are below 1s in all the simulations and it is Stonegate 3, both with a closed and an open wagon, which has values within the range associated with theatres. Furthermore, it is the combination with the open wagon that has the longest reverberation time. When the open models of Stonegate are examined it can be noted that it is the combination of Stonegate 4 with the open wagon that has the longest reverberation time. All clarity values in all the simulations are appropriate for speech.

On Vocal Music: As observed when analysing the side-on wagons, the reverberation time values recorded in all the computer models are lower than those generally associated with music performances. Clarity values are also above the recommended range for music. Spatial impression values seem more suitable for music, in particular when using the combination of Stonegate 3 and the open wagon, which presents $IACC_{E3}$ and LF_{E4} values associated with concert halls.

Model	Range	Results per Parameter					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-CL-FR	Min.	0.26s	0.27s	3.63dB	7.68dB	0.28	0.07
	Max.	0.64s	0.62s	19.05dB	24.94dB	0.59	0.2
Stonegate 1-OP-FR	Min.	0.28s	0.3s	5.62dB	9.29dB	0.24	0.07
	Max.	0.66s	0.65s	19.11dB	24.28dB	0.56	0.23
Stonegate 2-CL-FR	Min.	0.25s	0.26s	5.50dB	9.54dB	0.35	0.07
	Max.	0.54s	0.5s	19.62dB	25.61dB	0.61	0.17
Stonegate 2-OP-FR	Min.	0.23	0.25s	8.73dB	12.80dB	0.2	0.05
	Max.	0.51s	0.52s	20.24dB	26.68dB	0.66	0.19
Stonegate 3-CL-FR	Min.	0.30s	0.31s	2.60dB	7.02dB	0.35	0.06
	Max.	0.74s	0.75s	18.13dB	23.39dB	0.61	0.19
Stonegate 3-OP-FR	Min.	0.31s	0.32s	4.52dB	7.94dB	0.25	0.08
	Max.	0.77s	0.75s	16.61dB	22.07dB	0.55	0.16
Stonegate 4-CL-FR	Min.	0.27s	0.27s	3.83dB	9.56dB	0.27	0.06
	Max.	0.6s	0.58s	19.16dB	25.23dB	0.63	0.25
Stonegate 4-OP-FR	Min.	0.27s	0.28s	6.98dB	10.76dB	0.29	0.07
	Max.	0.62s	0.64s	19.06dB	24.14dB	0.61	0.22

Table 5.4 – Range of values recorded for the CL-FR and OP-FR simulations.

5.6.3 Acoustical Effects of Side-on and Front-on Wagon Orientations

A crucial aspect of research on the staging of the York Mystery Plays is related to the orientation of the wagons in relation to the street space. The present section reflects on the acoustical effects of side-on and front-on wagons by comparing their effects in connection to all the street space simulations. The analysis was conducted by grouping on the one hand, the closed wagons and, on the other, the open wagons. This grouping enables the study of the influence of the orientation on each type of wagon. When percentages of results affected by significant differences are reported such percentages are calculated, in the case of reverberation time and clarity, out of all the values per frequency band and source position but averaging across receivers. In the case of $IACC_{E3}$ and LF_{E4} no averaging is applied.

Comparison between different orientations of the Closed Wagon

A. Reverberation Time: T_{20} and T_{30}

Appendix – Tables 5.84-5.92

The comparison of T_{20} and T_{30} values between closed wagons with different orientations demonstrates that there are significant differences in all street simulations. Furthermore, these differences indicate a clear propensity towards higher reverberation time when a side-on orientation is used. Stonegate 1 is affected in 88% and 78% of the results for T_{20} and T_{30} respectively with significant differences ranging between 1-4.33JNDs. When considering Stonegate 2 68% of T_{20} and 63% of T_{30} results had notable differences, which were in the 1-3JNDs range. Differences in connection to Stonegate 3 showed that 85% of T_{20} and T_{30} results had differences of 1JND and above. Such differences extended from 1-4.67JNDs. Finally, the comparison between wagons in relation to Stonegate 4 resulted in notable differences present in 90% of both T_{20} and T_{30} values, and these differences were in the 1-5.67JNDs range.

B. Clarity: C_{50} and C_{80}

Appendix – Tables 5.93-5.101

Clarity was also affected by the alteration of the wagon orientation, which led to notable differences in C_{50} and C_{80} between orientations in all simulations of sixteenth-century Stonegate. In all cases differences in C_{50} and C_{80} indicated that higher clarity is linked to the use of a front-on wagon, which at the same time is a result of the drop in reverberation time when this orientation is used. Observed differences in Stonegate 1 showed that they affected 65% of C_{50} and 70% of C_{80} results, with significant differences in the range of 1.05-5.42JNDs. Results in connection to Stonegate 2 indicated that the change impacted on the results to a lesser degree, affecting 50% of C_{50} values and 55% of C_{80} results. The majority of the fluctuations in the results demonstrate a correlation between the use of a front-on wagon and an increase in clarity, with significant differences fluctuating between 1-5.88JNDs. The analysis of Stonegate 3 indicates that 78% and 83% of C_{50} and C_{80} results respectively are affected by fluctuations and notable differences extend from 1.24-5.65JNDs. Stonegate 4 was affected in 78% of its clarity values with variations ranging between 1.03-4.76JNDs.

Although all simulations evidenced higher clarity values in the majority of the results when the front-on orientation was used, they also showed a minority of results that indicated the opposite, that is, clarity increased when a side-on orientation was used. These results are concentrated at the lower frequency bands, 125-500Hz.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Appendix – Tables 5.102-5.110

The comparison of $IACC_{E3}$ and LF_{E4} values indicate significant differences in all simulations of Stonegate. The majority of these differences show that it is the inclusion of the front-on wagon within the virtual street space that results in higher spaciousness. Nevertheless, there are also some instances in which higher spaciousness is achieved through the use of a side-on wagon, especially when using receiver 2.

When analysing Stonegate 1 it can be observed that 93% and 73% of the results of $IACC_{E3}$ and LF_{E4} respectively were affected by significant differences. The majority of the results indicate higher values of $IACC_{E3}$ as a result of the use of a side-on wagon, with differences extending from 1.07-6.67JNDs, thus indicating higher spaciousness for the front-on configuration. Exceptions to this general tendency can be observed with the use of receiver 2 combined with sources B0-B2. In these cases it is the front-on wagon that has higher values of $IACC_{E3}$ with differences ranging between 1.6-4.13JNDs, indicating that it is the side-on wagon that results in an increase in ASW. Results for LF_{E4} indicate that all significant differences correspond to higher values as a result of the use of the front-on wagon and they range between 1-2.8JNDs.

Changes within Stonegate 2 amounted to 79% of $IACC_{E3}$ and 87% of LF_{E4} results. The notable differences that indicate higher $IACC_{E3}$ values when a side-on wagon is included in the street space range between 1.73-6JNDs. The only instances in which a front-on wagon has higher values are found for sources B0 and B2 combined with receiver 2. Although LF_{E4} values have a clear tendency towards an increase of 1-3JNDs when the front-on orientation is used, when considering sources B1 and B2 combined with receiver 2 it is the side-on orientation that has higher values rising by 1.2JNDs.

Stonegate 3 presented 73% of its $IACC_{E3}$ and LF_{E4} results as altered. The majority of $IACC_{E3}$ values were higher by 1.47-5.73JNDs when the side-on orientation was incorporated to Stonegate 3. Higher values for the front-on orientation coincide with the use of sources B1 and B2 combined with receiver 2 and source B2 combined with receiver 3; these values are higher by 1.33-4.13JNDs. The recorded LF_{E4} values show that when values are higher for the front-on wagon the differences range from 1.2-2.2JNDs. The combination B0xR2 is the only occurrence of a higher value, an increase of 1JND, when a side-on wagon is used.

As regards Stonegate 4, 80% and 87% of the results for $IACC_{E3}$ and LF_{E4} respectively were affected by significant differences. Those $IACC_{E3}$ values that are higher when the side-on wagon is added to the virtual model exhibit notable differences extending from 1.33-5.6JNDs. Instances in which values are higher for the front-on orientation can be observed at sources B0, B1 and B2 when combined with receiver 2, and source B2 when combined with receiver 1; the significant differences range between 1.47-3.07JNDs. Likewise, LF_{E4} values display an increase of between 1-3.8JNDs for the front-on wagon. It is only when sources B1 and B2 are combined with receiver 2 that the side-on wagon causes an increase in LF_{E4} values of 1.2-1.6JNDs.

Section Summary and Remarks on Results

The present section discussed the impact that the change in orientation of the closed wagon structure had on the acoustics of sixteenth-century Stonegate. All simulations as well as all parameters studied were affected by the change. The examination of T_{20} and T_{30} results showed that the side-on orientation resulted in a longer reverberation time. The analysis of C_{50} and C_{80} proved that the use of a front-on wagon resulted in higher levels of clarity in the performance space. Finally, the study of $IACC_{E3}$ and LF_{E4} proved that there is an increase in the ASW associated to the use of the front-on orientation.

<u>On Speech</u>: The longest reverberation time was recorded for Stonegate 3-CL-SI, with values within the range considered suitable for theatres, though below 1s. Among the simulations using an open version of Stonegate it is

Stonegate 1-CL-SI that has the higher reverberation time, including values within the recommended range for theatres. Clarity values are suitable for speech intelligibility in all the simulations.

<u>On Vocal Music</u>: Reverberation time and clarity values are outside the ranges considered suitable for music performances. $IACC_{E3}$ and LF_{E3}, on the other hand, present better results for music and Stonegate 1-CL-FR has values comparable to those recorded for concert halls.

Model	Range	Results per Parameter					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-CL-SI	Min.	0.28s	0.31s	5.66dB	8.83dB	0.28	0.04
	Max.	0.75s	0.72s	14.89dB	21.77dB	0.76	0.12
Stonegate 1-CL-FR	Min.	0.26s	0.27s	3.63dB	7.68dB	0.28	0.07
	Max.	0.64s	0.62s	19.05dB	24.94dB	0.59	0.2
Stonegate 2-CL-SI	Min.	0.23s	0.26s	6.04dB	9.63dB	0.28	0.04
	Max.	0.60s	0.56s	18.63dB	25.5dB	0.76	0.13
Stonegate 2-CL-FR	Min.	0.25s	0.26s	5.50dB	9.54dB	0.35	0.07
	Max.	0.54s	0.5s	19.62dB	25.61dB	0.61	0.17
Stonegate 3-CL-SI	Min.	0.31s	0.35s	0.42dB	3.84dB	0.3	0.05
	Max.	0.83s	0.86s	15.22dB	20.77dB	0.68	0.15
Stonegate 3-CL-FR	Min.	0.30s	0.31s	2.60dB	7.02dB	0.35	0.06
	Max.	0.74s	0.75s	18.13dB	23.39dB	0.61	0.19
Stonegate 4-CL-SI	Min.	0.26s	0.29s	2.18dB	6.25dB	0.3	0.05
	Max.	0.68s	0.68s	17.13dB	23.77dB	0.69	0.20
Stonegate 4-CL-FR	Min.	0.27s	0.27s	3.83dB	9.56dB	0.27	0.06
	Max.	0.6s	0.58s	19.16dB	25.23dB	0.63	0.25

Table 5.5 – Range of values recorded for the CL-SI and CL-FR simulations.

Comparison between different orientations of the Open Wagon

A. Reverberation Time: T_{20} and T_{30}

Appendix – Tables 5.111-5.119

Significant differences in reverberation time were observed in all simulations of Stonegate due to the change in wagon orientation but the impact this change had on the results was smaller than the same change for a wagon closed on three sides. Nevertheless, results demonstrated a clear tendency towards higher reverberation time values with a side-on wagon.

The analysis of Stonegate 1 demonstrated that the change affected 79% of T_{20} and 58% of T_{30} results. Furthermore, significant differences ranged between 1-3.67JNDs. The change in orientation applied to Stonegate 2 resulted in variations in 63% and 67% of T_{20} and T_{30} respectively, with notable variations extending from 1-3JNDs. Stonegate 3 revealed significant differences, in the 1-4JNDs range, in 79% (T_{20}) and 67% (T_{30}) of the results as a consequence of the change in orientation. The analysis of Stonegate 4 indicated that differences of 1JND or above were present in 71% of T_{20} and T_{30} results and variations extended from 1-5.33JNDs.

B. Clarity: C_{50} and C_{80}

Appendix – Tables 5.120-5.128

The change in orientation demonstrated that the front-on wagon resulted in higher clarity. Stonegate 1 was affected by changes in 71% of C_{50} and 88% of C_{80} results, with variations ranging between 1.11-5.62JNDs. Changes in Stonegate 2 could be observed in 71% and 63% of C_{50} and C_{80} results respectively and differences extended from 1.01-4.41JNDs. When analysing Stonegate 3 notable variations were observed in 63% of clarity results, and these variations were in the 1.25-5.1JND range. Stonegate 4 has significant differences, between 1.04-3.55JNDs, that affected 63% of C_{50} and 71% of C_{80} results.

Although, as it was indicated above, the larger part of the fluctuations indicates that higher clarity can be attributed to the use of a front-on wagon, it could also be observed that at low frequencies (125-250Hz), there were instances in which the use of a side-on wagon resulted in higher clarity.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Appendix – Tables 5.129-5.137

Significant differences in $IACC_{E3}$ and LF_{E4} are found in all simulations of Stonegate. These differences show a tendency towards an increase in spaciousness when a front-on wagon is used. Such tendency is represented by lower $IACC_{E3}$ and higher LF_{E4} values recorded in connection to the front-on wagon.

The analysis of Stonegate 1 demonstrates that significant differences are present in 78% of $IACC_{E3}$ and LF_{E4} results. Differences of between 1.73-4.13JNDs indicate higher $IACC_{E3}$ values for the side-on wagon. Likewise, $IACC_{E3}$ increased by 2.4JNDs for the front-on wagon using the B2xR2 combination. Increases of between 1-3JNDs in the LF_{E4} values were measured for the front-on wagon, whereas an increase of 1.2JNDs for B0xR2 meant that the side-on wagon recorded the highest results for this combination.

The analysis of Stonegate 2 shows significant differences in the range of 1.73-5.6JNDs for $IACC_{E3}$ and 1-2.2JNDs for LF_{E4}. The front-on orientation results in lower $IACC_{E3}$ values and higher LF_{E4} values. However, when considering B2xR2 the opposite can be observed; the addition of the side-on wagon to the street simulation causes lower $IACC_{E3}$ by 4.53JNDs and higher LF_{E4} by 1JND. All these significant differences affect 67% of $IACC_{E3}$ and LF_{E4} results.

Notable differences between wagon orientations affected 56% of both $IACC_{E3}$ and LF_{E4} values recorded for Stonegate 3. When considering $IACC_{E3}$, differences indicate higher values with the use of the side-on orientation, whereas all differences of LF_{E4} show an increase in values with the use of the front-on wagon. These differences extend from 1.73-5.33JNDs for $IACC_{E3}$ and 1.2-2.4JNDs for LF_{E4} values.

The study of Stonegate 4 shows that 67% of $IACC_{E3}$ and LF_{E4} results were affected as a consequence of the change in wagon orientation. Higher $IACC_{E3}$ values caused by the use of the side-on wagon are identified through notable differences in the 1.47-4.67JND range. It is also possible to observe that at B2xR2 the front-on wagon has a higher value by 4.53JNDs. LF_{E4} results present significant differences extending from 1-3.4JNDs and indicating that the use of the front-on orientation resulted in higher values. At B2xR3 it is the side-on wagon that has a higher value by 1.2JNDs.

Section Summary and Remarks on Results

This section examined the impact that the change in orientation of the open wagon had on the acoustics of sixteenth-century Stonegate. All simulations as well as all parameters studied were affected by the change. When analysing the parameters T_{20}, T_{30}, $IACC_{E3}$ and LF_{E4} it was noted that, although the use of different orientations for the open wagon resulted in significant differences, it was the change in orientation in connection to the use of the closed wagon that resulted in higher percentages of significant differences affecting the results. The examination of T_{20} and T_{30} results showed that the use of the open wagon in a side-on orientation resulted in longer reverberation times, whereas the use of the front-on orientation resulted in higher values of C_{50} and C_{80}. The study of $IACC_{E3}$ and LF_{E4} proved that there is an increase in spaciousness associated to the use of a front-on orientation.

On Speech: The longest reverberation time was recorded for the combination of Stonegate 3-OP-SI, which includes values suitable for theatres. The analysis of the models of Stonegate with open windows demonstrated that Stonegate 1-OP-SI has the highest values. All clarity results show the suitability of the space in terms of speech intelligibility.

On Vocal Music: Reverberation time and clarity results are outside the ranges deemed suitable for music performances. The spatial impression, on the other hand, seems more adequate. This is the case when combining Stonegate 1 with the open wagon in a front-on orientation, with resulting $IACC_{E3}$ and LF_{E4} values comparable to those recorded for concert halls.

Model	Range	Results per Parameter					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-OP-SI	Min.	0.31s	0.32s	2.88dB	5.94dB	0.38	0.05
	Max.	0.68s	0.7s	13.09dB	19.66dB	0.67	0.21
Stonegate 1-OP-FR	Min.	0.28s	0.3s	5.62dB	9.29dB	0.24	0.07
	Max.	0.66s	0.65s	19.11dB	24.28dB	0.56	0.23
Stonegate 2-OP-SI	Min.	0.25s	0.27s	6.94dB	13.05dB	0.32	0.05
	Max.	0.54s	0.52s	16.31dB	23.03dB	0.72	0.11
Stonegate 2-OP-FR	Min.	0.23	0.25s	8.73dB	12.80dB	0.2	0.05
	Max.	0.51s	0.52s	20.24dB	26.68dB	0.66	0.19
Stonegate 3-OP-SI	Min.	0.33s	0.36s	4.19dB	7.97dB	0.42	0.05
	Max.	0.85s	0.79s	12.51dB	18.94dB	0.68	0.11
Stonegate 3-OP-FR	Min.	0.31s	0.32s	4.52dB	7.94dB	0.25	0.08
	Max.	0.77s	0.75s	16.61dB	22.07dB	0.55	0.16
Stonegate 4-OP-SI	Min.	0.29s	0.31s	5.7dB	10.00dB	0.4	0.05
	Max.	0.61s	0.6s	15.5dB	21.32dB	0.66	0.16
Stonegate 4-OP-FR	Min.	0.27s	0.28s	6.98dB	10.76dB	0.29	0.07
	Max.	0.62s	0.64s	19.06dB	24.14dB	0.61	0.22

Table 5.6 – Range of values recorded for the CL-SI and CL-FR simulations.

5.6.4 Acoustical Effects of Different Sound Source Positions

This section explores the changes in the results for the different acoustical parameters produced by the different positions of the sound source. Thereby determining the existence of more suitable positions for the performers of the York Mystery Plays. These possible differences among sources are evaluated by considering all street spaces and all wagon configurations. When analysing simulations including the closed wagons, eight comparisons between source positions were conducted, whereas work on the open wagons are based on three sets of comparisons. These differences in the number of comparisons are related to the smaller number of sources incorporated to the simulations of the open wagons. Details on all the comparisons carried out are included in Tables 5.7-5.8.

Sound Sources Comparisons – CL-SI and CL-FR	
B0-B1	The comparison of two sound sources atop the lower wagon deck. Source B0 towards the back and source B1 towards the front.
B0-B2	The comparison of a sound source towards the back of the lower wagon deck (B0) and another one at street level (B2).
B1-B2	The comparison of a sound source towards the front of the lower wagon deck (B1) and another one at street level (B2).
B3-B4	The comparison of two sound sources atop the upper wagon deck. Source B3 towards the back and source B4 towards the front.
B2-B3	The comparison of a sound source at street level (B2) and another one towards the back of the upper wagon deck (B3).
B2-B4	The comparison of a sound source at street level (B2) with another one towards the front of the upper wagon deck (B4).
B0-B3	The comparison of two sound sources towards the back of the wagon structure, one atop the lower wagon deck (B0) and the other one atop the higher wagon deck (B3).
B1-B4	The comparison of two sound sources towards the front of the wagon structure, one atop the lower deck (B1) and the other one atop the higher wagon deck (B4).

Table 5.7 – Comparison between pairs of sound sources carried out for simulations including the closed wagons.

Sound Sources Comparisons – OP-SI and OP-FR	
B0-B1	The comparison of two sound sources atop the lower wagon deck. Source B0 towards the back and source B1 towards the front.
B0-B2	The comparison of a sound source towards the back of the lower wagon deck (B0) and another one at street level (B2).
B1-B2	The comparison of a sound source towards the front of the lower wagon deck (B1) and another one at street level (B2).

Table 5.8 – Comparison between pairs of sound sources carried out for simulations including the open wagons.

The comparisons between results for the different pairs of sources mentioned above demonstrate that significant differences in reverberation time, clarity and spaciousness can be found as a consequence of changes to the source position. The extent to which results are affected by these changes is dependent upon the simulation studied, the sources being considered as well as the frequency bands analysed. The percentages of reverberation time and clarity values affected by significant differences are computed by taking into account the results per frequency band but averaging across receiver positions. Percentages related to $IACC_{E3}$ and LF_{E4} are calculated per receiver position, with no mean values being considered.

CLOSED-SIDE ON WAGON

Appendix – Tables 5.138-5.167

Comparison of sources B0 and B1

A. Reverberation Time: T_{20} and T_{30}

Notable variations in reverberation time are observed in all street simulations when the source position moves from B0 to B1 and it is source B1 that results in higher values. In the case of Stonegate 1 these changes had significant effects on 88% of T_{20} and 25% of T_{30} values, with differences extending from 1-1.67JNDs. Changes in source position in connection to Stonegate 2 affected 50% and 38% of T_{20} and T_{30} results respectively with differences ranging between 1-3.33JNDs. Stonegate 3 had variations in the range of 1-2.67JNDs and they affected 75% of T_{20} and 25% of T_{30} results. Stonegate 4 was the most affected with 100% of T_{20} and 75% of T_{30} results presenting differences in the 1-5JND range.

B. Clarity: C_{50} and C_{80}

In terms of clarity, all significant differences indicate an increment in C_{50} and C_{80} results with the use of source B0. This is a property of the lower reverberation time calculated for source B0. Furthermore, clarity results were more sensitive to the change in source position resulting in higher percentages of the results being affected. For Stonegate 1 it is possible to observe that 75% of C_{50} and 88% of C_{80} results are affected by significant differences, which extend from 1.1-2.56JNDs. With Stonegate 2 75% of both C_{50} and C_{80} results are altered, with differences ranging between 1.73-3.15JNDs. Results for Stonegate 3 show that 88% of the values of both clarity parameters are affected, with differences extending from 1.2-4.28JNDs. All results calculated for Stonegate 4 presented significant variations in the range of 1.76-5.28JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Spatial impression parameters, $IACC_{E3}$ and LF_{E4}, were not affected to the same extent when compared to one another. $IACC_{E3}$ presented significant differences in all the simulations, whereas LF_{E4} was less sensitive to the change and was only affected when considering Stonegate 4. The majority of $IACC_{E3}$ values indicate that the use of source B1 results in a larger ASW. Stonegate 1 and 2 are only affected in connection to receiver 1 and the significant differences range between 1.2-2JNDs. The results for Stonegate 3 demonstrate that it is receiver 2 that presents a significant variation of 1.87JNDs. The analysis of Stonegate 4 shows that receiver 2 follows the common tendency by indicating an increase in ASW with the use of source B1, such tendency is indicated by the increase in $IACC_{E3}$ by 1.87JNDs with the use of source B0. However, when analysing the results for LF_{E4} the opposite can be observed, that is, the source-receiver combination B0xR2 has higher values, indicating that this combination results in a larger ASW. An additional variation in $IACC_{E3}$ results can be found for receiver 1, where it is source B1 that causes an increase in $IACC_{E3}$ of 1.07JNDs.

Comparison of sources B0 and B2

A. Reverberation Time: T_{20} and T_{30}

The impact of the change in source positions between sources B0 and B2 was also studied. This alteration had a smaller influence on the reverberation time than the previous sources comparison and indicated a tendency towards higher values when source B2 was employed. However, this was only particularly evident when Stonegate 2 was involved. When using this street simulation 63% of T_{20} and 50% of T_{30} results were affected and significant differences fluctuated by 1-4.67JNDs. Stonegate 1 was only affected when considering T_{20} and alterations in the results were only found in 38% of the recorded values. Furthermore, differences at 250Hz and 2kHz indicated higher values for source B0, whereas at 16kHz it was source B2 that had a higher reverberation time. All differences recorded were of 1JND. Stonegate 3 only had a significant variation of 1.5JNDs at 1kHz (13% of its total results), which followed the common tendency of higher values for source B2. The analysis of Stonegate 4 showed it was affected in 25% of T_{20} and T_{30} values. Notable fluctuations extended from 1-4.33JNDs and affected the 125Hz and 1kHz bands where B2 had higher results and the 500Hz band were B0 resulted in a higher reverberation time.

B. Clarity: C_{50} and C_{80}

The analysis of the differences in clarity between sources B0 and B2 demonstrated that all simulations present notable differences. Furthermore, the differences recorded in connection to Stonegate 1-3 show that it is the use of source B0 that causes an increase in clarity. In the case of Stonegate 1 38% of C_{50} results and 50% of C_{80} results were affected by the change in the source position. These variations in the results can be observed in the 2-16kHz frequency bands and extend from 1.07-1.96JNDs. The results corresponding to Stonegate 2 exhibit a larger impact on the clarity values with 88% of C_{50} and C_{80} results affected by the change. The values that are affected are found in the 250Hz-16kHz-frequency range and the differences recorded extend from 1.09-4.7JNDs. The analysis of Stonegate 3 indicates that 75% of C_{50} and 63% of C_{80} results are affected by significant differences, which range between 1.21-2.55JNDs, and can be observed in the 500Hz-16kHz-frequency range. In the case of Stonegate 4 63% of the clarity results present notable alterations with the majority corresponding to higher clarity values for source B0. These differences are concentrated in the 500Hz-16kHz-frequency range and extend from 1.28-2.86JNDs. However, at 125Hz it is source B2 that presents higher clarity by 2.2-2.78JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The analysis of $IACC_{E3}$ results demonstrates that significant fluctuations are found in all virtual models and it is source B0 that presents the higher values, which indicates that the use of this source results in a decrease in the ASW. The simulations of Stonegate 1-3 show notable differences, which range between 1-1.87JNDs, when considering receivers 1 and 2. The study of Stonegate 4 demonstrates that the only significant difference, which is of 1.47JNDs, is observed when receiver 3 is used.

The analysis of LF_{E4} demonstrates that it is the use of source B0 that causes an increase in ASW, which seems to contradict the results reported in connection to $IACC_{E3}$. Such a result is related to the fact that the LF_{E4} parameter records lower values when the receivers are closer to the source (Barron 2000), and source B2 is placed in closer proximity to the receivers than source B0. When considering Stonegate 1-3 alterations in the results are only found for receiver 1 and the differences between sources range between 1-1.2JNDs. Stonegate 4 exhibits significant differences of 1-1.2JNDs in receivers 1 and 2.

Comparison of sources B1 and B2

A. Reverberation Time: T_{20} and T_{30}

The comparison between sources B1 and B2 indicates that this change has a large impact on the reverberation time results. Stonegate 1, 3 and 4 evidence a tendency towards an increase in reverberation time when source B1 is used. Stonegate 1 is affected in 75% and 25% of its T_{20} and T_{30} results, with noteworthy differences between 1-2.67JNDs. Stonegate 3 has significant variations in 63% and 50% of the T_{20} and T_{30} values with variations in the range of 1-2.33JNDs. The comparison of the data sets for Stonegate 4 demonstrated significant variations in 88% of T_{20} and 50% of T_{30} results, with differences extending from 1-2.33JNDs. The analysis of Stonegate 2, on the other hand, indicated that results followed the opposite tendency, that is, reverberation time values increase when source B2 is used. Significant differences were found in 38% and 25% of T_{20} and T_{30} results respectively, with differences in the 1.33-2JNDs range.

B. Clarity: C_{50} and C_{80}

All street simulations presented significant differences in terms of clarity. The examination of the results for Stonegate 1, 3 and 4 indicate an increment in clarity values when source B2 is employed. Stonegate 1 has significant differences that affect 25% of its C_{50} and 38% of its C_{80} results. These differences are found at 125Hz and 500Hz-1kHz and extend from 1.06-2.08JNDs. In the case of Stonegate 3 differences affect 88% and 100% of C_{50} and C_{80} results and differences range between 1.15-2.48JNDs. For Stonegate 4 the differences affect all results and extend from 1.3-7.09JNDs. The analysis of Stonegate 2 shows that 75% of C_{50} and 50% of C_{80} results are altered due to the change in source position. Source B2 only presents higher values when considering C_{50} at 125Hz and 500Hz but source B1 is responsible for an increment in C_{50} and C_{80} values at 250Hz and 4-16kHz.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison between sources B1 and B2 in terms of spatial impression shows that notable differences are only found when studying the $IACC_{E3}$ parameter. Furthermore, these differences are concentrated in the simulations of Stonegate 2-4. The virtual models of Stonegate 2 and 3 have higher $IACC_{E3}$ values when source B1 is used. In the case of Stonegate 2 this is observed in relation to receiver 2 and the difference between sources is of 1.47JNDs. In the case of Stonegate 3 this is observed when considering receiver 3 and the difference is of 1.6JNDs. Results for Stonegate 4 demonstrate that receivers 1 and 3 have higher $IACC_{E3}$ values, of 1.47-2.13JNDs, when combined with source B1, whereas receiver 2 has a higher value of 1.33JNDs when combined with source B2.

Comparison of sources B3 and B4

A. Reverberation Time: T_{20} and T_{30}

The comparison between sources B3 and B4 also showed significant differences in all the simulations studied. Results for the reverberation time parameters indicate a clear tendency in Stonegate 1 and 2 towards a higher reverberation time when source B3 is used. Stonegate 1 is affected in 63% of T_{20} and 50% of T_{30} results and the differences recorded range between 1-3.25JNDs. The analysis of Stonegate 2 shows that 50% and 63% of T_{20} and T_{30} results are significantly altered and changes extend from 1-2.67JNDs. Although these differences indicate a propensity towards an increase in reverberation time when source B3 is used, values recorded at 250Hz and 8kHz show that at these frequency bands the use of source B3 results in a lower reverberation time. Stonegate 3 exhibits noteworthy differences in 75% and 13% of T_{20} and T_{30} results respectively. A higher reverberation time at 125Hz, 1kHz and 8-16kHz is observed when source B3 is used and all differences are of 1JND. At 250-500Hz it is source B4 that results in a longer reverberation time. Stonegate 4 is the least affected of the street simulations with only 25% of T_{20} and 13% of T_{30} results exhibiting notable differences. These differences are concentrated in the 125-500Hz bands and show that at 125Hz it is source B3 that results in a higher T_{20} by 1JND and at 250-500Hz it is source B4 that has higher values by 1.33-1.67JNDs.

B. Clarity: C_{50} and C_{80}

Significant differences in clarity are found in all the street simulations. However, there is not a clear connection between the source position and the increase/decrease in clarity. In the case of Stonegate 1 50% of C_{50} and C_{80} results are affected by notable differences. C_{50} and C_{80} values are higher for source B3 at 125Hz, with differences between sources ranging between 3.69-3.96JNDs. C_{50} also exhibits values that are higher when source B3 is used at 8-16kHz and the differences extend from 1.06-1.31JNDs. It is also possible to observe that at 125Hz for C_{50} and 250Hz-1kHz for C_{80} it is the use of source B4 that results in higher clarity values, with differences extending from 1.08-2.78JNDs. The examination of the results recorded for Stonegate 2 demonstrates that 50% of C_{50} and 25% of C_{80} results exhibit significant differences. The use of source B3 is connected to an increase in clarity at 2kHz and 8-16kHz when considering C_{50} and at 16kHz when considering C_{80}. These significant differences range between 1.03-1.78JNDs. In contrast, at 250Hz it is source B4 that causes an increase in clarity by 2.24-2.54JNDs for both C_{50} and C_{80}. When considering Stonegate 3 changes are observed in 38% of C_{50} and 25% of C_{80} results. Source B3 has a higher C_{50} by 1.33-2JNDs at 8-16kHz and a higher C_{80} by 1.52JNDs at 16kHz. At 250Hz both C_{50} and C_{80} are higher by 2.52-3.25JNDs with the use of source B4. The results for Stonegate 4 show that 50% of C_{50} and 38% of C_{80} results are affected by notable differences. Source B3 has a higher C_{50} at 2kHz and a higher C_{50} and C_{80} at 8-16kHz, differences range between 1.25-3.42JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

As regards spatial impression, $IACC_{E3}$ values exhibit significant variations in all simulations but only when receiver 2 is used. Moreover, all differences show that there is a correlation between the use of source B3 and the increase in $IACC_{E3}$ values. The examination of LF_{E4} demonstrates that only Stonegate 3 is affected by significant differences. Furthermore, these differences can only be observed when receiver 2 is used and it is the inclusion of source B4 that results in a higher LF_{E4} by 1.4JNDs.

Comparison of sources B2 and B3

A. Reverberation Time: T_{20} and T_{30}

Notable changes in reverberation time are caused by the substitution of source B2 for source B3. The virtual models of Stonegate 1, 3 and 4 show a distinct correlation between the use of source B3 and an increase in reverberation time. Stonegate 1 is affected in 88% of T_{20} and 50% of T_{30} results and deviations extend from 1-5.67JNDs. The results for Stonegate 3 present variations, which range between 1-2.67JNDs, in 63% of T_{20} and 50% of T_{30} results. The observation of results for Stonegate 4 shows that 88% of T_{20} and T_{30} results have noteworthy fluctuations within the 1-3.67JND range. In contrast to the results examined above, Stonegate 2 indicates a connection between the use of source B2 and the increase in reverberation time by 1-3.33JNDs.

B. Clarity: C_{50} and C_{80}

Differences in clarity were found at all simulations, with Stonegate 3 and 4 showing variations in all their results. The percentages of affected C_{50} results are of 13% and 75% for Stonegate 1 and 2 respectively, and when considering C_{80} both virtual models present 50% of their results affected by the change in source position. All significant differences observed for

Stonegate 1, 3 and 4 indicate higher clarity values for source B2 with differences ranging between 1.06-2.84JNDs for Stonegate 1, 1.25-5.28JNDs for Stonegate 3 and 1.66-5.12JNDs for Stonegate 4. In contrast, all significant differences found for Stonegate 2 correspond to higher clarity values when source B3 is used and the differences between sources extend from 1.23-2.46JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The change in source position had an impact in the $IACC_{E3}$ results of all the simulations. When considering receivers 1-2 all simulations indicate that it is the use of source B3 that corresponds to an increase in $IACC_{E3}$ values. This increase is of 3.47-3.6JNDs for Stonegate 1, 2.93-3.47JNDs for Stonegate 2, 2-2.53JNDs for Stonegate 3 and 1.2-3.07JNDs for Stonegate 4. When used in the context of Stonegate 1 and 2, the results for receiver 3 indicate that it is the use of source B2 that causes higher $IACC_{E3}$ values of 1.6JNDs in the case of Stonegate 1 and 1.07JNDs for Stonegate 2. Results for the LF_{E4} parameter show that only Stonegate 2 and 4 have results that have been altered due to the change in source position. Furthermore, these alterations are only found when considering receiver 2 and it is the inclusion of source B2 that results in a higher LF_{E4} of 1.4JNDs for Stonegate 2 and 1JND for Stonegate 4.

Comparison of sources B2 and B4

A. Reverberation Time: T_{20} and T_{30}

The comparison between sources B2 and B4 indicates that when combined with Stonegate 1, 3 and 4 it is source B4 that attains the higher reverberation time. In the case of Stonegate 1 only low frequencies exhibit significant changes, representing 25% and 13% of T_{20} and T_{30} results and having significant variations extending from 1.33-3.33JNDs. Stonegate 3 and 4 are affected to a larger extent, the former exhibiting significant variations in 88% and 50% of T_{20} and T_{30} values, whereas the latter displays the impact of the changes in 100% and 75% of T_{20} and T_{30} results. Variations range between 1-2.67JNDs for Stonegate 3 and 1.33-4JNDs for Stonegate 4. As in previous comparisons, Stonegate 2 is shown to present contrasting results and it is the use of source B2 that coincides with the increase in reverberation time, with variations concentrated in the 125Hz-1kHz frequency range and extending from 1-4JNDs.

B. Clarity: C_{50} and C_{80}

The analysis of clarity results shows notable differences at all simulations. The simulations of Stonegate 3 and 4 present significant differences in all their results and these differences indicate higher clarity when source B2 is employed. The differences range between 1.25-4.87JNDs for Stonegate 3 and 1.64-5.22JNDs for Stonegate 4. In the case of Stonegate 1, 38% of C_{50} and 50% of C_{80} results are affected by significant differences. Source B2 has higher C_{50} values at 125Hz and 16kHz, and higher C_{80} values at 125Hz and 8-16kHz, differences extending from 1.06-3.25JNDs. However, at 250Hz both C_{50} and C_{80} have higher values by 1.56-2.34JNDs when source B4 is used. The study of Stonegate 2 shows that 25% of C_{50} and 63% of C_{80} results are altered due to the change in source position. Furthermore, these alterations indicate that higher clarity values are achieved when source B4 is used.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison between sources B2 and B4 in terms of $IACC_{E3}$ shows significant differences for all simulations of Stonegate. Stonegate 1 and 2 are only affected in relation to receiver 1 and it is the inclusion of source B4 that results in higher $IACC_{E3}$ values of 3.2JNDs and 3.07JNDs for Stonegate 1 and 2 respectively. Stonegate 3 and 4 present notable differences for receivers 1 and 2. In Stonegate 3 both receiver positions present higher $IACC_{E3}$ values when combined with source B4, with differences between sources ranging between 1.33-2.4JNDs. In the case of Stonegate 4 a higher $IACC_{E3}$ value for receiver 1 of 2.67JNDs results from its combination with source B4, whereas receiver 2 has a higher value, by 1.33JNDs, when it is combined with source B2. The analysis of LF_{E4} results shows that only Stonegate 3 is affected by the change in source position. Additionally, it is only the result for receiver 2 that is altered, indicating a higher value of 1.2JNDs when source B4 is used.

Comparison of sources B0 and B3

A. Reverberation Time: T_{20} and T_{30}

The reverberation time is greatly affected by the change in source position from B0 to B3. Significant differences are present at all the simulations and indicate that higher reverberation times are caused by the use of source B3. The analysis of Stonegate 1 shows that 88% of T_{20} and 38% of T_{30} results have significant differences in the range of 1-5.67JNDs. The study of Stonegate 2 indicates that 63% of both T_{20} and T_{30} results are affected by dissimilarities in the range of 1-1.67JNDs. Results for Stonegate 3 show 63% and 50% of T_{20} and T_{30} results respectively, presenting notable differences, which extend from 1.5-4JNDs. Stonegage 4 exhibits notable dissimilarities in the range of 1.33-4.33JNDs in 88% of both T_{20} and T_{30} results.

The higher reverberation time recorded for source B3 is a consequence of the highly reflective wooden surface behind source B3 which results in low absorption of sound energy (see Figures 5.19). On the contrary, source B0 is in front of a highly absorbent curtained surface, which causes sound to be absorbed when bouncing off it.

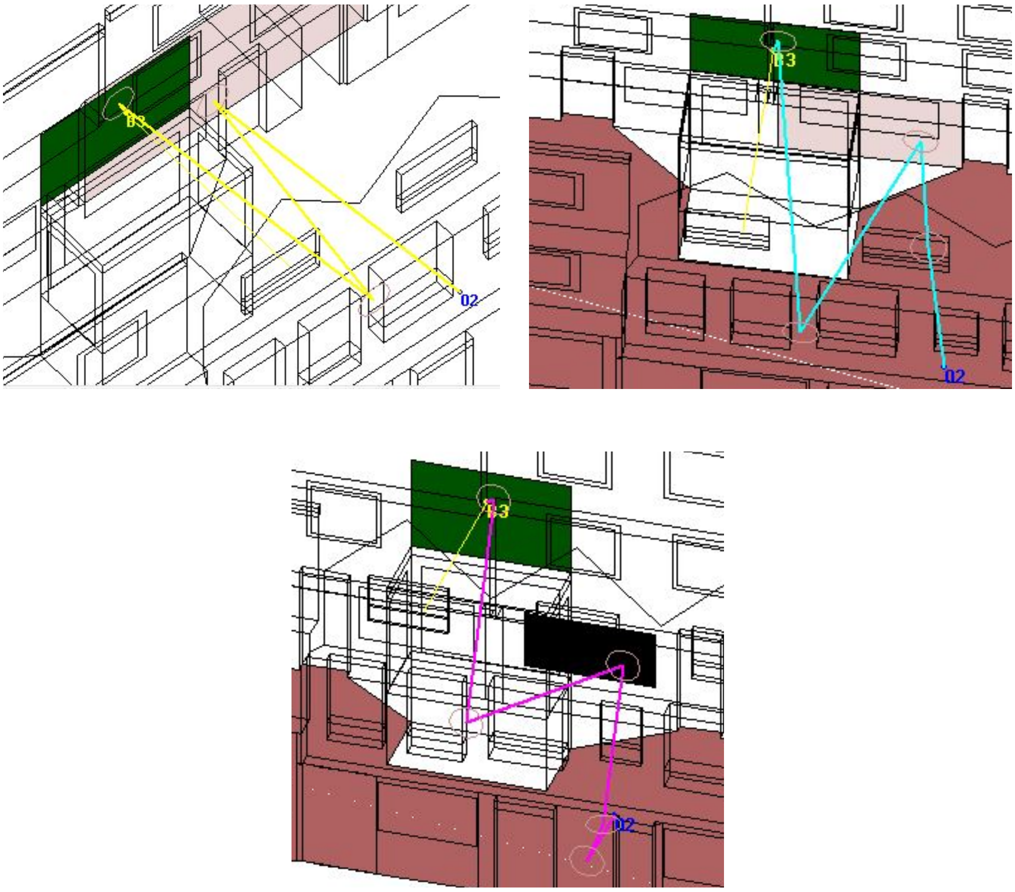


Figure 5.19 – Computer model of Stonegate 4-CL-SI showing the specular reflection paths for source-receiver combination B3xR2. Left: Third order reflection. Right: Fourth order reflection. Bottom centre: Fifth order reflection.

B. Clarity: C_{50} and C_{80}

Significant differences in clarity between sources B0 and B3 are recorded in all the street simulations. Notable alterations in the results can be observed as affecting 75% and 38% of C_{50} results for Stonegate 1 and 2 respectively, whereas both Stonegate 1 and 2 show that 88% of their C_{80} results are affected. All results recorded for Stonegate 3 and 4 are altered. All significant differences in virtual models Stonegate 2-4 indicate higher clarity values when source B0 is employed. The differences range between 1.49-2.55JNDs for Stonegate 2, 1.99-6JNDs for Stonegate 3 and 1.27-5.7JNDs for Stonegate 4. In the case of Stonegate 1 the majority of the differences also indicate higher clarity for source B0 but at 125Hz when considering C_{50} it is source B3 that has a higher value by 1.3JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Notable differences in $IACC_{E3}$ values can be observed in all the simulations. Receiver 3 and its combination with source B0 resulted in higher $IACC_{E3}$ values when used in Stonegate 1 and Stonegate 3; significant differences were of 1.33JNDs and 1.07JNDs for Stonegate 1 and 3 respectively. The observation of Stonegate 1 and 2 indicated that higher values are achieved when source B3 is used with receivers 1 and 2, with differences of 2.27JNDs for Stonegate 1 and 1.33-2.27JNDs for Stonegate 2. The analysis of Stonegate 4 indicates that it is only when combined with receiver 1 that there is a significant difference between the sources. This difference is of 2.67JNDs and it is source B3 that causes an increment in $IACC_{E3}$.

The examination of LF_{E4} shows that only Stonegate 2-4 are affected by notable differences. Furthermore, all differences demonstrate that there is a connection between the use of source B0 and the increase of LF_{E4}. Stonegate 2 only has a significant difference of 1JND in connection to receiver 1. Stonegate 3 also has a variation of 1JND but it is related to the use of receivers 1-2. Stonegate 4 recorded a significant difference of 2.2JNDs with the use of receiver 2.

Comparison of sources B1 and B4

A. Reverberation Time: T_{20} and T_{30}

Differences between sources B1 and B4 are present in all the street simulations but there is not a consistent correlation between reverberation time and changes in the source position. The examination of the results for Stonegate 1 shows that 50% of T_{20} and 38% of T_{30} comparisons indicate significant differences. At the 250Hz frequency band these differences are of 2-2.33JNDs with a higher reverberation time corresponding to the use of source B4. On the other hand, at 1-4kHz dissimilarities indicate that the addition of source B1 results in a higher reverberation time and the differences extend from 1.33-2.33JNDs. Results for Stonegate 2 only have notable differences in 38% and 25% of T_{20} and T_{30} results and in all cases these differences, which extend from 1-2.67JNDs, indicate higher values when source B1 is used. Stonegate 3 is only affected in 25% of both T_{20} and T_{30} results. At 125Hz a higher reverberation time by 2.75JNDs is caused by the employment of source B1, whereas at 500Hz and 4kHz it is the use of source B4 that results in higher values by 1.33-2JNDs. When Stonegate 4 is analysed it is noted that 50% of T_{20} and 63% of T_{30} comparisons have dissimilarities. At 125Hz the use of source B1 results in a higher reverberation time of 2-2.67JNDs. At 1-8kHz the higher reverberation time of 1-2JNDs was caused by the use of source B4.

B. Clarity: C_{50} and C_{80}

Similarly to what was observed for the reverberation time parameters, the comparison of clarity between sources B1 and B4 shows that there are significant differences at all simulations but there is not a clear indication of what source results in a higher or lower clarity. The analysis of Stonegate 1 shows that 63% of C_{50} and 38% of C_{80} results are influenced by the change in source position. The use of source B1 results in a higher C_{50} at 125Hz and 8-16kHz, with differences between sources ranging between 1.19-2.42JNDs. A higher C_{80} by 1.86JNDs for this same source can be found at 125Hz. Source B4 has a higher C_{50} at 250Hz and 1kHz, whereas C_{80} is higher at 500Hz and 1kHz, differences are in the range of 1.05-2.42JNDs. The change in source position affected 63% of the C_{50} and 25% of the C_{80} results calculated for Stonegate 2. Moreover, this simulation has a higher C_{50} value by 1.09JNDs for source B1 at 16kHz whereas the use of source B4 results in higher C_{50} values at 125Hz-1kHz and higher C_{80} values at 1-2kHz, and in these cases significant differences are in the range of 1.01-2.29JNDs. The observation of Stonegate 3 shows alterations in 63% of C_{50} and 88% of C_{80}, such alterations point towards higher clarity values when source B1 is used and they extend from 1.11-2.7JNDs. The analysis of Stonegate 4 demonstrates that 50% of C_{50} and 75% of C_{80} results are altered. Higher clarity values for source B1 can be observed when considering C_{50} at 4-16kHz and C_{80} at 1-16kHz, in these cases differences extend from 1.2-2.8JNDs. At 125Hz it is source B4 that has higher clarity values by 1.94-2.5JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The analysis of sources B1 and B4 in relation to $IACC_{E3}$ and LF_{E4} parameters demonstrates that only the former parameter exhibits variations. In all the simulations it is the use of receiver 1 in combination with source B4 that results in higher $IACC_{E3}$ values. Differences between the results of the two sources are of 3.2JNDs for Stonegate 1, 3.47JNDs for Stonegate 2, 1.33JNDs for Stonegate 3 and 1.2JNDs for Stonegate 4. The analysis of Stonegate 3 indicates alterations in the results when considering receivers 2 and 3. Receiver 2 results in higher values of $IACC_{E3}$ of 2.27JNDs when combined with source B4, whereas receiver 3 exhibits an increase by 1.73JNDs when used with source B1. Stonegate 4 has a significant difference of 1.73JNDs with higher values of $IACC_{E3}$ a result of the use of the source-receiver combination B1xR3.

Section Summary and Remarks on Results

The present section reflected on the impact of changes in source positions on the acoustics of the simulations of sixteenth-century Stonegate combined with the CL-SI wagon. Results were analysed in terms of reverberation time, clarity and spatial impression. Although all parameters recorded differences in connection to changes in source positions, LF_{E4} was the least sensitive to the changes. Furthermore, spatial impression parameters were often found to be highly dependent on the positions of the receivers, as a consequence it is not always possible to refer to a general tendency in the results.

The comparison between sources B0 and B1 indicates that longer reverberation times result from the use of source B1 and the highest clarity results from the inclusion of source B0. The majority of $IACC_{E3}$ results show that the use of source B1 causes an increment in ASW. LF_{E4} only presents a significant difference in connection to Stonegate 4 but it is source B0 that results in an increase in ASW.

The comparison of sources B0 and B2 shows a general tendency towards the increase of reverberation time with the use of source B2. However, such tendency is clear only when connected to Stonegate 2, whereas for Stonegate 1, 3 and 4 results vary depending on the frequency band. The analysis of clarity indicates that the use of source B0 and the increase in clarity are correlated. Spatial impression parameters, $IACC_{E3}$ and LF_{E4}, exhibit contrasting results, whereas $IACC_{E3}$ indicates that source B2 results in an increment in ASW, LF_{E4} indicates that it is source B0 that is responsible for the larger ASW.

The comparison between sources B1 and B2 demonstrated that whereas Stonegate 1, 3 and 4 exhibit a higher reverberation time with the use of source B1, Stonegate 2 has higher values when source B2 is used. In terms of clarity Stonegate 1, 3 and 4 have higher values when source B2 is considered. Stonegate 2, on the other hand, only has higher values for source B2 at 125 and 500Hz, whereas at 250Hz and 4-16kHz it is source B1 that results in higher clarity. $IACC_{E3}$ results show a tendency towards an increase in ASW when source B2 is used.

The analysis of sources B3 and B4 indicates that for Stonegate 1-2 it is source B3 that results in a higher reverberation time. Results for Stonegate 3-4 show that at 125Hz it is source B3 that has the highest values, whereas for 250-500Hz it is source B4 that has the longest reverberation time. Variations in clarity do not exhibit a clear connection with the change of source positions. The examination of the spatial impression parameters indicates that significant changes apply only to receiver 2 and indicate an increment in ASW as a consequence of the use of source B4.

The study of sources B2 and B3 showed that Stonegate 1, 3 and 4 recorded a longer reverberation time for source B3 but a higher clarity for source B2. In the case of Stonegate 2 the opposite is true, longer reverberation times are related to source B2 and higher clarity is the result of using source B3. The analysis of spatial impression indicates that receivers 1 and 2 record greater spaciousness when source B2 is used, whereas for receiver 3 it is source B3 that shows an increase in ASW.

The comparison of sources B2 and B4 shows that Stonegate 1, 3 and 4 have a longer reverberation times when source B4 is used. In contrast, Stonegate 2 has a longer reverberation time when source B2 is included in the simulation. The majority of clarity values for Stonegate 1, 3 and 4 are higher when source B2 is used but in the case of Stonegate 2 it is the inclusion of source B4 that increases clarity. The larger part of the spatial impression results indicate that source B2 is responsible for the increase in spaciousness.

The examination of sources B0 and B3 demonstrated that longer reverberation time values correspond to source B3, whereas higher clarity is related to source B0. Spatial impression results improve when source B0 is used and are related to receivers 1 and 2.

The comparison between sources B1 and B4 does not show a clear correlation between a source position and the increase/decrease of reverberation time and clarity results. $IACC_{E3}$ values indicate that receivers 1 and 2 recorded greater spaciousness when source B1 is used, whereas receiver 3 results in greater spaciousness with source B4.

<u>On Speech</u>: The highest reverberation time was recorded for Stonegate 3 when using source B3. The results include values within the range considered appropriate for theatres. When considering the open versions of the street space it is Stonegate 4 that has the highest values when source B1 is used but these values are below 0.7s. Clarity is suitable for speech intelligibility in all the simulations and source positions.

<u>On Vocal Music</u>: Reverberation time and clarity results are outside the range considered suitable for music. However, Stonegate 3 combined with source B3 presents the most appropriate combination, with higher reverberation time and lower clarity. The parameters for spatial impression indicated suitable characteristics for Stonegate. When considering $IACC_{E3}$ values

comparable to those found in concert halls were recorded for Stonegate 3 when using sources B0 and B2 and for Stonegate 4 when using source B2. LF_{E4} results demonstrated suitable spaciousness for music when considering Stonegate 1 and 2, using source B0 and Stonegate 3 and 4, when using sources B0 and B1.

Model	Range	Results per Parameter – CL-SI					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-B0	Min.	0.28s	0.31s	5.76dB	10.09dB	0.38	0.09
	Max.	0.67s	0.67s	14.89dB	21.77dB	0.66	0.11
Stonegate 1-B1	Min.	0.33s	0.33s	5.66dB	8.93dB	0.32	0.05
	Max.	0.67s	0.68s	13.68dB	19.21dB	0.64	0.12
Stonegate 1-B2	Min.	0.31s	0.31s	5.75dB	9.87dB	0.28	0.04
	Max.	0.66s	0.67s	13.29dB	19.81dB	0.68	0.11
Stonegate 1-B3	Min.	0.32s	0.33s	5.61dB	8.19dB	0.55	0.05
	Max.	0.75s	0.72s	13.37dB	18.68dB	0.76	0.08
Stonegate 1-B4	Min.	0.31s	0.32s	4.16dB	7.07dB	0.35	0.05
	Max.	0.70s	0.68s	11.93dB	18.34dB	0.74	0.08
Stonegate 2-B0	Min.	0.23s	0.26s	7.82dB	13.15dB	0.38	0.09
	Max.	0.50s	0.50s	18.63dB	25.5dB	0.66	0.10
Stonegate 2-B1	Min.	0.28s	0.29s	7.15dB	12.30dB	0.4	0.07
	Max.	0.56s	0.51s	15.58dB	22.41dB	0.73	0.13
Stonegate 2-B2	Min.	0.28s	0.28s	6.04dB	9.63dB	0.28	0.04
	Max.	0.60s	0.56s	13.82dB	20.8dB	0.68	0.11
Stonegate 2-B3	Min.	0.27s	0.27s	7.71dB	11.12dB	0.55	0.05
	Max.	0.54s	0.53s	16.34dB	23.26dB	0.76	0.08
Stonegate 2-B4	Min.	0.29s	0.29s	8.26dB	12.44dB	0.35	0.05
	Max.	0.51s	0.50s	14.38dB	21.86dB	0.74	0.08
Stonegate 3-B0	Min.	0.31s	0.35s	5.16dB	8.34dB	0.44	0.09
	Max.	0.78s	0.78s	15.22dB	20.77dB	0.58	0.13
Stonegate 3-B1	Min.	0.39s	0.39s	3.51dB	6.64dB	0.3	0.08
	Max.	0.81s	0.79s	11.32dB	16.49dB	0.63	0.12
Stonegate 3-B2	Min.	0.32s	0.35s	5.18dB	8.15dB	0.3	0.05
	Max.	0.80s	0.83s	12.95dB	18.22dB	0.51	0.09
Stonegate 3-B3	Min.	0.42s	0.41s	0.42dB	3.84dB	0.49	0.05
	Max.	0.86s	0.83s	10.75dB	15.31dB	0.65	0.08
Stonegate 3-B4	Min.	0.39s	0.40s	3.1dB	5.53dB	0.4	0.08
	Max.	0.84s	0.84s	8.55dB	13.79dB	0.68	0.15
Stonegate 4-B0	Min.	0.26s	0.3s	7.3dB	10.56dB	0.44	0.09
	Max.	0.6s	0.6s	17.13dB	23.77dB	0.64	0.2
Stonegate 4-B1	Min.	0.35s	0.35s	3.28dB	6.25dB	0.3	0.08
	Max.	0.68s	0.68s	12.73dB	18.49dB	0.69	0.12
Stonegate 4-B2	Min.	0.28s	0.29s	7.44dB	11.44dB	0.4	0.05
	Max.	0.66s	0.61s	15.39dB	20.91dB	0.53	0.14
Stonegate 4-B3	Min.	0.34s	0.34s	2.18dB	6.32dB	0.49	0.06
	Max.	0.67s	0.66s	13.41dB	18.82dB	0.7	0.09
Stonegate 4-B4	Min.	0.35s	0.35s	5.2dB	8.19dB	0.3	0.05
	Max.	0.67s	0.64s	9.65dB	15.82dB	0.67	0.12

Table 5.9 – Range of results recorded for the CL-SI wagon.

CLOSED-FRONT ON WAGON

Appendix – Tables 5.168-5.197

Comparison of sources B0 and B1

A. Reverberation Time: T_{20} and T_{30}

The comparison of sources B0 and B1 indicates significant differences in terms of reverberation time. Results for Stonegate 1, 3 and 4 indicate a clear tendency towards a higher reverberation time when source B1 is used. Stonegate 1 is affected by significant differences in 75% of T_{20} and T_{30} results and differences between sources extend from 1-2.67JNDs. Results for Stonegate 3 show notable differences ranging between 1-3JNDs and affecting 88% of T_{20} and T_{30} values. For Stonegate 4, significant changes are observed in 25% of T_{20} and T_{30} results with differences ranging from 1-6.33JNDs. Moreover, at 1kHz it is source B0 that causes an increase in T_{20} of 1.67JNDs. Stonegate 2 varies significantly in 25% of T_{20} and T_{30} results but tends towards an increase in reverberation time when source B0 is used. This can be observed at 125Hz and 500Hz where the differences are of 1-1.33JNDs, whereas at 1kHz a higher reverberation time by 1JND is caused by source B1.

B. Clarity: C_{50} and C_{80}

When considering the differences in clarity between sources B0 and B1, it is the use of source B0 that, in the majority of the cases, was correlated to an increase in clarity. In the case of Stonegate 1 all notable differences follow this tendency. Moreover, these differences affect 75% of C_{50} and C_{80} results and the differences extend from 1.41-4.61JNDs. For Stonegate 2-4, the increase in clarity due to the inclusion of source B0 is particularly evident in the 500Hz-16kHz frequency bands, however, in the 125-250Hz bands it is possible to observe an increase in values when source B1 is used.

Results for Stonegate 2 showed that 88% of clarity values were affected, whereas for Stonegate 3 the percentages of results affected amounted to 100% of C_{50} and 88% of C_{80} results. The differences recorded at 500Hz-16kHz, which indicate higher values for B0, ranged between 1.03-2.67JNDs for Stonegate 2 and 1.13-3.78JNDs for Stonegate 3. At low frequencies (125-250Hz) the differences demonstrated that longer reverberation times result from the use of source B1; the differences for Stonegate 2 extend from 1.15-1.28JNDs, whereas for Stonegate 3 they range between 1.1-1.27JNDs. Stonegate 4 was the least affected of the simulations with 63% of C_{50} and 38% of C_{80} results presenting variations of 1JND or over. In this simulation higher values for source B0 are observed at 4-16kHz with differences ranging between 1.14-2.21JNDs and 1.16-1.95JNDs for C_{50} and C_{80} respectively. At 125Hz it is also B0 that has a higher value by 1.55JNDs for C_{50}, whereas at 250Hz source B1 results in an increment of C_{50} by 1.74JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison of sources B0 and B1 in terms of spatial impression shows that $IACC_{E3}$ is more sensitive to the changes in source position presenting significant differences in all the simulations. However, these differences only affect receiver 3 and it the use of source B0 that results in an increase of $IACC_{E3}$ values of 1.33-2.8JNDs. When considering LF_{E4} notable fluctuations can only be found for Stonegate 3 and 4. Results for Stonegate 3 show that only receiver 1 has a notable change, which indicates a higher value for source B0 by 1JND. Results for Stonegate 4 show that it is receiver 3 that is affected and once more it is source B0 that has a higher value by 1.8JNDs. This last result shows contradicting results between $IACC_{E3}$ and LF_{E4}. While $IACC_{E3}$ indicates that receiver 3 records a higher level of spaciousness when source B1 is used, LF_{E4} shows that it is source B0 that results in higher levels of spaciousness for receiver 3.

Comparison of sources B0 and B2

A. Reverberation Time: T_{20} and T_{30}

The alternation between sources B0 and B2 also had an impact on the reverberation time. When considering Stonegate 1-3, it is the inclusion of source B2 that results in higher values. The analysis of Stonegate 1 indicated that 38% of its T_{20} and T_{30} results have notable dissimilarities extending from 1-3.67JNDs. Although these differences show the general tendency of source B2 to achieve higher reverberation times, these results concentrate in the 125Hz-1kHz-frequency range and at 1kHz T_{20} is higher by 1JND when source B0 is employed. Results for Stonegate 2 are only affected when studying T_{20} and they amount to 50% of T_{20} results; significant differences are in the 1-2.33JND range. The study of Stonegate 3 shows significant variations in 50% and 25% of T_{20} and T_{30} results respectively, with differences between data sets extending from 1-3.33JNDs. When considering Stonegate 4, 50% and 25% of its T_{20} and T_{30} results are noted as having significant fluctuations. Moreover, it is the use of source B0 that causes an increase in reverberation time by 1-2.33JNDs, although at 250Hz T_{20} has a higher value when source B2 is used, the difference between values being of 1.67JNDS.

B. Clarity: C_{50} and C_{80}

When comparing C_{50} and C_{80} values between sources B0 and B2 all simulations present results with significant differences. Moreover, all computer models show a clear tendency towards higher clarity when source B2 is used. When analysing the results for Stonegate 1 and 2 it can be observed that 63% of C_{50} and 50% of C_{80} results are affected by significant differences. These differences are found in the 125Hz-2kHz-frequency range and in the case of Stonegate 1 they extend from 1.21-5.06JNDs, whereas in the case of Stonegate 2 they range between 1.05-5.97JNDs. Although both Stonegate 1 and 2 follow the general tendency towards higher clarity values for source B2, in the case of Stonegate 2 at 16kHz it is source B0 that evidences an increment in C_{50} by 1JND. When considering Stonegate 3 and 4 they both present significant differences in the 125Hz-8kHz frequency bands. These differences in Stonegate 3 affect 88% of its C_{50} and C_{80} results and they range between 1.24-4.02JNDs. The differences in Stonegate 4, which extend from 1.12-5.31JNDs, affect 63% of C_{50} and 88% of C_{80} values.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The analysis of sources B0 and B2 demonstrated that the change had an impact on the $IACC_{E3}$ values of all the simulations of Stonegate. Moreover, in Stonegate 2-4 all receiver positions are affected by notable differences, which indicate higher $IACC_{E3}$ values when source B2 is employed, with differences ranging between 1.07-2.13JNDs. Stonegate 1 only presents significant differences for receivers 2 and 3. For receiver 2 it is source B2 that has a higher $IACC_{E3}$ value by 1.2JNDs, whereas for receiver 3 it is source B0 that has a higher value by 1.07JNDs.

The results for LF_{E4} demonstrate that only Stonegate 2 and 4 were affected and it is the inclusion of source B0 that resulted in higher values of LF_{E4}. In the case of Stonegate 2 only receiver 1 is affected and the difference between sources is of 1.2JNDs, whereas for Stonegate 4 only receiver 3 is altered and the difference is of 2.8JNDs.

Comparison of sources B1 and B2

A. Reverberation Time: T_{20} and T_{30}

The comparison of T_{20} and T_{30} for sources B1 and B2 demonstrated that the simulations of Stonegate 1, 3 and 4 have, in the majority of the cases, a higher reverberation time when source B1 is used. Stonegate 1 and 3 were affected by significant differences in 88% of T_{20} and 63% of T_{30} results, with differences in the range of 1-2.67JNDs for Stonegate 1 and 1-

3.3JNDs for Stonegate 3. Although, as it was indicated above, the use of source B1 results in higher values, at 125 and 500Hz it is source B2 that results in an increment by 1-2.33JNDs when considering Stonegate 1 and 1-2.63JNDs when considering Stonegate 3. Stonegate 4 presents notable variations in the 1-6.67JND range affecting reverberation time values in 50% of T_{20} and T_{30} results. In this simulation it is once more possible to observe a strong correlation between the use of source B1 and an increment in the reverberation time, although it is also possible to note that source B2 causes an increment in reverberation time by 1-2JNDs at 250-500Hz. Stonegate 2 is the least affected of the simulations since it only presents significant differences in 25% and 13% of T_{20} and T_{30} results. These variations between sources extend from 2-3JNDs and evidence longer decay times for source B2 at 125 and 500Hz.

B. Clarity: C_{50} and C_{80}

The comparison between sources B1 and B2 exhibits significant differences that indicate that the use of source B2 results in higher clarity. Furthermore, these differences are present in all simulations and at all frequency bands, the only exception being Stonegate 3 which, when considering C_{80}, at 125Hz presents a difference below 1JND. Significant differences range between 2.69-5.54JNDs for Stonegate 1, 1.27-4.69JNDs for Stonegate 2, 2.23-5.02JNDs for Stonegate 3 and 1.71-5.3JNDs for Stonegate 4.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison of sources B1 and B2 indicates that significant differences in $IACC_{E3}$ are found in all the simulations and all differences show that the use of source B2 results in higher $IACC_{E3}$ values. Stonegate 2-4 exhibit differences in all the receiver positions and differences between sources range between 1.47-3.07JNDs for Stonegate 2, 1.73-3.47JNDs for Stonegate 3 and 1.33-4.4JNDs for Stonegate 4. Stonegate 1 only exhibits notable variations when using receivers 2 and 3 and the differences extend from 1.47-1.73JNDs.

The examination of the results for LF_{E4} show that this parameter is much less sensitive to the change and notable alterations in the results are only observed for Stonegate 2 and 4, where it is the use of source B1 that is connected to the increase in LF_{E4}. In the case of Stonegate 2 it is only receiver 1 that is affected and the difference between sources is of 1.6JNDs, whereas when considering Stonegate 4 it is receiver 3 that is affected and the difference is of 1JND.

Comparison of sources B3 and B4

A. Reverberation Time: T_{20} and T_{30}

Significant differences in reverberation time between sources B3 and B4 are concentrated in the 125Hz-1kHz-frequency range. When considering Stonegate 1, 3 and 4 these differences show that an increment in reverberation time is caused by the use of source B3. In Stonegate 1 these differences range between 1-2JNDs and influence 38% of T_{20} and 25% of T_{30} results. The impact on Stonegate 3 is smaller, with only 13% and 25% of the results being affected and the variations extending from 1.25-1.5JNDs. Significant differences in Stonegate 4 can be found in 13% and 18% of T_{20} and T_{30} results. The increase in values resulting from the incorporation of source B3 to the virtual model can be seen at 250-500Hz with differences in the 1-1.33JND range. An increase in reverberation time of 2JNDs due to the use of source B4 is observed at 125Hz. The analysis of Stonegate 2 indicates that 50% of T_{20} and 38% of T_{30} results are significantly altered with the change in source position. Furthermore, these results only follow the common tendency at 125Hz, where a longer reverberation time is the result of the use of source B3. The remaining differences show that the use of source B4 results in higher values of 1-1.67JNDs.

B. Clarity: C_{50} and C_{80}

Notable differences in clarity results between sources B3 and B4 are observed in all the street simulations. These differences indicate a tendency towards higher values for source B4 when Stonegate 1, 3 and 4 considered. However, these differences have a very small impact on the total results. In the case of Stonegate 1 results are only affected in connection to C_{50} at 4kHz where the difference between sources is of 1.23JNDs. The analysis of Stonegate 3 shows that only 13% of both C_{50} and C_{80} values are affected by significant differences, which can be observed at 125Hz and 1kHz and range between 1.28-2.41JNDs. Results for Stonegate 4 demonstrate that 13% of C_{50} and 38% of C_{80} results were altered. Such results are in the 125-250Hz and 4kHz frequency bands and differences range between 1.08-4.75JNDs. The examination of the results for Stonegate 2 shows that, on the one hand, it followed the tendency of the rest of the virtual models by presenting an increase in C_{50} by 1.08JNDs at 500Hz as a result of the use of source B4. On the other hand, it has a higher C_{50} by 1.14JNDs for source B3 at 16kHz and a higher C_{80} by 1.12-1.25JNDs at 125Hz and 16kHz.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison of sources B3 and B4 in terms of $IACC_{E3}$ shows that only Stonegate 3 exhibits significant differences between sources. Moreover, it is receiver 1 that is affected and it is source B3 that causes an increase in $IACC_{E3}$ of 1.07JNDs. When considering LF_{E4} notable variations can be observed in Stonegate 1 and 2. Stonegate 1 is affected in relation to receivers 1 and 2; when using receiver 1 it is source B4 that has a higher LF_{E4} of 1.2JNDs, whereas when using receiver 2 it is source B3 that has a higher value by 1JND. Stonegate 2 only has an alteration regarding LF_{E4} when receiver 2 is used and it is source B3 that results in a higher value of 1.4JNDs.

Comparison of sources B2 and B3

A. Reverberation Time: T_{20} and T_{30}

The analysis of the differences between sources B2 and B3 shows a significant impact in all simulations, in particular Stonegate 1, 3 and 4. In these simulations a higher reverberation time is caused by the use of source B3, the only exception being Stonegate 1 at 125Hz. When considering Stonegate 1 88% of T_{20} and 63% of T_{30} results are affected and differences extend from 1-2JNDs. Stonegate 3 has significant variations in 88% and 100% of its T_{20} and T_{30} results respectively, with fluctuations ranging between 1-4.33JNDs. Stonegate 4 has significant differences in 75% and 88% of T_{20} and T_{30} values. These differences range between 1-2.33JNDs. Results for Stonegate 2 present notable differences in only 25% of T_{20} and T_{30} results. It is only at 250Hz that the use of source B3 results in a higher value by 1JND. The majority of the differences, between 1-2.67JNDs, indicate that source B2 results in a higher reverberation time.

B. Clarity: C_{50} and C_{80}

Notable fluctuations in clarity between sources B2 and B3 are found across all simulations and the impact on the results ranges between 88-100%. All significant differences recorded for Stonegate 1, 3 and 4 indicate higher clarity values for source B2 with differences ranging between 1.27-6JNDs for Stonegate 1, 1.12-7.04JNDs for Stonegate 3 and 1.18-6.68JNDs for Stonegate 4. Although Stonegate 2 evidences a majority of values with higher clarity for source B2, which are concentrated in the 250Hz-16kHz-frequency range and have differences extending from 1.92-3.98JNDs, it also presents a higher C_{50} and C_{80} by 1.39-1.42JNDs for source B3 at 125Hz.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

All simulations of Stonegate present notable differences in $IACC_{E3}$ between sources B2 and B3. All differences indicate that it is source B2 that presents higher values. Stonegate 1 exhibits values that are altered due to the change in source position only when considering receivers 1-2 and differences between sources range between 2-4.4JNDs. When examining Stonegate 2-4 all receiver positions are affected by the change and differences extend from 2.93-4.8JNDs for Stonegate 2, 3.2-4.53JNDs for Stonegate 3 and 3.6-5.33JNDs for Stonegate 4.

The analysis of LF_{E4} shows that all simulations are affected by the change in source position and it is source B3 that results in an increase in LF_{E4} values. Stonegate 1 and 3 only exhibit notable differences for receiver 2 and these differences are of 2JNDs for Stonegate 1 and 2.6JNDs for Stonegate 3. Results recorded for Stonegate 2 and 4 have variations for receivers 1 and 2; differences ranging between 1.6-2.2JNDs for Stonegate 2 and 2-2.8JNDs for Stonegate 4.

Comparison of sources B2 and B4

A. Reverberation Time: T_{20} and T_{30}

Notable differences between sources B2 and B4 are observed in all simulations of Stonegate. Although there are instances in which a higher reverberation time is achieved through the use of source B2, the majority of the results demonstrate that it is the use of source B4 that results in higher values in all simulations. The analysis of Stonegate 1 shows that 88% of T_{20} and 50% of T_{30} results are affected by significant variations between sources, with differences ranging between 1-2JNDs. Stonegate 2 is the least affected of the virtual models with 38% of T_{20} and 25% of T_{30} results affected by the change in source position and the fluctuations are in the 1-2JND range. When considering Stonegate 3 fluctuations in reverberation time are seen to impact on 75% of T_{20} and T_{30} results and these fluctuations range between 1.33-3.67JNDs. Stonegate 4 is affected in 63% of T_{20} and 88% of T_{30} results by 1-3.67JNDs.

B. Clarity: C_{50} and C_{80}

The analysis of the results for sources B2 and B4 shows significant differences in all the simulations, with the percentage of results affected ranging from 88-100%. All notable differences in Stonegate 1 and 3 indicate higher clarity for source B2, with differences extending from 1.56-6.31 for Stonegate 1 and 1.74-6.68JNDs for Stonegate 3. Stonegate 2 and 4 also present differences between sources that indicate that the increase in C_{50} and C_{80} is connected to the use of source B2. These differences range between 1.07-5.23JNDs and 1.93-5.96JNDs for Stonegate 2 and 4 respectively. However, at 125Hz it is source B4 that results in a higher C_{50} by 2.04JNDs for Stonegate 2 and 2.1JNDs for Stonegate 4.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

When considering sources B2 and B4 notable fluctuations of $IACC_{E3}$ values can be observed in all the street simulations. All significant differences indicate that there is a strong correlation between the use of source B2 and the increase of $IACC_{E3}$ values. Stonegate 1 is affected in connection to receivers 1-2 and significant differences range between 2.4-4.27JNDs. Stonegate 2 exhibits differences in relation to receivers 1 and 3 and these differences extend from 2.93-3.87JNDs. Results for Stonegate 3 and 4 demonstrate that all receiver positions are affected and differences range between 3.73-4.4JNDs for Stonegate 3 and 3.2-4.4JNDs for Stonegate 4.

LF_{E4} results show that the inclusion of source B4 results in an increase in values. Stonegate 1 and 4 are affected by significant differences between sources for receivers 1-2 and differences are of 1JND for Stonegate 1 and 2-2.2JNDs for Stonegate 4. Stonegate 2 is only affected in relation to receiver 1 with a variation between sources of 1.8JNDs, whereas Stonegate 3 is only affected when receiver 2 is used and the difference is of 2.4JNDs. The results for both $IACC_{E3}$ and LF_{E4} show that an increase in the ASW is achieved through the use of source B4.

Comparison of sources B0 and B3

A. Reverberation Time: T_{20} and T_{30}

The comparison between sources B0 and B3 shows significant differences in all simulations of Stonegate. The analysis of these differences demonstrates a strong correlation between the use of source B3 and the increase in reverberation time. The examination of the results for Stonegate 1 demonstrates that significant variations affect 88% and 63% of T_{20} and T_{30} results by 1-3JNDs. Stonegate 2 is the least affected simulation with only 25% and 38% of T_{20} and T_{30} results affected by differences ranging between 1.33-2JNDs. The analysis of Stonegate 3 shows that 88% of T_{20} and T_{30} values have variations of 1-6.33JNDs. For Stonegate 4 significant differences affected 63% of T_{20} and T_{30} results and differences extended from 1-3.33JNDs.

B. Clarity: C_{50} and C_{80}

The comparison of sources B0 and B3 indicates that there are significant differences in clarity values in all the simulations. The analysis of Stonegate 1 and 2 demonstrates that 88% of C_{50} and C_{80} results are affected by significant differences. When considering Stonegate 3 75% of C_{50} and 63% of C_{80} results are affected, whereas for Stonegate 4 differences have an impact on 88% of C_{50} and 75% of C_{80} values. The results for Stonegate 1-3 indicate that in the 1-16kHz-frequency range it is the use of source B0 that results in higher clarity. The differences at these frequency bands extend from 1.21-5.99JNDs for Stonegate 1, 1.4-4.98JNDs for Stonegate 2 and 2.78-6.17JNDs for Stonegate 3. Stonegate 4 not only exhibits an increase in clarity with the use of source B0 at 1-16kHz but it also shows this tendency at 125Hz and the differences between sources ranges between 1.02-5.87JNDs. It can also be observed that at lower frequency bands the use of source B3 results in an increase in clarity. The examination of the results for Stonegate 1 demonstrates that C_{50} and C_{80} values are higher by 3.05-3.63JNDs at 125-250Hz when source B3 is used. Additionally, C_{80} also follows this tendency at 500Hz where source B3 is higher by 1.01JNDs. The use of source B3 results in higher clarity, by 2.72-4.7JNDs, when combined with Stonegate 2 at 125-250Hz. Stonegate 3 and 4 have a higher C_{50} associated with the use of source B3 only at 250Hz, with differences between sources ranging between 1.83-2.05JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Notable differences between $IACC_{E3}$ values for source positions B0 and B3 are observed at all simulations as well as all receiver positions. Furthermore, it is source B0 that results in an increase in values. Significant differences between sources range from 1.73-3.2JNDs for Stonegate 1, 1.2-3.6JNDs for Stonegate 2, 1.6-2.93JNDs for Stonegate 3 and 1.87-4.27JNDs for Stonegate 4.

The analysis of LF_{E4} results shows that differences can be observed in all simulations. When considering receiver 2 it is source B3 that results in an increase in values; this is observed for all simulations and differences are of 1.4JNDs for Stonegate 1, 2.2JNDs for Stonegate 2 and 3 and 2JNDs for Stonegate 4. In contrast, results connected to receiver 3 are higher when using source B0. Such differences are of 1.4JNDs and 2.2JNDs for Stonegate 1 and 4 respectively. The use of receiver 1 is connected to changes in LF_{E4} in Stonegate 3-4. In the case of Stonegate 3 it is source B0 that causes an increase in values, whereas in Stonegate 4 it is its combination with B3 that results in an increase in LF_{E4}.

Comparison of sources B1 and B4

A. Reverberation Time: T_{20} and T_{30}

Notable differences between sources B1 and B4 are observed in all the simulations and, in the majority of the cases, these differences indicate higher reverberation times for source B4. The only exception to this is found in Stonegate 4 at 125Hz and 8kHz where it is source B1 that results in a higher reverberation time by 1.67-5.67JNDs. By analysing Stonegate 1 it can be noted that only T_{20} results are affected and these differences, which range between 1-1.33JNDs, have an impact on 63% of the results. Stonegate 2 presents significant differences extending from 1-2JNDs in 38% of T_{20} and T_{30} values. The analysis of Stonegate 3 evidences notable changes in 75% of T_{20} and 13% of T_{30} results. These changes range between 1-3.33JNDs. Stonegate 4 has notable differences in the 1-2JND range that affect 75% and 63% of T_{20} and T_{30} results respectively.

B. Clarity: C_{50} and C_{80}

The comparison between clarity for sources B1 and B4 demonstrates that there are significant differences across all simulations. The results demonstrate that at higher frequency bands it is the use of source B1 that causes an increment in clarity, whereas at lower frequency bands it is the use of source B4 that results in an increase in clarity. The analysis of Stonegate 1 demonstrates that 50% of its C_{50} and 88% of its C_{80} results are altered as a result of the change in source position. The significant differences observed for C_{50} at 125-500Hz and for C_{80} at 125Hz-4kHz and 16kHz show that it is the use of source B4 that results in higher clarity with significant differences in the range of 1.05-3.46JNDs. At 16kHz C_{50} is higher by 1.96JNDs when source B1 is used. For Stonegate 2 the change in source position affected 75% of C_{50} and C_{80} values. At 125-500Hz there is a correlation between the inclusion of source B4 and the increase in clarity, with differences ranging between 1.15-3.94JNDs. At 4-16kHz it is the use of source B1 that is responsible for higher C_{50} and C_{80} values of 1.52-3.45JNDs. The observation of Stonegate 3 shows that 63% of C_{50} and 38% of C_{80} results have notable variations due to the change in source position. When using source B1 there is an increase in clarity in the 4-16kHz-frequency range with differences extending from 1.45-3.35JNDs. In contrast, higher clarity can also be observed when source B4 is used but in the 125Hz and 500Hz frequency bands, with variations that range between 1.46-3.08JNDs. Stonegate 4 has significant differences in 75% and 88% of C_{50} and C_{80} results respectively. At 1-16kHz it is source B1 that results in higher clarity, with differences between sources extending from 1.18-3.61JNDs, whereas at 125-250Hz it is source B4 that can be associated with higher clarity, with changes in the range of 1.26-3.81JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Significant fluctuations in $IACC_{E3}$ values between sources B1 and B4 are observed at all simulations of Stonegate. Notable differences are found for Stonegate 1-3 only for receivers 1 and 2 and it is the use of source B1 that results in higher $IACC_{E3}$ values. These differences between sources range between 2.53-2.8JNDs for Stonegate 1, 2-2.4JNDs for Stonegate 2 and 1.47-2.53JNDs for Stonegate 3. In the case of Stonegate 4 all receiver positions present significant differences. Differences found for receivers 1 and 2 indicate that the use of source B1 results in higher $IACC_{E3}$ values of 2.27-2.53JNDs, whereas for receiver 3 it is the inclusion of source B4 that results in a higher $IACC_{E3}$ of 1.2JNDs.

LF_{E4} results only present variations when considering Stonegate 1, 2 and 4. These results indicate that for receivers 1 and 2 the use of B4 results in higher values. This can be observed in Stonegate 1 where the use of receiver 1 resulted in a difference of 1.2JNDs, in Stonegate 3 where the use of receiver 3 caused a variation of results by 1.6JNDs and in Stonegate 4 were receivers 1 and 2 caused fluctuations in the results with differences extending from 1.6-2.2JNDs. When considering Stonegate 1, the use of source B1 results in a higher LF_{E4} value by 1.2JNDs when combined with receiver 3.

Section Summary and Remarks on Results

This section examined the impact of changes in source position on the acoustics of the simulations of Stonegate that are combined with the CL-FR wagon. The comparison of sources B0 and B1 shows that Stonegate 1, 3 and 4 were the most affected simulations and the reverberation time was higher when source B1 was used. Clarity showed a tendency towards higher values for source B0 at 500Hz-16kHz, whereas at 125-500Hz source B1 tended towards higher clarity. $IACC_{E3}$ results were only affected in relation to receiver 3 and it was the use of source B1 that indicated a larger ASW. LF_{E4} results were only affected in connection to Stonegate 3 and 4 and source B0 presented higher values.

The examination of sources B0 and B2 demonstrated that the results for Stonegate 1-3 had higher reverberation times when source B2 was used, whereas Stonegate 4 had higher values when source B0 was used. Clarity results were higher for source B2. The majority of $IACC_{E3}$ and LF_{E4} results demonstrated an increase in ASW when source B0 was included in the simulations.

The comparison of sources B1-B2 showed that higher reverberation time values for source B2 were observed at 125-500Hz, whereas at higher frequencies it was source B1 that resulted in higher values. Clarity results were higher when source B2 was incorporated. Both $IACC_{E3}$ and LF_{E4} results indicate that greater levels of spaciousness are achieved with source B1.

The analysis of sources B3 and B4 demonstrated that source B3 resulted in a higher reverberation time when Stonegate 1, 3 and 4 were used and the 125Hz-1kHz frequency bands were considered. Stonegate 2 tended towards higher reverberation times when source B4 was used. The change in source position had very little impact on clarity. The changes observed showed a tendency towards higher clarity for source B4 when Stonegate 1, 3 and 4 were used. Stonegate 2 followed such a tendency at 500Hz but otherwise Stonegate 2 had higher clarity when source B3 was employed. Spatial impression results indicated that a larger ASW for receiver 1 was related to the use of source B4, whereas for receiver 2 it was source B3 that caused an increase in ASW.

The change from source position B2 to source position B3 had the greatest impact on Stonegate 1, 3 and 4, where the use of source B3 caused an increase in reverberation time. Clarity results were higher when source B2 was incorporated. The results for spatial impression demonstrated that a greater spaciousness was achieved with source B3.

The comparison of sources B2 and B4 demonstrated that higher reverberation times were the consequence of using source B4, whereas higher clarity values were related to the use of source B2. Both $IACC_{E3}$ and LF_{E4} parameters demonstrated a tendency towards a larger ASW with the use of source B4.

The examination of sources B0 and B3 indicated that higher reverberation times resulted from the use of source B3. Clarity results at 125-500Hz were higher when source B3 was used, whereas in the 1-16kHz-frequency range higher clarity was related to the use of source B0. Spatial impression parameters tended towards a larger ASW when source B3 was used.

The comparison between sources B1 and B4 demonstrated that source B4 resulted in a higher reverberation time. In terms of clarity, B4 presented higher values in the 125-500Hz-frequency range, whereas source B1 tended towards higher clarity in the 1-16kHz-frequency range. Spatial impression parameters showed a connection between the use of source B4 and the increase of the ASW for receivers 1 and 2, whereas for receiver 3 it was source B1 that resulted in greater spaciousness.

<u>On Speech</u>: The highest reverberation time is recorded for Stonegate 3, when using source B3. This simulation has values at 125Hz-2kHz that are within the range suggested for theatres. The analysis of the open versions of the street space shows that Stonegate 4 has the longest reverberation time

when using sources B1 and B3, but these values are below those recommended for theatre performances. Clarity results indicate speech intelligibility in all the simulations.

On Vocal Music: Reverberation time and clarity results are not ideal for music performances but spatial impression parameters indicate favourable characteristics for music. $IACC_{E3}$ and LF_{E4} values are within the range associated with "good" to "superior" concert halls, the only exception being Stonegate 3 and 4, when source B2 is used.

Model	Range	Results per Parameter – CL-FR					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-B0	Min.	0.27	0.29	3.77	7.68	0.4	0.1
	Max.	0.57	0.57	19.04	24.49	0.5	0.2
Stonegate 1-B1	Min.	0.33	0.32	3.63	7.68	0.28	0.08
	Max.	0.61	0.62	14.27	19.88	0.46	0.2
Stonegate 1-B2	Min.	0.26	0.27	7.79	10.37	0.39	0.07
	Max.	0.64	0.61	19.05	24.94	0.59	0.17
Stonegate 1-B3	Min.	0.30	0.31	7.36	10.54	0.26	0.13
	Max.	0.63	0.65	12.45	19.15	0.33	0.17
Stonegate 1-B4	Min.	0.29	0.30	7.33	10.32	0.24	0.12
	Max.	0.61	0.61	12.11	18.79	0.35	0.19
Stonegate 2-B0	Min.	0.25	0.26	5.5	9.54	0.45	0.07
	Max.	0.48	0.50	19.62	25.61	0.52	0.15
Stonegate 2-B1	Min.	0.27	0.26	6.43	9.58	0.35	0.07
	Max.	0.48	0.48	16.68	23.15	0.46	0.17
Stonegate 2-B2	Min.	0.27	0.26	8.25	13.25	0.57	0.07
	Max.	0.54	0.50	18.52	25.18	0.61	0.13
Stonegate 2-B3	Min.	0.25	0.25	8.49	12.52	0.25	0.16
	Max.	0.52	0.52	14.14	21.2	0.36	0.18
Stonegate 2-B4	Min.	0.28	0.27	8.04	12.89	0.28	0.11
	Max.	0.53	0.51	12.89	19.95	0.36	0.18
Stonegate 3-B0	Min.	0.31	0.32	2.6	7.18	0.45	0.08
	Max.	0.65	0.69	17.63	22.55	0.49	0.13
Stonegate 3-B1	Min.	0.38	0.37	2.7	7.02	0.35	0.1
	Max.	0.68	0.75	14.89	18.77	0.44	0.15
Stonegate 3-B2	Min.	0.30	0.31	6.83	8.88	0.57	0.06
	Max.	0.74	0.72	18.13	23.39	0.61	0.16
Stonegate 3-B3	Min.	0.33	0.34	3.44	7.49	0.27	0.13
	Max.	0.80	0.77	10.84	17.2	0.33	0.19
Stonegate 3-B4	Min.	0.34	0.35	4.81	7.91	0.25	0.15
	Max.	0.78	0.72	11.2	16.77	0.33	0.18
Stonegate 4-B0	Min.	0.28	0.28	4.52	9.56	0.45	0.06
	Max.	0.56	0.55	18.41	24.53	0.55	0.25
Stonegate 4-B1	Min.	0.28	0.27	3.83	9.62	0.27	0.06
	Max.	0.60	0.58	15.98	22.58	0.49	0.16

Stonegate 4-B2	Min.	0.27	0.27	5.71	13.66	0.58	0.06
	Max.	0.57	0.54	19.16	25.23	0.63	0.11
Stonegate 4-B3	Min.	0.29	0.29	4.41	6.98	0.23	0.14
	Max.	0.59	0.61	12.23	18.66	0.32	0.25
Stonegate 4-B4	Min.	0.29	0.29	6.28	10.88	0.3	0.14
	Max.	0.56	0.59	12.75	19.28	0.36	0.21

Table 5.10 – Range of results recorded for the CL-FR wagon.

OPEN-SIDE ON WAGON

Appendix – Tables 5.198-5.212

Comparison of sources B0 and B1

A. Reverberation Time: T_{20} and T_{30}

When comparing sources B0 and B1 significant differences in reverberation time are found in all simulations of Stonegate but Stonegate 1 and 2 were the most affected. Stonegate 1 presented variations in 63% and 75% of its T_{20} and T_{30} results, whereas Stonegate 2 had variations in 88% and 63% of its T_{20} and T_{30} values. Differences recorded for Stonegate 1 are within the 1-3.33JND range and indicate that the use of source B1 corresponds to a higher reverberation time. Results for Stonegate 2 show the use of source B0 results in higher reverberation times at 250Hz-1kHz with differences between 1-1.67JNDs. On the other hand, at 125Hz and 2-16kHz, source B1 has higher values by 1-1.67JNDs. Stonegate 3 presents differences in 50% of T_{20} and 13% of T_{30} results and all variations show that B1 has higher values of 1-2.25JNDs. The analysis of Stonegate 4 evidences differences in 38% of its T_{20} and 25% of its T_{30} results. At 125Hz and 8-16kHz values for source B1 are higher by 1-1.67JNDs, at 500-1kHz it is source B0 that has higher values by 1-2JNDs.

B. Clarity: C_{50} and C_{80}

Differences in clarity between sources B0 and B1 demonstrated that C_{50} and C_{80} results were affected to a lesser extent than with the closed wagons. When considering Stonegate 1 only 38% of C_{50} results and 88% of C_{80} values were affected. At 125-250Hz it is source B1 that resulted in higher clarity by 1-3.49JNDs. An increase in C_{50} by 1.27JNDs when source B0 is used is only observed at 2kHz. However, when considering C_{80} the tendency towards higher values for source B0 is recorded at 500Hz and 2-16kHz with differences extending from 1.19-1.56JNDs. The change in source position only had an impact on 13% of Stonegate 2's C_{50} and C_{80} results. These differences consist of an increase in C_{50} at 125Hz by 1.65JNDs when source B1 is used and an increase in C_{80} at 1kHz by 1.24JNDs when source B0 is used. For Stonegate 3 differences were only recorded for C_{80} and the fluctuations affected 50% of the values. These differences are concentrated in the 2-16kHz range and indicate an increase in values when source B0 is used, with differences ranging between 1.23-2.29JNDs. The analysis of Stonegate 4 showed that 88% of C_{50} and 75% of C_{80} results presented variations. All significant differences ranged between 1.49-2.81JNDs and showed higher values with the inclusion of source B0.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Notable differences in $IACC_{E3}$ values were found between sources B0 and B1 for Stonegate 1-3, whereas significant differences for LF_{E4} are only present in Stonegate 1. $IACC_{E3}$ values for Stonegate 1 are only affected at receiver 1 and it is the use of source B0 that results in a higher value by 1.6JNDs. LF_{E4} values for this simulation show that a significant difference can be observed at receiver 2 and it is source B0 that causes an increase by 2.4JNDs. When considering Stonegate 2 it is only receiver 3 that presents a notable difference in $IACC_{E3}$ and it is the inclusion of source B1 that results in a higher value by 1.33JNDs. Stonegate 3 is affected at receivers 1 and 2 and it is source B0 that causes an increment in $IACC_{E3}$ by 1.07-3.33JNDs.

Comparison of sources B0 and B2

A. Reverberation Time: T_{20} and T_{30}

The comparison between sources B0 and B2 shows that although there are significant differences in reverberation time and clarity in all simulations of Stonegate these differences only affect a small percentage of the results. Notable reverberation time differences in Stonegate 1 and 3 were only observed for 25% of the T_{20} results. When considering Stonegate 1 these differences extend from 1-1.33JNDs and indicate a higher reverberation time when source B0 is used, whereas for Stonegate 3 differences range between 1-1.25JNDs and show that it was source B2 that has higher values. The analysis of Stonegate 2 demonstrated that 38% of T_{20} and T_{30} results were affected by notable differences. At 125Hz-1kHz the differences ranged between 1-1.67JNDs and meant that source B0 resulted in higher values, but at 8-16kHz it was source B2 that had a higher reverberation time by 1-1.33JNDs. The analysis of Stonegate 4 showed that 25% of T_{20} and 13% of T_{30} results were altered as a result of the changes in source position. At 125Hz source B2 has a higher reverberation time by 1JND, whereas at 250-500Hz, source B0 has a higher value by 1-1.33JNDs.

B. Clarity: C_{50} and C_{80}

The analysis of the differences in clarity between sources B0 and B2 shows that there is not a clear correlation between the source position and the increase/decrease of C_{50} and C_{80} values. The change in source position only had an impact on 13% of the C_{50} and C_{80} values recorded for Stonegate 1. These differences are found at 125Hz and they indicate that it is source B2 that has higher values by 5.59-6.93JNDs. Stonegate 2 has 25% of its results affected by significant differences. Such results indicate higher C_{50} and C_{80} values by 2.73-3.13JNDs at 250Hz for source B0 but when considering C_{50} at 4kHz and C_{80} at 500Hz it is source B2 that has higher values by 1.15-1.31JNDs. Notable differences affected 38% of the C_{50} and

50% of the C_{80} results corresponding to Stonegate 3. The results evidence higher values by 1.1-1.85JNDs for source B0 when considering both C_{50} and C_{80} at 125-250Hz, and only C_{80} at 16kHz. Both C_{50} and C_{80} results at 500Hz indicate a higher value for source B2 by 1.38-1.95JNDs. The analysis of Stonegate 4 demonstrated that 13% and 38% of C_{50} and C_{80} results present significant differences. On the one hand when considering C_{80} at 125Hz Stonegate 4 exhibits an increase in clarity by 1.2JNDs when source B0 is used, on the other hand, source B2 has higher values by 1.1-1.42JNDs for C_{50} at 250Hz and C_{80} at 250Hz and 4kHz.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison of $IACC_{E3}$ results for sources B0 and B2 shows significant differences in all the simulations of Stonegate. The differences recorded for Stonegate 1, 2 and 4 correspond to an increase in $IACC_{E3}$ values with the use of source B0. In the case of Stonegate 1 only receiver 1 is affected by a difference of 2.13JNDs, whereas Stonegate 2 presents noticeable differences ranging between 1.6-1.87JNDs at receivers 1 and 2. When considering receivers 2 and 3, Stonegate 4 exhibited differences between sources extending from 1.73-2.27JNDs. Stonegate 3 also presents an increase by 2JNDs in $IACC_{E3}$ when source B0 is used and this can be observed at receiver 1, whereas it is source B2 that results in a higher value by 1.47JNDs when receiver 3 is considered.

The analysis of LF_{E4} showed that the results were affected by the change in source position only when Stonegate 1 and 4 were considered. In the case of Stonegate 1 only receiver 2 was affected and it was source B0 that resulted in a higher LF_{E4} value by 2.6JNDs, whereas for Stonegate 4 it was receiver 3 that varied in its result and it was source B2 that caused the increase in LF_{E4}.

Comparison of sources B1 and B2

A. Reverberation Time: T_{20} and T_{30}

The comparison of sources B1 and B2 shows that all virtual models of Stonegate have significant differences in reverberation time. The majority of these differences indicate that source B1 is linked to an increase in the reverberation time. The only exception to this is for Stonegate 2 at 250-500Hz where source B2 that has higher values by 1JND. The examination of Stonegate 1 shows that 88% of T_{20} and 63% of T_{30} results have notable differences when source B1 is changed for source B2. These differences extend from 1-3JNDs. When considering Stonegate 2 only 25% and 38% of T_{20} and T_{30} results respectively varied significantly. Besides the results at 250-500Hz mentioned above, it is possible to observe notable differences at 125Hz and 8kHz where source B1 has a higher reverberation time by 1-1.67JNDs. Results for Stonegate 3 exhibit notable dissimilarities of 1-2JNDs in 50% of T_{20} and 38% of T_{30} results. Stonegate 4 has notable differences extending from 1-1.33JNDs only in 50% of T_{20} results.

B. Clarity: C_{50} and C_{80}

The comparison of C_{50} and C_{80} values between sources B1 and B2 shows significant differences in all simulations. Significant differences affect 25% and 88% of the C_{50} and C_{80} results recorded for Stonegate 1. The majority of the differences indicate that the use of source B2 causes an increment in clarity. All significant differences observed for C_{50} (at 125Hz and 1kHz) indicate higher values by 1.2-2.88JNDs for source B2. Differences in C_{80} indicate that source B2 has higher values at 125Hz and 500Hz-8kHz, with differences ranging between 1.06-3.44JNDs. However, when considering C_{80} at 250Hz it is source B1 that evidences an increase by 1.51JNDs when using source B1. Stonegate 2 has 88% of C_{50} and 13% of C_{80} results altered as a consequence of the change in source position. A higher C_{50}, by 1.15-3.39JNDs, can be observed for source B1 at 125-250Hz but at

500Hz-8kHz it is the use of source B2 that results in an increase of C_{50} by 1.16-1.93JNDs. C_{80} is only affected at 250Hz, where it is source B1 that has a higher value by 3.27JNDs. The analysis of Stonegate 3 shows that 38% and 63% of C_{50} and C_{80} results present notable differences. An increment, by 1.82-2JNDs, in C_{50} is the consequence of the use of source B1 at 125-250Hz, whereas at 500Hz it is source B2 that has a higher value by 1.07JNDs. When considering C_{80} source B1 has a higher value at 250Hz by 1.64JNDs, whereas source B2 has higher values at 500Hz and 2-4kHz and the differences extend from 1.08-1.51JNDs. Stonegate 4 is affected by differences in 100% of C_{50} and 88% of C_{80} results and the differences, which extend from 1.48-2.99JNDs, exhibit higher clarity values when source B2 is used.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The study of the impact on $IACC_{E3}$ and LF_{E4} results of the alternation between sources B1 and B2 showed that $IACC_{E3}$ had significant differences in Stonegate 2-4, whereas LF_{E4} was only affected in the context of Stonegate 3 and 4. When considering Stonegate 2 and 4 it is the use of source B1 that produces an increment in $IACC_{E3}$. In the case of Stonegate 2 it only affects receiver 2 with a difference of 1.47JNDs between sources, whereas in the case of Stonegate 4 it affects receivers 2 and 3, with differences ranging between 1.73-1.87JNDs. Stonegate 3 presents notable differences in $IACC_{E3}$ at all receiver positions and source B2 results in higher values by 1.33-2JNDs. When considering LF_{E4} the differences observed for Stonegate 3 and 4 indicate that it is the use of source B2 that causes an increase in values. Furthermore, these significant differences are only connected to the use of receiver 3 and they extend from 1-2.2JNDs.

Section Summary and Remarks on Results

The comparison between sources B0 and B1 indicated that Stonegate 1 and 2 were the most affected simulations in terms of reverberation time. Results differed depending on the street simulation but a tendency towards higher results when source B1 was used was observed, in particular in the 2-16kHz-frequency range. Clarity was higher at 500Hz-16kHz when source B0 was used, whereas at 125-250Hz it was source B1 that resulted in higher clarity. Spatial impression results were highly dependent on the receiver position and the parameter. $IACC_{E3}$ results showed an increase in ASW for source B0 when receiver 3 was used, whereas source B1 resulted in an increase in spaciousness when combined with receivers 1 and 2. LF_{E4} recorded an increase only for Stonegate 1, where receiver 2 had a higher value when source B0 was used.

The analysis of sources B0 and B2 demonstrated that only a small percentage (0-38%) of the reverberation time results were affected by the change in source position and there is not a clear connection between the inclusion of one of the source positions and the increase/decrease of reverberation time. The examination of clarity values also showed that a clear correlation between source position and clarity could not be determined and only 13-50% of the results were affected by the change in position. Nevertheless, the results that were affected were concentrated in the 125-500Hz frequency bands. Spatial impression parameters showed a tendency towards an increase in spaciousness when source B2 is used.

The examination of sources B1 and B2 demonstrated that the majority of differences recorded in terms of reverberation time indicated an increase in values when source B1 was used. Regarding clarity, most of the results indicated that it was the use of source B2 that resulted in higher clarity. Such results were concentrated in the 125Hz and 500Hz-16kHz range, whereas at 250Hz a tendency was observed towards higher clarity with the use of source B1. Spatial impression results showed that the larger part of the results presented higher levels of spaciousness when source B2 was used.

On Speech: The highest reverberation time was recorded for Stonegate 3 with the use of source B1. In the 125Hz-2kHz-frequency range this simulation's values are within the range recommended for theatre performances. When considering the open models of Stonegate it is version

4, combined with sources B0 and B1 that results in the highest reverberation time, but these values are below the range thought to be appropriate for theatre. Clarity is suitable for speech intelligibility in all the simulations and source positions.

On Vocal Music: Both reverberation time and clarity parameters recorded values that indicate that the space does not possess characteristics associated with music performances. In contrast, the spatial impression parameters presented values similar to those found in concert halls. This is particularly evident in Stonegate 1 and 3 with the use of sources B1 and B2, and in Stonegate 4 when combined with source B2.

Model	Range	Results per Parameter – OP-SI					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-B0	Min.	0.31s	0.32s	2.88dB	5.94dB	0.38	0.06
	Max.	0.66s	0.66s	13.09dB	19.66dB	0.67	0.21
Stonegate 1-B1	Min.	0.34s	0.35s	5.86dB	8.6dB	0.38	0.05
	Max.	0.68s	0.7s	12.72dB	18.12dB	0.55	0.09
Stonegate 1-B2	Min.	0.31s	0.32s	6.78dB	10.05dB	0.38	0.06
	Max.	0.64s	0.67s	12.51dB	18.69dB	0.59	0.08
Stonegate 2-B0	Min.	0.25s	0.27s	7.94dB	13.05dB	0.44	0.06
	Max.	0.52s	0.52s	15.53dB	23.03dB	0.67	0.11
Stonegate 2-B1	Min.	0.29s	0.3s	8.51dB	13.35dB	0.43	0.05
	Max.	0.54s	0.52s	15.28dB	22.59dB	0.72	0.1
Stonegate 2-B2	Min.	0.29s	0.28s	6.94dB	11.68dB	0.32	0.05
	Max.	0.50s	0.49s	16.31dB	22.27dB	0.66	0.1
Stonegate 3-B0	Min.	0.33s	0.36s	4.75dB	7.99dB	0.47	0.05
	Max.	0.76s	0.77s	12.51dB	18.94dB	0.68	0.09
Stonegate 3-B1	Min.	0.37s	0.38s	4.9dB	8.11dB	0.42	0.05
	Max.	0.85s	0.79s	11.68dB	16.65dB	0.43	0.09
Stonegate 3-B2	Min.	0.35s	0.36s	4.19dB	7.97dB	0.53	0.05
	Max.	0.81s	0.77s	12.22dB	17.73dB	0.58	0.11
Stonegate 4-B0	Min.	0.29s	0.31s	7.18dB	10.06dB	0.4	0.05
	Max.	0.61s	0.6s	15.44dB	21.18dB	0.66	0.13
Stonegate 4-B1	Min.	0.32s	0.33s	5.7dB	10dB	0.41	0.05
	Max.	0.57s	0.61s	12.68dB	19.06dB	0.62	0.11
Stonegate 4-B2	Min.	0.3s	0.31s	8.28dB	11.31dB	0.27	0.06
	Max.	0.58s	0.59s	15.54dB	21.32dB	0.54	0.16

Table 5.11 – Range of results recorded for the OP-SI wagon.

OPEN-FRONT ON WAGON

Appendix – Tables 5.213-5.227

Comparison of sources B0 and B1

A. Reverberation Time: T_{20} and T_{30}

The comparison of sources B0 and B1 showed notable variations in all the street simulations, although differences do not show clear tendencies nor affect large percentages of the results. Stonegate 1 is only affected as regards its T_{20} results and the significant variations have an impact on 50% of those results. Differences indicate that at 125Hz and 16kHz source B1 has a higher reverberation time by 1.33JNDs, whereas at 250-500Hz it is source B0 that has a higher value also by 1.33JNDs. When considering Stonegate 2 significant differences affect 63% of T_{20} and 25% of T_{30} results with differences extending from 1-1.67JNDs. All differences show higher values of reverberation time when source B1 is used. Stonegate 3 presents notable variations only at 125Hz, representing 13% of T_{20} and T_{30} results and with differences ranging between 1.25-1.5JNDs. These variations evidence a higher reverberation time when source B0 is used. The analysis of Stonegate 4 demonstrates notable fluctuations in 25% of T_{20} and T_{30} values. All differences show higher values when source B0 is used, they are concentrated on the 125Hz and 2kHz frequency bands and range between 1-7JNDs.

B. Clarity: C_{50} and C_{80}

Differences in clarity for sources B0 and B1 showed that the change in source position had a smaller influence in the results than reported for the closed wagons. In Stonegate 1-3 all significant differences between values corresponded to higher clarity associated with the use of source B1. When combined with Stonegate 1 only 13% of clarity results had notable differences, which are observed at 125Hz and range between 2.12-2.21JNDs. The results recorded for Stonegate 2 show that the change affected 63% of C_{50} and 38% of C_{80} values. In the case of C_{50} the 500Hz and 2-16kHz frequency bands are affected, whereas for C_{80} changes are recorded at 250Hz and 2-4kHz; differences for these parameters are in the range of 1.07-1.58JNDs. Results for Stonegate 3 showed that 63% and 75% of C_{50} and C_{80} results were altered and differences concentrated at the 125Hz and 500Hz-8kHz frequency bands and extend from 1.06-1.96JNDs. When considering Stonegate 4 the change in position affected 25% of C_{50} and 38% of C_{80} results. C_{50} is only affected at 4kHz and 16kHz, and it is at 16kHz that an increase by 2.46JNDs due to the use of source B0 can be seen. At 4kHz it is the inclusion of source B1 that results in a higher value by 1.28JNDs. All significant differences in C_{80} show that source B1 results in higher clarity by 1.12-1.47JNDs at 250-500Hz and 2kHz.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Notable differences in $IACC_{E3}$ results between sources B0 and B1 can be observed in all simulations of Stonegate. All significant differences indicate higher $IACC_{E3}$ values when source B1 is used, which means that the use of this source results in a decrease in the ASW. Stonegate 1 and 4 present variations in the results only when receiver 2 is considered and differences range between 2.13-2.4JNDs. Stonegate 2 is affected at all receiver positions and differences extended from 2.27-2.4JNDs. The results for Stonegate 3 show that the only difference recorded is of 1.2JNDs for receiver 1.

The examination of the LF_{E4} results corroborates the findings reported for $IACC_{E3}$ by indicating that it is source B0 that results in a larger ASW. When considering Stonegate 1 and 3, receivers 1 and 2 were affected by differences extending from 1-1.2JNDs. The study of Stonegate 2 indicates that in this simulation only receiver 2 presented a difference of 1JND between sources. The analysis of Stonegate 4 demonstrated that only the result of receiver 2 was altered by 1.4JNDs.

Comparison of sources B0 and B2

A. Reverberation Time: T_{20} and T_{30}

Results for sources B0 and B2 demonstrate significant differences in reverberation time in all simulations. In Stonegate 2-4 all significant differences indicate that the use of B0 results in an increase in reverberation time. Stonegate 2 only presents a notable variation at 250Hz for T_{20} of 1JND. The results for Stonegate 3 and 4 show that significant differences have an impact on 63% of T_{20} and 38% of T_{30} results. Differences observed for Stonegate 3 extend from 1-3.5JNDs and those for Stonegate 4 range between 1-3.33JNDs. Stonegate 1 presents notable dissimilarities in 50% and 38% of T_{20} and T_{30} results. At 125-250Hz, source position B2 resulted in a higher reverberation time by 1-2JNDs. At 1-4kHz it is source B0 that has higher values by 1-1.67JNDs.

B. Clarity: C_{50} and C_{80}

The change in source position from B0 to B2 had a large impact on clarity and all notable variations indicate that source B2 resulted in higher values. All C_{50} and C_{80} results recorded for Stonegate 1 varied as a result of the change in source position and changes ranged from 1.54-4.06JNDs. When considering Stonegate 2 and 3, 88% of the values for both C_{50} and C_{80} present significant differences. In the case of Stonegate 2, these differences are observed in the 250Hz-16kHz frequency bands and extend from 1.13-3.8JNDs, whereas for Stonegate 3 they are found at 125Hz and 500Hz-16kHz and extend from 1.84-4.54JNDs. The analysis of Stonegate 4 demonstrates that 63% of C_{50} and 88% of C_{80} results are affected, differences are found at 250Hz-16kHz and they extend from 1.67-4.21JNDs.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The comparison of $IACC_{E3}$ values between sources B0 and B2 demonstrates significant differences in all the results in all the simulations of Stonegate. Furthermore, there is a clear correlation between the use of source B2 and the increase in $IACC_{E3}$ values. Significant differences range between 2.4-4.13JNDs for Stonegate 1, 2.27-4.67JNDs for Stonegate 3, 2.4-3.33JNDs for Stonegate 3 and 2.13-4.27JNDs for Stonegate 4.

Significant differences in LF_{E4} are also found in all the simulations of Stonegate and it is source B0 that resulted in higher values. However, only Stonegate 1 was affected in all receiver positions, presenting variations within 1.2-1.6JNDs. Stonegate 2 exhibited notable differences in connection to receivers 2 and 3 and they extended from 1-1.8JNDs. When considering Stonegate 3 and 4 only receiver 1 is affected and the differences range between 1-1.16JNDs.

Comparison of sources B1 and B2

A. Reverberation Time: T_{20} and T_{30}

The comparison of sources B1 and B2 shows that there are significant differences in all virtual models of Stonegate. In the case of Stonegate 2 and 3 these differences correspond to higher values of reverberation time for source B1. Stonegate 2 has significant differences in the range of 1-2.33JNDs that affect 63% of T_{20} and 38% of T_{30} results. Notable differences of 1-2.67JNDs in Stonegate 3 affect 63% of T_{20} and 50% of T_{30} results. Stonegate 1 presents significant differences that affect 88% of T_{20} and 38% of T_{30} results. At 250-500Hz, source B2 causes an increase in reverberation time of 1.67-2.67JNDs, whereas at 1-16kHz it is source B1 that has higher values by 1-1.67JNDs. Stonegate 4 has notable differences that affect 50% and 13% of T_{20} and T_{30} results respectively. At 125Hz it is the use of source B2 that indicates a higher reverberation time by 2.33-

3.67JNDs, whereas at 250-500Hz and 4kHz it is source B1 that represents an increase in reverberation time by 1-1.33JNDs.

B. Clarity: C_{50} and C_{80}

The analysis of sources B1 and B2 indicate notable fluctuations in clarity values between source positions in all simulations of Stonegate. Moreover, all differences show higher clarity for source B2. Significant differences range between 1.39-3.92JNDs for Stonegate 1, 1.16-2.7JNDs for Stonegate 2, 1.09-2.69JNDs for Stonegate 3 and 1.12-3JNDs for Stonegate 4.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

Notable differences in $IACC_{E3}$ values between sources B1 and B2 are found in all simulations of Stonegate. All significant differences correspond to higher $IACC_{E3}$ values when source B2 is used. In the case of Stonegate 1, 3 and 4 all receiver positions present notable differences, whereas Stonegate 2 is only affected in relation to receiver 2. Variations between sources are within 2-2.93JNDs for Stonegate 1, 2.4JNDs for Stonegate 2, 1.73-2.93JNDs for Stonegate 3 and 1.6-2.4JNDs for Stonegate 4.

The study of LF_{E4} indicates that only Stonegate 2-4 were affected by variations in the results. Furthermore, these differences show that the use of source B1 results in higher LF_{E4} values. Stonegate 1 only has a significant difference for receiver 1 and this difference is of 1JND. When considering Stonegate 3 and 4 only receiver 3 is affected and differences are of 1JND for Stonegate 3 and 2.4JNDs for Stonegate 4.

Section Summary and Remarks on Results

The comparison of sources B0 and B1 shows that there was little impact of the change in source position on the reverberation time results. Stonegate 2 was the most affected and had higher values when source B1 was used. Regarding clarity, the majority of the results indicated that higher values were connected to the use of source B1 and these variations had the greatest impact on Stonegate 2 and 3. Spatial impression parameters indicated that the use of source B0 resulted in an increase in the ASW.

The examination of sources B0 and B2 indicated that reverberation time values were higher when source B0 was used whereas source B2 resulted in higher clarity. Spatial impression parameters indicated that a larger ASW was related to the use of source B0.

The analysis of sources B1 and B2 showed that the majority of the results had a higher reverberation time when source B1 was used, although opposite results were also observed for Stonegate 1 and 4 in the 125-500Hz-frequency range. Clarity values showed significant differences in 75-88% of the results and they indicated higher values for source B2. Spatial impression parameters demonstrated that higher levels of spaciousness are achieved through the use of source B1.

On Speech: The highest reverberation time was recorded for Stonegate 3 combined with sources B0 and B1. In the 125Hz-1kHz-frequency range these combinations have values that are suitable for theatre performances. When considering the open versions of Stonegate all simulations have values below the recommended range for theatre but it is Stonegate 4 combined with source B0 that has the longest reverberation time. All simulations include clarity values that are suitable for speech.

On Vocal Music: Reverberation time and clarity are below the values associated with music performances. In contrast, spatial impression parameters recorded values comparable to those found in concert halls for all the simulations as well as all source positions. Particularly suitable values were found for Stonegate 1 and 3 combined with sources B0 and B1 and Stonegate 2 and 4 combined with source B0.

Model	Range	Results per Parameter – OP-FR					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
Stonegate 1-B0	Min.	0.28s	0.3s	5.62dB	9.29dB	0.25	0.15
	Max.	0.64s	0.65s	15.86dB	21.78dB	0.38	0.23
Stonegate 1-B1	Min.	0.32s	0.32s	6.99dB	10.42dB	0.24	0.09
	Max.	0.64s	0.63s	16dB	21.21dB	0.41	0.19
Stonegate 1-B2	Min.	0.29s	0.3s	8.08dB	10.83dB	0.46	0.07
	Max.	0.66s	0.65s	19.11dB	24.28dB	0.56	0.16
Stonegate 2-B0	Min.	0.23s	0.25s	9.43dB	12.8dB	0.2	0.1
	Max.	0.5s	0.51s	16.64dB	23.69dB	0.35	0.19
Stonegate 2-B1	Min.	0.27s	0.28s	8.73dB	13.87dB	0.37	0.07
	Max.	0.51s	0.52s	18.18dB	24.24dB	0.53	0.15
Stonegate 2-B2	Min.	0.23s	0.25s	10.58dB	15.08dB	0.43	0.05
	Max.	0.48s	0.5s	20.24dB	26.68dB	0.66	0.1
Stonegate 3-B0	Min.	0.33s	0.34s	4.52dB	7.94dB	0.25	0.13
	Max.	0.77s	0.74s	13.97dB	19.48dB	0.37	0.16
Stonegate 3-B1	Min.	0.32s	0.34s	6.05dB	9.49dB	0.28	0.08
	Max.	0.74s	0.75s	14.86dB	20.15dB	0.41	0.18
Stonegate 3-B2	Min.	0.31s	0.32s	6.54dB	10.58dB	0.5	0.08
	Max.	0.75s	0.74s	16.61dB	22.07dB	0.55	0.14
Stonegate 4-B0	Min.	0.27s	0.28s	7.41dB	10.76dB	0.29	0.14
	Max.	0.62s	0.64s	19.06dB	22.47dB	0.37	0.18
Stonegate 4-B1	Min.	0.29s	0.3s	6.98dB	12.21dB	0.36	0.07
	Max.	0.58s	0.57s	16.35dB	22.52dB	0.47	0.22
Stonegate 4-B2	Min.	0.28s	0.29s	7.65dB	12.22dB	0.53	0.07
	Max.	0.52s	0.55s	18.62dB	24.14dB	0.61	0.1

Table 5.12 – Range of results recorded for the OP-FR wagon.

5.7 Audience Areas: Acoustical Analysis

This section analyses the impact of the audience areas modelled on the simulations of sixteenth-century Stonegate in terms of reverberation time, clarity and spatial impression. The virtual models studied are the same as in the previous sections but with the addition of two areas for audiences that are standing and three scaffold levels for seated audiences. These models are referred to by adding the letters Aud. to the name of the simulation, for instance, Stonegate 1-CL-SI-Aud., refers to the combination of Stonegate 1 and the closed side-on wagon with the addition of the audience areas (see Tables 5.1-5.2). The results were studied by separating them in five different areas: the standing audience area towards Little Stonegate, the standing audience area towards Petergate and the three different levels of the scaffold.

The analysis of the results presented below was carried out by considering the mean values across all receiver positions of the area in question but considering source positions separately. However, when reporting the results in the body of the text the differences related to the change in source position will not be analysed as this has been covered in connection to the simulations without audience areas (see section 5.6.4). Furthermore, results have also been considered in connection to the minimum and maximum values calculated for each parameter.

CLOSED-SIDE ON WAGON

A. Reverberation Time: T_{20} and T_{30}

The analysis of the reverberation time in connection to the audience areas indicates that the results for the various simulations of Stonegate differ regarding the areas with the highest and lowest values. When considering Stonegate 1 the highest mean values are encountered in the receiver positions that represent a standing audience, whereas the lowest values are related to the receiver positions within the second level of the scaffold. The results for Stonegate 2 indicate that the highest values correspond to the positions at the second and third levels of the scaffolds. In this simulation, the same as in Stonegate 1, the lowest values correspond to the use of the second level of the scaffold. The analysis of Stonegate 3 shows that the longest reverberation times correspond to the third level of the scaffold as well as the audience area towards Little Stonegate. On the other hand, the lowest reverberation times are observed at the first and second levels of the scaffold. When examining the results for Stonegate 4 it is also the use of the third level of the scaffold that results in the highest values, whereas the lowest values are connected to the use of the second level of the scaffolds.

B. Clarity: C_{50} and C_{80}

The analysis of clarity for different audience areas demonstrated that the highest values were recorded for the scaffold at level three in the case of Stonegate 1 and 2, and at levels two and three for Stonegate 3 and 4. The areas that result in the lowest clarity vary across the various simulations. The study of Stonegate 1 indicates that the lowest values are connected to the area located towards Little Stonegate. When considering Stonegate 2 it is the standing audience towards Petergate as well as the first level of the scaffold that present the lowest clarity. The examination of Stonegate 3 shows that the areas for standing audiences recorded the lowest clarity. Stonegate 4 has the lowest results for the area towards Little Stonegate.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The lowest values of $IACC_{E3}$, which indicate a greater perceptual broadening of the sound source, corresponded to the areas at the sides of the wagon. In the case of Stonegate 1 this was true for the area located towards Little Stonegate, whereas for Stonegate 2-4 the lowest values of $IACC_{E3}$ were recorded for the audience area towards Petergate. The analysis of the highest values of $IACC_{E3}$ demonstrated that for Stonegate 1 these were found at the second and third levels of the scaffold. For Stonegate 2 they corresponded to the second level of the scaffold and for Stonegate 3 and 4 to the third level of the scaffold.

LF_{E4} results follow the same tendencies indicated for $IACC_{E3}$, results indicate a greater ASW for standing audiences and a lower ASW for seated audiences. All the simulations of Stonegate show that it is the audience area towards Little Stonegate that presents the highest LF_{E4} values. In contrast, the lowest values were associated with the second and third levels of the scaffold for Stonegate 1-3 and only the third level for Stonegate 4.

CLOSED-FRONT ON WAGON

A. Reverberation Time: T_{20} and T_{30}

The differences among audience areas found for the simulations indicate that for Stonegate 1 the highest reverberation time values are connected to the audience located towards Petergate as well as the second level of the scaffold. The lowest values were recorded for the scaffold at levels one and three as well as for the standing audience located towards Little Stonegate. Both Stonegate 2 and 3 have the highest reverberation time values at the second level of the scaffold structure. However, when analysing the areas with the lowest values it can be observed that while Stonegate 2 presents these at the first level of the scaffold, Stonegate 3 has the lowest reverberation time for the audience located towards Little Stonegate. Results for Stonegate 4 demonstrate that the use of the scaffold at the second and third levels results in higher reverberation times. In contrast, the receivers in the first level of the scaffold area have the lowest values.

B. Clarity: C_{50} and C_{80}

The highest clarity values are connected to the receiver positions located towards Petergate, that is, those positions that are facing the sound sources. The audience area towards Little Stonegate exhibited the lowest values of reverberation time when combined with Stonegate 1, 3 and 4, whereas for Stonegate 2 it was the second level of the scaffold that resulted in the lowest reverberation time.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The lowest $IACC_{E3}$ values are observed at the audience area located towards Little Stonegate, whereas the highest results are connected to the scaffold. Stonegate 1-2 have the highest results at the second level and Stonegate 3-4 exhibit such results at the first level.

The analysis of LF_{E4} results supports the tendencies reported for $IACC_{E3}$ by indicating that in the standing audience areas there are higher values of LF_{E4} and as a consequence an increase in ASW, whereas the scaffold areas have the lowest values indicating a smaller ASW. When considering Stonegate 1 and 3 the highest values correspond to the use of the audience area located towards Little Stonegate, whereas for Stonegate 2 and 4 results are higher for the audience area towards Petergate. The lowest values of LF_{E4} correspond to the second and third levels of the scaffold for Stonegate 1, all three levels for Stonegate 2 and the first level for Stonegate 3 and 4.

OPEN-SIDE ON WAGON

A. Reverberation Time: T_{20} and T_{30}

The highest reverberation time values in all simulations correspond to the third level of the scaffold structure. When studying Stonegate 1 and 2 the lowest reverberation time was calculated for the scaffold area at the first level. Results for Stonegate 3 and 4 show that the first and second levels of the scaffold result in the lowest reverberation times.

B. Clarity: C_{50} and C_{80}

Stonegate 1, 3 and 4 present a correlation between the use of the first level of the scaffold and an increase in clarity, whereas Stonegate 2 has higher clarity values at the third level of the scaffold. The lowest clarity values for Stonegate 1, 2 and 4 are recorded in the audience area towards Petergate. In the case of Stonegate 3 both areas corresponding to standing audiences have the lowest values.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The lowest $IACC_{E3}$ values are found in the areas for standing audiences. In the case of Stonegate 1 and 3 these values correspond to the area towards Little Stonegate, whereas for Stonegate 2 and 4 it corresponds to the area towards Petergate. All simulations exhibit the highest values of $IACC_{E3}$ in connection to the top level of the scaffold.

The results corresponding to LF_{E4} also show that a larger ASW is associated with the area towards Little Stonegate, whereas the lowest levels are connected to the use of the scaffold at the second level in the case of Stonegate 1-3 and the third level when Stonegate 4 is considered.

OPEN-FRONT ON WAGON

A. Reverberation Time: T_{20} and T_{30}

The highest reverberation times in all the simulations coincided with the use of the third level of the scaffold. Within the simulation of Stonegate 1 the lowest reverberation time corresponds to the first and second levels of the scaffold. For Stonegate 2 and 4 the lowest values were also connected to the use of the first level of the scaffold but in the case of Stonegate 2 the audience area towards Petergate also produced similar results. In the case of Stonegate 3 the second level of the scaffold exhibited the lowest values.

B. Clarity: C_{50} and C_{80}

All simulations of Stonegate exhibit higher clarity in the audience area located towards Petergate. In contrast, a tendency towards a decrease in clarity values can be found for the audience area towards Little Stonegate when considering Stonegate 1 and 3. For Stonegate 2 the lowest values correspond to the second and third levels of the scaffold. In the case of Stonegate 4 the lowest clarity is recorded at the third level of the scaffold.

C. Spatial Impression: $IACC_{E3}$ and LF_{E4}

The examination of $IACC_{E3}$ shows that it follows different tendencies from those reported for the rest of the wagons. The simulations analysed above showed that standing audience areas resulted in the lowest values of $IACC_{E3}$ and the scaffold in the highest values, but the OP-FR-Aud. simulation only follows this tendency when combined with Stonegate 1. Stonegate 1 has the lowest values in the area towards Little Stonegate and the highest values are found at the top level of the scaffold. When considering Stonegate 2 and 4 the lowest $IACC_{E3}$ results are found at the second level of the scaffold, whereas the highest values correspond to the use of the audience area towards Petergate. The analysis of Stonegate 3 shows that the audience area towards Little Stonegate has the lowest values, whereas the highest values are found for the audience area towards Petergate.

Although the results calculated for $IACC_{E3}$ seem to indicate that the ASW for this simulation shows different tendencies from that reported for the rest of the simulations, when considering LF_{E4} results the tendency observed for the rest of the simulations can also be observed for the OP-FR-Aud. model. All simulations include the highest LF_{E4} values in the audience area towards Little Stonegate, while the lowest values are related to the use of the top level of the scaffold.

The different tendency shown between the $IACC_{E3}$ and the LF_{E4} results might be related to the predominance of direct sound in the audience area towards Petergate. The predominance of direct sound affects $IACC_{E3}$ values, as direct sound and early reflections are both considered as part of the parameter calculation. In contrast, LF_{E4} is not directly affected by the direct sound as it is not included in the calculations of the results. The effect of direct sound in the calculation of $IACC_{E3}$ can be corroborated through the observation of the maximum values recorded for the CL-FR.Aud. simulation for this same audience area (see Table 5.14), which are significantly higher than those observed in other areas.

Section Summary and Remarks on Results

The present section studied reverberation time, clarity and spatial impression in relation to the different audience areas added to the simulations of Stonegate. The observation of the overall results, averaged across receiver positions and frequency bands, indicates that when considering the CL-SI, OP-SI and OP-FR wagons higher reverberation times correspond to the use of the third level of the scaffold, whereas when the CL-FR wagon is studied it is the second level that produces a longer reverberation time. The shorter reverberation times are observed at the second level of the scaffold when considering the CL-SI wagon, at the first level as well as towards Little Stonegate for the CL-FR wagon and the first and second levels of the scaffold for the open wagons.

The highest clarity values were observed in the second and third levels of the scaffold when the CL-SI wagon was considered, in the area towards Petergate when the CL-FR and OP-FR wagons were studied and at the first level of the scaffold when the OP-SI wagon was examined. In contrast, the lowest clarity is found for the CL-SI wagon in the areas for standing audiences, for the CL-FR wagon in the area towards Little Stonegate as well as at the second level of the scaffold, for the OP-SI wagon in the area towards Petergate and for the OP-FR wagon in the area towards Little Stonegate as well as the third level of the scaffold.

Spatial impression parameters indicate a tendency towards a larger ASW when audiences are simulated as standing, whereas lower levels of ASW are associated with the different scaffold levels.

The observation of the minimum and maximum values averaged across the different receiver positions also allows the observation on the impact of the results on speech and vocal music.

On Speech: The highest reverberation time value observed corresponded to Stonegate 2 combined with the CL-SI wagon and it was recorded for the receiver positions at the second level of the scaffold. Moreover, 76% of T_{30} results in the 125Hz-4kHz frequency range were above 0.7s and 56% were within the range of 0.7-1.2s recommended for theatres. Despite the increase in reverberation time as a result of the introduction of audience areas, in particular the reflective surfaces of the scaffold, clarity was still high and suitable for speech intelligibility.

On Vocal Music: The higher reverberation times recorded with the incorporation of audience areas indicate a more suitable space for the performance of vocal music. In the case of Stonegate 2 combined with the CL-SI wagon, values recorded in connection to sources B3 and B4 at 2-4kHz range from 1.5-1.86s, which are within the range associated with music performances (Barron 1993; Beranek 1962). Clarity values are higher than those associated with music performances. The most favourable spatial impression results, which are comparable to those found in concert halls, were found for Stonegate 1 and 3 combined with the OP-SI wagon and they coincide with the use of the areas dedicated to standing audiences.

Model-Aud. Area	Range	Results per Parameter – CL-SI.Aud.					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
1-Little Stg.	Min.	0.36	0.41	3.1	5.18	0.22	0.05
	Max.	1.17	1.56	18.47	22.09	0.54	0.027
1-Petergate	Min.	0.31	0.33	5.25	7.54	0.18	0.04
	Max.	1.21	1.26	18.81	22.76	0.69	0.36
1-Level 1	Min.	0.14	0.22	2.44	6.3	0.33	0.01
	Max.	1.14	2.04	24.55	31.06	0.81	0.19
1-Level 2	Min.	0.21	0.26	7.79	9.95	0.36	0.01
	Max.	1.77	1.76	21.5	26.66	0.85	0.11
1-Scaff. Level 3	Min.	0.24	0.32	7.12	9.15	0.41	0.01
	Max.	1.27	1.31	22.09	26.86	0.87	0.07
2-Little Stg.	Min.	0.22	0.29	6.35	9.22	0.22	0.03
	Max.	0.93	1.31	21.72	26.32	0.83	0.27
2-Petergate	Min.	0.29	0.27	6.15	9.32	0.2	0.03
	Max.	0.8	1	20.15	24.73	0.68	0.37
2-Level 1	Min.	0.15	0.22	4.22	9.02	0.33	0.02
	Max.	0.58	1.22	24.24	30.77	0.81	0.17
2-Level 2	Min.	0.21	0.25	8.04	11.04	0.41	0.01
	Max.	1.73	1.86	21.5	28.26	0.85	0.09
2-Level 3	Min.	0.22	0.31	8.61	10.95	0.39	0.01
	Max.	1.24	1.23	22.71	27.5	0.89	0.07
3-Little Stg.	Min.	0.3	0.35	-0.6	2.09	0.16	0.07
	Max.	1.38	1.6	15.12	21.07	0.54	0.26
3-Petergate	Min.	0.31	0.32	2.23	4.47	0.15	0.03
	Max.	1.19	1.17	15.2	21.75	0.68	0.29

3-Level 1	Min.	0.14	0.24	2.4	5.1	0.33	0.02
	Max.	1.28	1.77	24.62	30.38	0.88	0.3
3-Level 2	Min.	0.18	0.23	3.91	8.52	0.38	0.02
	Max.	1.53	1.54	22.31	28.95	0.94	0.15
3-Level 3	Min.	0.29	0.34	4.55	9.08	0.39	0.02
	Max.	1.44	1.52	23.05	27.53	0.89	0.16
4-Little Stg.	Min.	0.28	0.31	1.99	5.31	0.18	0.03
	Max.	1.25	1.58	19.25	23.81	0.75	0.27
4-Petergate	Min.	0.26	0.26	5.53	8.75	0.15	0.02
	Max.	0.89	1.03	18.27	24.16	0.83	0.26
4-Level 1	Min.	0.14	0.22	4.65	8.01	0.32	0.01
	Max.	0.7	1.39	24.8	31.11	0.87	1.23
4-Level 2	Min.	0.18	0.21	7.01	9.92	0.39	0.01
	Max.	1.6	1.58	22.62	29.96	0.94	0.11
4-Level 3	Min.	0.26	0.29	7.82	10.69	0.39	0.01
	Max.	1.51	1.46	24.84	30.26	0.93	0.12

Table 5.13 – Range of results recorded for the CL-SI.Aud. simulation.

Model/Aud. Area	Range	Results per Parameter – CL-FR.Aud.					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
1-Little Stg.	Min.	0.35	0.34	1.87	5.33	0.18	0.02
	Max.	0.89	1.08	19.85	24.02	0.64	0.42
1-Petergate	Min.	0.31	0.36	5.27	7.28	0.2	0.01
	Max.	1.22	1.28	21.84	26.52	1.3	0.23
1-Level 1	Min.	0.22	0.22	2	6.08	0.35	0.02
	Max.	1.2	1.43	18.15	24	0.84	0.15
1-Level 2	Min.	0.35	0.34	1.84	5.21	0.42	0.01
	Max.	1.2	1.35	17.71	21.92	0.85	0.13
1-Scaff. Level 3	Min.	0.27	0.41	1.45	4.06	0.29	0.01
	Max.	0.88	1.01	18.99	23.68	0.87	0.17
2-Little Stg.	Min.	0.2	0.3	4.99	9.08	0.21	0.01
	Max.	1.23	1.15	23.19	27.45	0.71	0.23
2-Petergate	Min.	0.22	0.29	7.88	11.58	0.2	0.01
	Max.	0.93	0.95	23.43	29.39	1.32	0.22
2-Level 1	Min.	0.19	0.23	5.37	9.28	0.36	0.02
	Max.	0.57	1.13	19.4	24.46	0.87	0.16
2-Level 2	Min.	0.27	0.29	2.07	6.76	0.45	0.02
	Max.	1.17	1.15	17.32	23.84	0.85	0.12
2-Level 3	Min.	0.25	0.34	3.96	7.58	0.26	0.01
	Max.	0.82	0.84	19.23	24.72	0.91	0.21
3-Little Stg.	Min.	0.37	0.35	-1.68	1.63	0.17	0.02
	Max.	1.01	1.13	17.63	20.14	0.66	0.3
3-Petergate	Min.	0.36	0.38	3.6	5.86	0.14	0.01
	Max.	1.2	1.22	21.27	25.52	1.28	0.29
3-Level 1	Min.	0.3	0.35	1.89	4.05	0.34	0.02
	Max.	1.33	1.68	18.39	23.69	0.83	0.1
3-Level 2	Min.	0.38	0.35	0.38	4.29	0.21	0.02
	Max.	1.51	1.51	14.4	18.91	0.75	0.15
3-Level 3	Min.	0.38	0.37	-1.34	2.11	0.2	0.03
	Max.	1.04	1.1	18.24	20.58	0.81	0.24

4-Little Stg.	Min.	0.31	0.3	0.44	3.31	0.2	0.02
	Max.	0.83	0.86	21.03	23.95	0.67	0.24
4-Petergate	Min.	0.23	0.31	5.48	9.06	0.16	0.03
	Max.	0.88	0.9	22.94	28.17	1.31	0.32
4-Level 1	Min.	0.23	0.28	5.08	8.11	0.32	0.02
	Max.	0.67	0.89	18.69	24.02	0.86	0.11
4-Level 2	Min.	0.33	0.32	2.47	5.56	0.31	0.02
	Max.	1.62	1.31	16.56	21.49	0.76	0.16
4-Level 3	Min.	0.35	0.32	1.8	5.54	0.25	0.02
	Max.	0.97	0.93	17.54	20.73	0.83	0.27

Table 5.14 – Range of results recorded for the CL-FR.Aud. simulation.

Model/Aud. Area	Range	Results per Parameter – OP-SI.Aud.					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
1-Little Stg.	Min.	0.33	0.35	4.47	7.36	0.13	0.08
	Max.	1.11	1.39	16.15	19.47	0.49	0.3
1-Petergate	Min.	0.31	0.37	3.9	7.66	0.21	0.08
	Max.	1.22	1.27	14.49	18.07	0.57	0.32
1-Level 1	Min.	0.17	0.24	7.9	11.58	0.36	0.01
	Max.	1.12	1.38	23.08	29.55	0.84	0.21
1-Level 2	Min.	0.29	0.31	10.53	13.13	0.5	0.01
	Max.	1.13	1.17	18.82	24.18	0.77	0.06
1-Scaff. Level 3	Min.	0.28	0.29	9.37	12.22	0.55	0.01
	Max.	1.43	1.47	20.61	28.52	0.89	0.13
2-Little Stg.	Min.	0.29	0.32	7.42	11.12	0.22	0.03
	Max.	1.24	1.38	18.46	23.38	0.82	0.29
2-Petergate	Min.	0.28	0.29	5.46	9.15	0.23	0.05
	Max.	1.09	1.16	16.69	21.43	0.65	0.3
2-Level 1	Min.	0.16	0.24	6.96	12.34	0.33	0.02
	Max.	0.94	1.44	23.51	29.81	0.83	0.17
2-Level 2	Min.	0.26	0.29	10.83	13.92	0.52	0.01
	Max.	1.13	1.17	18.94	24.44	0.77	0.07
2-Level 3	Min.	0.25	0.24	10.98	12.98	0.57	0.01
	Max.	1.47	1.43	20.46	29.98	0.87	0.06
3-Little Stg.	Min.	0.33	0.37	3.31	6.95	0.14	0.1
	Max.	1.08	1.22	12.75	9.43	0.52	0.41
3-Petergate	Min.	0.42	0.44	4.39	7.06	0.19	0.06
	Max.	1.2	1.29	11.88	16.55	0.55	0.28
3-Level 1	Min.	0.18	0.25	7	10.52	0.36	0.02
	Max.	1.07	1.51	23.04	29.06	0.86	0.25
3-Level 2	Min.	0.27	0.31	5.78	10.63	0.45	0.01
	Max.	0.99	1.23	18.84	24.13	0.85	0.14
3-Level 3	Min.	0.33	0.37	3.94	8.87	0.48	0.03
	Max.	1.47	1.37	6.89	24.93	0.92	0.11
4-Little Stg.	Min.	0.32	0.31	6.59	9.74	0.19	0.03
	Max.	1.1	1.26	16.69	20.87	0.67	0.27
4-Petergate	Min.	0.27	0.31	5.31	9.07	0.24	0.03
	Max.	0.87	0.98	16.56	21.77	0.64	0.22
4-Level 1	Min.	0.25	0.23	8.42	12.09	0.3	0.02
	Max.	1.51	1.66	23.37	29.85	0.84	0.52

4-Level 2	Min.	0.24	0.26	9.85	13.01	0.44	0.01
	Max.	1.02	1.39	18.84	25.67	0.86	0.13
4-Level 3	Min.	0.29	0.27	8.22	10.73	0.47	0.01
	Max.	1.59	1.38	21.43	28.81	0.91	0.07

Table 5.15 – Range of results recorded for the OP-SI.Aud. simulation.

Model/Aud. Area	Range	Results per Parameter – OP-FR.Aud.					
		T_{20}	T_{30}	C_{50}	C_{80}	$IACC_{E3}$	LF_{E4}
1-Little Stg.	Min.	0.39	0.4	2.44	5.74	0.2	0.08
	Max.	1.11	1.25	15.50	19.38	0.54	0.26
1-Petergate	Min.	0.31	0.36	7.52	10.39	0.3	0.01
	Max.	1.11	1.15	20.25	25.63	1.3	0.21
1-Level 1	Min.	0.28	0.32	5.97	9.01	0.28	0.03
	Max.	1.12	1.45	16.79	21.97	0.74	0.12
1-Level 2	Min.	0.31	0.34	1.94	5.21	0.24	0.04
	Max.	1.02	1.3	13.91	18.95	0.71	0.26
1-Scaff. Level 3	Min.	0.33	0.38	3.32	5.99	0.43	0.02
	Max.	1.38	1.49	14.36	19.10	0.86	0.13
2-Little Stg.	Min.	0.31	0.32	4.85	8.81	0.29	0.06
	Max.	0.96	1.21	18.58	22.41	0.66	0.28
2-Petergate	Min.	0.2	0.29	10.09	14.48	0.22	0.01
	Max.	0.87	0.96	22.70	28.28	1.33	0.22
2-Level 1	Min.	0.23	0.25	6.74	10.7	0.24	0.03
	Max.	0.76	1.25	19.62	25.81	0.79	0.13
2-Level 2	Min.	0.29	0.32	2.81	6.59	0.24	0.03
	Max.	0.93	1.01	14.79	20.07	0.73	0.18
2-Level 3	Min.	0.3	0.31	4.55	8.97	0.35	0.02
	Max.	1.3	1.22	15.33	21.7	0.86	0.13
3-Little Stg.	Min.	0.39	0.41	0.78	4.73	0.22	0.1
	Max.	1.01	1.1	9.95	13.99	0.62	0.29
3-Petergate	Min.	0.36	0.4	6.27	9.17	0.24	0.03
	Max.	1.05	1.09	20.27	24.24	1.28	0.22
3-Level 1	Min.	0.35	0.36	4.19	7.61	0.36	0.05
	Max.	1.08	1.39	10.98	16.81	0.72	0.14
3-Level 2	Min.	0.33	0.35	2.56	6.16	0.25	0.04
	Max.	0.93	1.2	13.74	18.82	0.65	0.2
3-Level 3	Min.	0.37	0.44	2.51	5.16	0.3	0.05
	Max.	1.33	1.43	7.64	13.14	0.7	0.13
4-Little Stg.	Min.	0.33	0.32	3.15	7.21	0.29	0.04
	Max.	0.83	1.05	17.22	21.17	0.63	0.22
4-Petergate	Min.	0.25	0.31	8.39	13.01	0.29	0.01
	Max.	0.82	0.95	22.35	27.4	1.3	0.18
4-Level 1	Min.	0.28	0.3	5.03	9.48	0.29	0.03
	Max.	0.78	1.25	17.35	24.07	0.71	0.12
4-Level 2	Min.	0.3	0.32	4.11	8.27	0.17	0.02
	Max.	0.73	0.86	14.92	19.92	0.67	0.16
4-Level 3	Min.	0.34	0.32	2.91	6.74	0.36	0.03
	Max.	1.3	1.29	13.86	18.31	0.74	0.16

Table 5.16 – Range of results recorded for the OP-FR.Aud. simulation.

5.8 Conclusions

The present chapter explored different hypotheses on staging configurations by examining what their effects might have been in relation to the acoustics of sixteenth-century Stonegate. This exploration was achieved through the simulation of two different wagon structures, two wagon orientations and five different sound source positions. However, the analysis was not just focussed on these elements but it also studied how they interacted with the different simulations of sixteenth-century Stonegate. The acoustical analysis was conducted through an examination of the results of different acoustical parameters related to reverberation time (T_{20} and T_{30}), clarity (C_{50} and C_{80}) and spatial impression ($IACC_{E3}$ and LF_{E4}).

The first part of the analysis focussed on determining whether the inclusion of a wagon structure resulted in any changes in the values of the acoustical parameters studied. The results showed that all parameters were affected by the inclusion of a wagon structure. The reverberation time was shown to decrease in all simulations with the exception of the computer models of Stonegate 2-4 combined with the CL-SI wagon. The impact of the wagons on clarity was highly dependent on the simulation of Stonegate being used. The incorporation of the wagons to the simulation of Stonegate 1 resulted in an increase in clarity. Stonegate 2 presented a decrease in clarity with the inclusion of the CL-SI, CL-FR and OP-SI wagons but an increase when the OP-FR wagon was used. Stonegate 3 and 4 evidenced higher clarity when the CL-FR, OP-SI and OP-FR wagons were used, but presented a decrease with the use of the CL-SI wagon. The $IACC_{E3}$ and LF_{E4} parameters showed an increase in the ASW as a consequence of the introduction of wagon structures, which can be an asset for the performance of musical items.

Variations in the acoustical parameters were also observed between the wagon structures closed on three sides and those open on all sides. Although differences in the reverberation time were found when considering the structures in both a side-on and front-on orientation, it was noted that the differences were more pronounced when front-on wagons were used. When comparing the CL-SI to the OP-SI wagon their combination with Stonegate 1 and 4 resulted in the largest impact on the reverberation time. In the case of Stonegate 1 it was the use of the open wagon that resulted in higher values whereas for Stonegate 4 it was the use of the closed wagon that was related to an increase in reverberation time. The comparison between the CL-FR and the OP-FR wagons showed that the simulations of Stonegate 1, 3 and 4 were the most affected and the use of the open wagon resulted in the longest reverberation time.

The clarity parameters were more sensitive to the changes in wagon structures than the reverberation time. When considering the side-on wagons, the highest clarity was related to the use of the closed wagon when considering Stonegate 1, 3 and 4, but it was the use of the open wagon that resulted in the highest clarity when it was incorporated to Stonegate 2. The study of the front-on wagons showed that the greatest impact was achieved in Stonegate 2 and it was the use of the open wagon that resulted in higher clarity.

The study of $IACC_{E3}$ and LF_{E4} in relation to the change of the wagon structure demonstrated that $IACC_{E3}$ was more sensitive to the change. The side-on wagons were particularly affected when considering the closed versions of Stonegate but there was not a clear indication as to a correlation between one of the wagon structures and the increase/decrease in the ASW. In the case of the front-on wagons it was possible to observe an increase in ASW in connection to the use of the open wagon.

The effect of the change in wagon orientation showed that the differences in acoustical parameters were more prominent when the wagon structure closed on three sides was employed. Results indicated that side-on wagons resulted in longer reverberation times but lower clarity and a smaller ASW, whereas front-on wagons had shorter reverberation times but higher clarity and a larger ASW. The fact that Stonegate, in the context of the York Mystery Plays, was being used as a multipurpose space, which needed to be adequate for both speech and music performances is of the utmost performance when reflecting on the advantages of the results presented for the side-on and front-on orientations. Clarity and the ASW evidence an increase in the front-on orientation compared to the values recorded for the side-on orientation. These attributes seem beneficial for the performance of the York Mystery Plays, higher clarity being beneficial for speech and a larger ASW being preferable for musical performances. However, the choice of this orientation, based on these characteristics, would have been at the expense of the reverberation time. Moreover, the higher clarity values would have been to the benefit of the actors but to the detriment of the singers of plainchant items. Furthermore, although at first sight it seems that the use of side-on wagons might be a questionable choice due to the lower C_{50}, $IACC_{E3}$ and LF_{E4}, it should be noted that even with the lower values the clarity is still suitable for speech and the ASW is still suitable for the performance of music, making it overall a better choice for the performance of the York Mystery Plays.

The examination of different sound sources allowed the reflection of some possible performer positions in relation to the wagon and street area. When comparing two sound sources located on the main wagon deck, one towards the back (B0) and one towards the front (B1), it was observed that a performer situated towards the front would result in longer reverberation times, which would be an asset for the performance of plainchant items, while still maintaining high clarity, which is essential for speech intelligibility.

The choice between a performer situated towards the back of the wagon deck (B0) or one at street level (B2) does not pose any challenges in connection to the reverberation time, which is not clearly correlated to either of the sources. However, the location at the street level does have an impact on clarity results, which are higher for this position and, when using a side-on wagon, this sound source is also related to a larger ASW.

The comparison between a performer, who is located towards the front of the wagon deck (B1) and one located at street level (B2), demonstrated that a higher reverberation time is attained with the use of the position atop the wagon deck. Although clarity is lower for this position it still provides very high levels and the ASW is larger for source B0 when a front-on wagon is used but lower when a side-on wagon is employed.

The comparison of two performer positions atop the upper wagon deck, which represents heaven, one located towards the back (B3) and the other towards the front (B4), showed that this difference has little impact on the reverberation time, clarity or LF_{E4} parameters. The only clear tendency is for $IACC_{E3}$ where source B4 is connected to an increase in ASW.

The analysis of the positions atop the heaven deck (B3 and B4) and that at street level (B2) demonstrated that the positions atop the upper deck resulted in a higher reverberation time, lower clarity, a higher LF_{E4} and a decrease in $IACC_{E3}$ if used in a front-on orientation. The characteristics of the positions atop the heaven decks indicate that they have attributes that are more suitable for the performance of musical items. This is of particular significance due to the fact that upper decks were used to simulate heaven and might have presented both a good visual and acoustic spot in which to locate the singers, which might have represented angels.

When comparing the positions at the deck representing heaven (B3 and B4) and those positions representing the earth (B0 and B1) a similar tendency was observed, with values for the upper deck showing an increase in reverberation time, a larger ASW when used in a front-on orientation and lower clarity values.

The study of the reverberation time and clarity parameters in relation to the different simulations of Stonegate combined with the four different wagons as well as the audience areas proved that, although some general tendencies can be observed in connection to the correlation between audience areas and the highest/lowest values for each parameter, the abundance of differences across simulations is also evident.

When considering the CL-SI-Aud. simulation the highest reverberation times were found at the standing audience areas (Stonegate 1 and 3), the second level of the scaffold (Stonegate 2) and the top level of the scaffold (Stonegate 2-4). The lowest reverberation times are connected to the use of the first (Stonegate 3) and the second level of the scaffold (Stonegate 1-4).

The study of CL-FR-Aud. simulation indicates that the highest T_{20} and T_{30} values are related to the audience area towards Petergate (Stonegate 1), the second level of the scaffold (Stonegate 2-4) and the third level (Stonegate 4). The shortest reverberation times can be observed at the first and third levels of the scaffold for Stonegate 1, only the first level for Stonegate 2 and 4 and the audience area towards Little Stonegate for Stonegate 3.

The computer models referred to as OP-SI-Aud. and OP-FR-Aud. demonstrate the correlation between the use of the top level of the scaffold and a longer reverberation time. Stonegate 1 and 2 combined with the OP-SI-Aud. simulation have their shortest sound decay at the first level of the scaffold and Stonegate 3 and 4, both at the first and second levels. The shortest reverberation time for the OP-FR-Aud. model is connected to the use of levels one and two of the scaffold (Stonegate 1), the first level as well as the audience located towards Petegate (Stonegate 2), only the second level of the scaffold (Stonegate 3) and only the first (Stonegate 4).

Regarding results for clarity, when considering the CL-SI-Aud. model the highest values were found at the middle (Stonegate 3-4) and the top level of the scaffold (Stonegate 1-4), whereas the lowest values were related to the audience area located towards Little Stonegate (Stonegate 1, 3 and 4), the area towards Petergate (Stonegate 2 and 3) and the first level of the scaffold (Stonegate 2).

When examining C_{50} and C_{80} results for the simulations of the CL-FR-Aud. and the OP-FR-Aud. it was observed that the audience area towards Petergate, which is located facing the sound sources presented the highest clarity values. The lowest values for the CL-FR-Aud. simulation were found in the area towards Little Stonegate (Stonegate 1, 3 and 4) and at the second level of the scaffold (Stonegate 2). In the case of the OP-FR-Aud. model the lowest values of C_{50} and C_{80} are related to the use of the audience area towards Little Stonegate (Stonegate 1 and 3), the second level of the scaffold (Stonegate 2) as well as the top level (Stonegate 2 and 4). The results recorded for the OP-SI-Aud. demonstrated that the highest clarity is achieved at the first level of the scaffold, when considering Stonegate 1, 3 and 4, whereas the lowest values are connected to the use of the standing audience area towards Petergate in Stonegate 1-4 as well as the one towards Little Stonegate in the case of Stonegate 3.

The data corresponding to $IACC_{E3}$ and LF_{E4} shows that although there are differences between the parameters and across simulations, when studying the simulations including the CL-SI, CL-FR and OP-SI wagons it could be observed that the listener positions representing the standing audiences have the largest ASW whereas the positions in the scaffold area correspond to a smaller ASW. The simulations including the OP-FR wagon also seem to follow this tendency when considering the LF_{E4} parameter but when examining the $IACC_{E3}$ results, these indicate that the largest ASW corresponds to the positions towards Little Stonegate (Stonegate 1 and 3) and at the second level of the scaffold (Stonegate 2 and 4), whereas the smallest ASW is related to the use of the top level of the scaffold (Stonegate 1) and the audience area situated towards Petergate (Stonegate 2-4). The difference between the results for $IACC_{E3}$ and LF_{E4} is related to the strong direct sound encountered in the audience area facing the sound sources. The direct sound is part of the calculation of $IACC_{E3}$ but not of LF_{E4} and therefore has a strong influence in the data collected.

The analysis of the acoustics of Stonegate and the wagon structures in relation to the different audience areas demonstrated the impact audiences had on the acoustics of the performance space. When studying the acoustics of theatres or concert halls, acousticians often warn venue designers of the impact of the presence of audiences on the acoustics, since they introduce additional absorption and scattering. However, the introduction of audience areas to Stonegate had a positive acoustical effect; the reverberation time increased, in particular in relation to the second and third levels of the scaffolds, making the space more suitable for vocal performances. Moreover, it is interesting to explore how different acoustical characteristics can be associated with different audience areas. Seated audiences, who would have paid for their seats, seem to have been at positions where the reverberation time is higher while still retaining high levels of clarity. These characteristics seem to indicate that paying audiences had better seats for both the spoken and sung extracts from the plays. However, when considering the ASW it is standing audiences that would have enjoyed better positions. These differences prompt questions on the aural preferences of audiences at the time of the performances, which might be relevant to the period studied but might not be the same characteristics preferred by modern audiences. Research into other spaces used at the time of the plays for both speech and music might shed light on the acoustic preferences in medieval York.

The results presented in this chapter do not have the aim of providing absolute answers to questions on the relationship between staging techniques and acoustics but on the contrary is focussed on the relative values that result from comparing different configurations and analysing the relevance of these in the context of the performance. This study provides an initial insight into the relationship between acoustics, staging and performance and further work needs to be conducted in order to strengthen the findings here presented. For instance, further experimentation in connection to different possible surface materials for the wagons needs to be explored. For example, the use of thinner curtains with lower absorption coefficients for the wagons closed on all sides would make a difference to the results of the different acoustical parameters. Moreover, the exploration of different wagon structures and orientations might also shed light on different staging possibilities and their impact on the acoustics of the performance space.

Chapter 6: Conclusions

6.1 Introduction

The present chapter reiterates the research questions explored in this thesis. A summary of the findings in connection to the research questions as well as conclusions on the results are discussed and future directions for research are introduced.

6.2 Research Questions

The present thesis explored two main research questions:

1. What were the effects of the acoustics of the street spaces used for the performance of the York Mystery Plays on both the spoken and musical parts of the plays?

2. What were the effects of the application of different staging techniques on the acoustics of the performance space?

6.3 Summary and Conclusions

Crucial to this thesis is the conviction that studies on the acoustics of historical performance spaces for music and drama require an interdisciplinary approach. Such approach should not only acknowledge the importance of those elements that are part of the performance, that is, the texts, the musical items, the staging techniques and the performance style, among others, but it should also place at the centre of the discussion an understanding of the culture within which both dramatic and musical elements, as well as performance spaces, originated and developed. Of particular interest is the awareness on notions of sound as well as of hearing and listening. The soundscape individuals from a particular culture inhabited would have had a powerful effect on their perception of dramatic and musical performances, infusing aural cues with meanings that are lost to modern ears. Besides the consideration of individual sounds as forming part of the soundscape, it is also important to consider the acoustic attributes of the spaces contemporaries visited and interacted in as part of everyday life; these could have had an impact, even if unconsciously, on the perception of a dramatic performance or musical piece, since audiences would bring with them the memories of the acoustic spaces they visited and could have used them as the basis for the assessment of their experience of a play.

The analysis of the historiography of the acoustics of drama and music spaces revealed the neglect of the study of those spaces used for medieval drama. The majority of research studies on medieval acoustics have concentrated on the liturgical elements in general and music in particular, within religious establishments. When considering religious vernacular drama in England as a subset of medieval drama traditions, it is possible to wonder whether the lack of acoustical studies is related to the fact that performances were carried out outdoors and no permanent structures were erected, but instead temporary stages were employed. Therefore, it is possible that scholars had preconceptions on the importance of the acoustics of these spaces, which were not specifically designed with the purpose of holding performances.

The present thesis attempted to integrate the study of medieval drama to the field of acoustics by focussing on the York Mystery Plays and using acoustic measurement techniques and virtual acoustics to explore aspects of the performance, staging and reception of the plays in connection to the acoustics of Stonegate and the staging techniques that might have been applied to this space.

Chapter 2 presented the history of the York Mystery Plays and explored theories related to the staging, performance and reception of the plays, while pointing out that the scarcity of evidence regarding these matters calls for the inclusion of acoustics as a discipline, which combined with studies on drama, music, history of art and archaeology, can further our understanding of the plays.

Chapter 3 established how the application of techniques within the field of virtual acoustics could enable the study of the York Mystery Plays through the consideration of the acoustics of the performance spaces. Concepts from the field of acoustics were introduced by concentrating on notions related to performers, audiences and spaces. With this in mind, concepts on the human voice as a sound source were presented as well as concepts on auditory perception. Furthermore, sound propagation in the open field as well as in enclosed areas was discussed. Special emphasis was placed on the discussion of the room acoustical parameters that can be derived from impulse responses measured on site or calculated through virtual models. The parameters were explained by emphasising their connection with auditory perception and the experience of speech and music in a space. Parameter values associated with theatres, concert halls and churches were provided as a point of reference for their subsequent use in the analysis of the York Cycle.

Although these parameters were presented as a useful means for exploring the acoustics of past environments it is essential to remember that they can only give us an indication of the acoustic characteristics of the space and when limited information is available the analysis might need to focus on the differences between several possible characteristics of the environment as well as different possibilities regarding its use. Therefore, it is possible that relative values are more revealing than absolute ones. Furthermore, these objective parameters cannot inform us as to how the plays were perceived and experienced in past cultures. Although research on sound and hearing in the medieval period can help us determine possible reactions to the plays, caution should be exercised when arriving at conclusions on what these meant to performers and audiences, as modern forms of listening should not be assigned to past cultures.

Chapters 4 and 5 presented the work conducted with the aim of answering the research questions. Chapter 4 studied the acoustics of Stonegate as an example of one of the stations of the York Cycle. Stonegate was chosen due to the fact that it is the better preserved of the stations, with buildings dating from the period of the performance of the plays still standing there today. Its state of preservation made it particularly appealing for an acoustical study as it allowed research to start by conducting acoustic measurements on site. The completion of these measurements was not free from challenges as an appropriate method for capturing impulse responses in an outdoors environment, which is also one of the busiest streets in York, had to be carefully selected. The method chosen was the ESS, using a 90-second sine sweep, and it was selected after conducting an experiment in a controlled environment to determine its reliability in the presence on the types of noise sources found in Stonegate. The measurements on site used one source position, which was located within a hypothetical performance area situated at the location of the station used in the 1569 performance. Three receiver positions, which represented audience members, were also used. Results demonstrated that Stonegate possesses a short reverberation time and high clarity, which are features that are beneficial for speech intelligibility and as a result suitable for the spoken extracts of the plays. However, those same characteristics make it a less satisfactory space for the performance of plainchant items, which are better suited to spaces with a long reverberation time and low clarity. Nevertheless, Stonegate does have an acoustic feature coveted for music performances, which is the high levels of ASW, which indicate the perceptual broadening of the sound source.

The next step in the study of the acoustics of modern Stonegate was the design of a computer model that attempted to reconstruct the acoustics of the space as it is today. The geometry and surface properties of the space were simulated using CATT-A and the acoustic predictions were carried out using TUCT. The results from the acoustic measurements conducted on site where used to carry out an objective comparison between the real-world acoustics and that predicted by the computer model. Through a process of calibration the virtual model was approximated as much as possible to the characteristics of the real space. The model was most accurate in relation to the parameters T_{20}, T_{30}, C_{50}, C_{80}, $IACC_{E3}$ and LF_{E4}, and as a consequence these were the parameters used for the remainder of the project.

A subjective analysis of the results was also implemented in order to establish the connection between the objective accuracy and listeners' perception. Furthermore, the analysis had the aim of determining whether there was a correlation between the perceived accuracy of the model and the source material utilised, as well as to study whether accuracy varied across receivers. The subjective analysis was executed through the design of a listening test using the double blind triple-stimulus with hidden reference test suggested in the ITU-R BS.1116-1 standard. The aim of the test was for subjects to compare an auralization derived from the real-world acoustic measurements to one derived from the virtual model and determine whether they could differentiate them and how large they thought the difference between samples was. The results indicated that subjects could tell the difference between real and simulated reality and 55% of the results rated the similarity between samples from 3-5 in the given scale, 5 being an imperceptible difference. Results also indicated that the auralizations that used receiver 2 presented the smallest perceived differences, owing to the accurate prediction of C_{50}, C_{80} and $IACC_E$. Furthermore, the statistical analysis demonstrated that the use of musical pieces for auralizations resulted in the differences between the real and the simulated space being perceived as smaller, this was particularly evident when the monophonic syllabic and melismatic chants were used.

Once the virtual model of modern Stonegate had been analysed both objectively and subjectively it was altered in order to fit the characteristics the street might have had in the sixteenth century. Information on what the street was like in this period only indicates some of the main characteristics of some of the buildings, for example, whether they were two- or three-storeyed buildings and the fact that they were timber-framed. Due to the lack of specific information regarding every building modelled it was decided that eight different versions would be generated. These versions differed from one another in relation to the height of the buildings, the windows being open or closed and the type of window used, in-line with the wall or projecting. The results of these models were then analysed in order to determine whether the changes across the simulations actually created differences in the results of the acoustical parameters. It was demonstrated that differences in reverberation time and clarity parameters were caused by the alternation between structures with open and closed windows, with the models that had no windows resulting in lower reverberation times and higher clarity values, which simulated the effect produced if all windows had been opened. Differences in the height of the street façades also produced variations in the reverberation time and clarity, higher buildings resulting in higher reverberation time and lower clarity. Changes in the window type did not produce any significant differences and, as a result, in subsequent analysis only one window type (in line with the wall) was considered, with the only exceptions being the buildings in which evidence indicated the use of projecting windows. The parameters of spatial impression, $IACC_{E3}$ and LF_{E4}, presented negligible variations as a result of the changes across the virtual models. Furthermore, the comparison of the sixteenth-century simulations to the virtual model of modern Stonegate demonstrated that when the latter was compared to the simulations with closed windows the differences in the results of the acoustical parameters were below 2JNDs. This indicates that modern performances in this space would be conducted in a similar acoustical setting than the performances of the sixteenth century.

Chapter 5 explores the impact of different staging configurations on the acoustics of sixteenth-century Stonegate. The four models of Stonegate that were shown to vary in their acoustics, as a result of the changes in the reflecting surfaces of the windows and the height of the buildings, were considered, whereas the models representing an alternative window type were discarded. Wagons were incorporated to the street simulations in order to explore five questions. Firstly, whether they produced an impact on the acoustics of the street space studied. Reverberation time and clarity were observed to be affected by the incorporation of the wagon structures, with the former presenting, in the greater number of cases, a drop in values, and the latter evidencing an increase. The $IACC_{E3}$ and LF_{E4} parameters were also influenced and a general tendency towards an improvement in the ASW was observed.

The second question explored was whether a difference in acoustics was produced when using a wagon closed on three sides or one open on all sides. The change in wagon structure was shown to have affected all parameters significantly. Variations in the structure when using the side-on orientation resulted in Stonegate 1 and 4 being the most affected simulations. Stonegate 1 had the longest reverberation time when an open wagon was used whereas Stonegate 4 had the longest reverberation time when the closed wagon was used. The study of the front-on wagons indicated a more straightforward correlation between the use of an open structure and the increase in reverberation time. Clarity parameters were more sensitive to the change in structure but these results differed depending on the street simulation analysed. Stonegate 2 had higher clarity when open wagons were used, whereas Stonegate 1, 3 and 4 evidence an increase in clarity when the closed wagon was incorporated. Spatial impression parameters $IACC_{E3}$ and LF_{E4} were also affected by the change but it was the former that was affected the most. Its examination in relation to the side-on wagons demonstrated that the results are highly dependent on the receiver position and general conclusions could not be reached. However, when studying front-on wagons it was observed that a larger ASW was the result of the use of an open wagon.

Another question explored was whether the change in wagon orientation had an impact on the acoustics. The examination of the results showed there were differences in all parameters as a result of the change in orientation but these differences were particularly evident when it was the closed wagon that changed orientation. The side-on orientation resulted in a higher reverberation time than the front-on wagon, whereas the front-on wagon resulted in higher clarity and a larger ASW. Nevertheless, it is important to bear in mind that although clarity and ASW are smaller for the side-on orientation they are still within the range considered appropriate for speech in the case of clarity and music in the case of the ASW. Furthermore, the increase in clarity in the front-on wagon is detrimental to the performance of plainchant items and it is at the expense of the reverberation time.

Another point for analysis was focussed on the effects of changes in the performer's location. When comparing positions atop the wagon deck which differed by being placed towards the back or the front of the wagon, it was observed that the position towards the front had a higher reverberation time, which would have been an asset for musical performances, while still maintaining high clarity values appropriate for speech. When the source placed towards the back of the wagon deck was compared to that at street level it was observed that the latter had higher clarity and when used in a front-on orientation also had a larger ASW. However, when the street level source was compared to that one towards the front of the wagon deck the latter had a longer reverberation time, while still recording appropriate clarity for speech. In the case of the side-on wagon the ASW was reduced with the use of the street level source, but the opposite was true for the front-on orientation. Differences between the two sound sources located on the wagon deck that represents heaven presented small differences, the only clear difference being found for $IACC_{E3}$ where it was the use of the source towards the front that resulted in the increase of the ASW. The comparison of the sources on the heaven deck to those at street level and on the lower deck, which represents the earth, demonstrated that the use of the sources in the upper deck resulted in higher reverberation times, lower clarity and an increase in ASW, particularly emphasised when using a front-on orientation. These tendencies seem fitting to the use of this space for musical performances representing angelic singing.

The results presented above regarding the wagon simulations, analysed the impact of the wagon structures without considering audience areas. The effect of audiences was analysed separately through the addition of two standing audience areas at the sides of the wagons and three levels of scaffolds placed against the right-hand side of the pageant route. The analysis of the results indicated that, although some general tendencies can be reported, results were highly dependent on the street simulation used as well as the wagon structure. In the case of the CL-SI-Aud. simulation the highest reverberation times were achieved at the standing audience areas as well as at the second and third levels of the scaffold. The highest levels of clarity were also recorded for the second and third levels of the scaffold. The study of the CL-FR-Aud. model showed that the highest reverberation time was connected to the use of the standing audience area located towards Petergate as well as the second and third levels of the scaffold. The audience area towards Petergate also recorded the highest clarity values. The OP-SI-Aud. and OP-FR-Aud. models had the highest reverberation time when the top level of the scaffold was used. Higher clarity for the OP-SI-Aud. version was achieved through the use of the first level of the scaffold whereas for the OP-FR-Aud. design it was through the use of the standing audience area towards Petergate. In all simulations there was a tendency towards a larger ASW for the standing audiences.

The analysis of the results in relation to the audience areas showed that the introduction of such areas to the virtual models had a positive impact on the acoustics, making the space more suitable for music. Furthermore, the tendency towards higher reverberation time at the scaffold seats, but higher ASW for standing audiences poses questions on the aural preferences of the time and whether it was the paying or non-paying audiences that were better located.

6.4 Future Work

The present thesis contributed to knowledge by establishing the relevance of acoustical studies on the performance spaces linked to medieval drama. The study of the York Mystery Plays exemplifies the importance of such an approach, through the examination of the acoustics of Stonegate and the study of the impact of different staging methods.

The acoustics of the street space was shown to be more appropriate for the speech extracts than from the musical items of the plays, particularly when focussing on the analysis of reverberation time and clarity. However, the characteristics regarding spatial impression are favourable to the performance of music, which might have partially made up for the less suitable reverberation and clarity.

Furthermore, it was shown that the inclusion of wagons had notable effects on the acoustics of the street space and changes in the type of structure, their orientation and the performers' positions resulted in significant differences which could result in an increase or decrease of reverberation time, clarity and ASW. These results contribute to the theories developed by scholars by providing further aspects to consider when discussing staging techniques and their possible advantages and disadvantages.

The differences in acoustics recorded as a consequence of the changes in relation to the staging of the plays makes it possible to argue that the organisers of the plays could have used the street spaces and their wagons to make the most of the acoustic characteristics. Although the physical reasons behind these differences in acoustics might not have been understood they might have been explored through a process of trial-and-error. The wagons themselves might have been built in different manners to accommodate the need for better-suited acoustics. When discussing Elizabethan drama it was mentioned that companies of actors considered the wooden frame of their theatres as an essential part of their equipment and could take it with them if necessary. It might be possible to apply a similar notion to the guilds and their wagons. These wagons were also an essential tool for the performances, guilds were willing to maintain them throughout the years, preserve them from damages, rebuild or adapt them and pay for special places for their storage. Therefore, they might have been to the guilds as precious as the wooden frames used for Elizabethan theatres and they might have also been aware of how their use modified sound during performances. For example, they might have noticed that locating singers representing angels at an upper wagon deck with a reflecting surface at their backs resulted in longer decay times than if they were located at street level. Both visual and aural aspects might have come together to make the most of the performance space through the use of the wagon structures.

Future work should include the consideration of a greater variation of staging possibilities. The Mercers' 1501 wagon, which was closed on three sides but whose surfaces were wooden, might have produced a very different effect than that of the closed wagon with absorbent curtains used for this project. Crucifixion plays have often been thought of as being performed on flat carts, which again would produce a different effect than those studied in the previous examples. The open wagon could also be modified to include a flat roof instead of a pitched roof enabling the study of the differences this change might have produced. Different surface materials should also be experimented with to determine their effect. Furthermore, performers' positions as well as audience areas could be varied to analyse their impact on speech and music. The design possibilities are vast and the larger the number of experiments the more conclusive the connection between staging and acoustics will become.

The simulation of Stonegate could also be modified by attempting to simulate its different features throughout the centuries. Although this will not necessarily produce absolute results it will enable the comparison between computer models and increase the palette of acoustic possibilities.

In addition to furthering research through the creation of more variations of the models it is also of importance to explore in more detail the soundscape of York at the time of the plays. The acoustic characteristics of other buildings used by contemporaries, for example, for preaching and the performance of plainchant and polyphonic music, might shed light on the acoustic settings that were familiar to the performers and audiences of the plays. A particularly interesting avenue for research is the study of the acoustics of medieval parish churches through a combination of acoustic measurements and virtual models in order to better determine what the acoustic aesthetics of the time might have been like (Masinton 2006). Such a study would allow the acoustics of the playing stations to be analysed in connection to the other spaces frequented by performers and audiences and arrive at a greater insight on what the acoustics of the performance spaces might have meant to medieval audiences.

Glossary

Abbreviations and Terms

Absorption	The removal of acoustic energy from a space as a consequence of the presence of different surface materials.
Anechoic Chamber	A room that is especially designed to eliminate all sound reflections by the use of sound absorbing material.
ASW	Apparent Source Width. A parameter associated with the perceptual broadening of the sound source.
'A/Y' Memorandum Book	This book records the different affairs of York including guild ordinances, accounts of events and records of council meetings, among others. The letter A indicates that it is the first record and Y specifies that it corresponds to York.
CATT-A	Computer Aided Theatre Technique-Acoustic. A computer application used to generate virtual models for acoustical studies.
Convolution	A mathematical operation that can be used to apply the acoustic characteristics of a space to an audio signal.
Corpus Christi Feast	Religious feast that celebrates the body of Christ in the host.

Dry Recording	Sound recording with no spatial information. It is carried out in an anechoic chamber.
EDT	Early Decay Time. A parameter that calculates reverberation time considering the first 10dB of the decay curve.
ESS	Exponential Sine Sweep. It refers to a method for impulse response measurements.
Free Field	A space where there are no sound reflections.
Homorhythmic	Usually used to refer to a polyphonic piece in which the voices share similar rhythmic characteristics.
HRTF	Head-Related Transfer Function
IACC	Interaural Cross-Correlation Coefficient
Incipit	The first words at the start of a text, such as a song.
IR	Impulse Response. The way in which a space responds to an impulse and modifies it.
JND	Just noticeable difference. The smallest perceptible difference between samples.
LTI	Linear time invariant. A system whose response to an audio signal does not change in time, if we input a signal now

	or in five minutes' time, the results will not vary. If we double the intensity of the input to the system, then the output signal will also double.
Monophonic	A musical piece with only one melodic line.
Musical Incipit	The first few notes of a musical piece.
Mysteries	Craft guilds
Ordo Paginarum	The Order of the Pageants, a document within the 'A/Y' Memorandum Book which dates from 1415 and consists of a list of the guilds and the content of their respective plays.
Planctus	A song or poem that is used to express grief and used for mourning.
Polyphonic	A musical piece with two or more melodic lines.
RCHM	Royal Commission on Historical Monuments England
REED	Records of Early English Drama
Tableaux	The static representation of an event by actors.
TUCT	The Universal Cone Tracer. A computer application used to carry out acoustic predictions.
Wavelength	The distance travelled by a wave within a cycle.

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