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The Application of Impulse Response Measurement Techniques to the Study of the Acoustics of *Stonegate*, a Performance Space Used in Medieval English Drama

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Summary
The present paper provides an insight into the acoustic characteristics of one of the spaces used for the performance of the *York Mystery Plays*: Stonegate, a street in central York (UK). An experiment conducted in a controlled environment with the aim of determining the optimal method for acoustic measurements on this site is first presented. The methods tested were the Exponential Sine Sweep (ESS) method with the application of time averaging of eight 15-second exponential sine sweeps and the ESS method with a 90-second sine sweep. Results demonstrate the greater robustness under the test conditions of the ESS method when used with a sine sweep of 90 seconds in length. Results from measurements at Stonegate using this method are then discussed, demonstrating that the space has appropriate reverberation time and clarity values to ensure speech intelligibility but would prove less satisfactory for the performance of the plainchant items that were part of the plays. Results also indicate that Stonegate presents low levels of spaciousness and high levels of listener envelopment at most of the receiver positions studied.

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1. Introduction

The relationship between acoustics and theatre performances throughout history has been an area of extensive study [1]. However, research on pre-seventeenth century theatre acoustics has focussed either on Greek and Roman [2, 3, 4, 5, 6, 7, 8, 9, 10, 11] or Elizabethan theatre [12]. The study of medieval acoustics has been centred on churches both as worship spaces [13, 14, 15] and as sites of liturgical drama [16], leaving aside the spaces used for the performance of medieval English drama. In the present paper medieval English drama refers to a group of plays in the vernacular and with a religious subject matter, which were first performed in England in the fourteenth century [17]. The scarcity of acoustic studies on this subject is mainly due to two characteristics of the performance spaces: they were outdoors and no theatres were built, instead temporarily assembled stages were used [18].

The *York Mystery Plays*, also known as the *York Cycle* is thought to have originated in the late fourteenth century and it was performed annually until the late 1560s [19]. The cycle consists of forty-eight separate plays that narrate events of relevance to the Christian faith. The plays included both spoken word and music in the form of plainchant and polyphonic items. The performances were staged on wagons that were specifically constructed for the occasion by the different guilds in charge of the plays and were manhandled through the streets of York. The wagons followed a predetermined route through the city and stopped at stations (street spaces) where the audience gathered to see the performance.

One of the better-preserved sites of the performances is found at Stonegate in central York. The preservation of this site together with the fact that in the Middle Ages it presented a semi-enclosed space, due to its narrow width and its jetties [20, 21], make it an interesting subject for acoustical analysis. Stonegate is also significant as it was used for performances during the entire life of the cycle, which suggests that its selection as a performance space might have been related to its acoustic characteristics, as much as by social and economical factors [22]. The fact that Stonegate is so well preserved means that the study of its acoustic characteristics through impulse response (IR) measurements can provide an insight into its use as a performance space.

Carrying out IR measurements in Stonegate requires the consideration of the challenges involved in acoustic measurements of outdoor urban sites. These considerations, as it will be seen in sections 2 and 5, include problems related to selecting an appropriate method to achieve a good

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signal-to-noise ratio (SNR) as well as issues in connection to site restrictions and the number of visitors to the space.

The present paper introduces an experiment in a controlled environment that was conducted with the objective of determining the most reliable technique for measurements when presented with the challenges mentioned above and also those particular to the site of interest. Then, the results of a set of measurements in Stonegate are presented and analysed in relation to the use of the street space for drama performances.

The research here presented forms part of a wider project whose aim is to recreate the acoustics of Stonegate in the Middle Ages as well as the acoustics of the wagon structures that could have been used. The measurements on site will be employed as a starting point for the construction of the virtual model of the medieval street space.

2. IR measurement techniques

Several techniques have been developed throughout the years with the objective of measuring the impulse responses (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 as excitation signals, 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 [23]. 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 SNR [24].

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 in the presence of 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) [25, 26, 27] which employs an exponential sine sweep with a pink spectrum and the deconvolution is linear, using an inverse filter (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) [25, 26, 27]. 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 [25]. 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 [27].

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 3 dB each time the number of measurements is doubled [24]. 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 [25, 28] and more significantly by the presence of passers-by. When time averaging is applied these variances will produce further errors in the calculation of the acoustical parameters [24, 28], 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 3 dB [24]. When considering fully enclosed spaces this technique has been shown to provide more reliable results than time averaging [24, 27], 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 [25].

3. Previous 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 [29, 30, 31, 32] and speech intelligibility [32], and great emphasis has been placed on the effects of weather conditions [32], and on the use of modelling to simulate sound propagation [30, 33]. Different researchers have chosen to use different excitation signals when carrying out IR measurements. In 1976 Yeow [34] used firecrackers to carry out measurements in Kuala Lumpur, while Picaut *et al.* [31] carried out IR measurements in Nantes, France, using

Table I. Methods tested in controlled experiment.

	Technique	Excitation Signal
Method 1 (90-second sweep method)	ESS	90-second exponential sine sweep. Frequency range = 22–22000 Hz
Method 2 (Time averaging method)	ESS	Eight 15-second exponential sine sweeps, time averaged after the measurements. Frequency range = 22–22000 Hz

an alarm pistol and an array of 9 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.* [35] 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 that same space.

Thomas *et al.* [36] 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. Sound pressure level (SPL) measurements were carried out during the concert.

There are, to the authors' knowledge, no extant acoustic studies that have considered urban spaces that have been regularly used by past cultures for drama and music performances. When carrying out measurements of such spaces it is of importance for the measurements to be based on an understanding of how the space was utilised in the historical period of interest (see section 5.1). For instance, the position of performers and audience in the space is essential when considering the positions of sources and receivers.

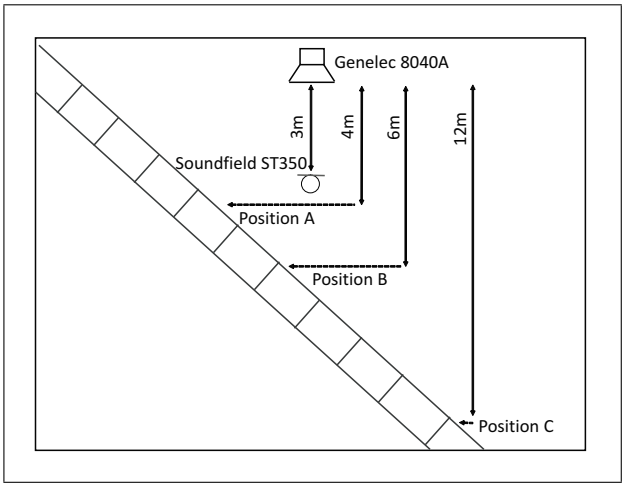

Figure 1. Setup in Black Box Theatre, Department of Theatre, Film and Television, University of York.

Table II. Attenuation of sound energy at the rear of the source (180°) compared to the sound energy at the front (0°). The data regarding the directivity of an opera singer was sourced from [39], whereas the directivity of a talker was sourced from [40]. The directivity of the Genelec 8040A was taken from the Common Loudspeaker Format (CLF) file.

Sound Source	Opera Singer	Talker	Genelec 8040A
500 Hz	-7.5 dB	-6.1 dB	-10 dB
1 kHz	-5.5 dB	-5.0 dB	-10 dB
2 kHz	-16.0 dB	-10.9 dB	-20 dB
4 kHz	-15.5 dB	-16.6 dB	-25 dB

4. Comparison of IR measurement techniques in noisy environments

4.1. Experiment in a controlled environment

An experiment was conducted in a controlled environment to determine what measurement method might be preferable for carrying out acoustic measurements in Stonegate [37]. The experiment was setup in the Black Box Theatre of the Department of Theatre, Film and Television (University of York) (Figure 1) and the methods tested are specified in Table I. 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 different measurement methods in order to determine the most reliable technique to conduct measurements on site.

For testing the ESS method with a long sweep a 90-second exponential sine sweep was utilised. This length was chosen due to its suitability for Stonegate, which has a reverberation time estimated as 1.5 s. To achieve acoustic measurements of 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 [25], making 1.5s the minimum length possible for the measurements in Stonegate. Using a 90-second sine sweep the SNR will improve by 17.78 dB, when compared to this minimum length (see section 2). 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 than with the 90-second sweep and keeping the measurement time as short as possible. Therefore an increase of 9 dB was achieved with a measurement time of 120 s by using eight 15-second sine sweeps.

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

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

The speaker used to play the excitation signal was a Genelec 8040A Monitoring System. It was considered appropriate due to its directivity. Although an omnidirectional source is recommended in ISO 3382 [38] a directional source was used due to the fact that in the measurements in Stonegate it would be representing an actor and/or singer. Vocal directivity is characterised by being omnidirectional at low frequencies and increasingly directional at higher frequencies, which is a result of the acoustic shadowing effect produced by the head and torso, as well as the effect of the mouth aperture [39]. The Genelec 8040A speaker has similar characteristics to the vocal directivity (Table II) allowing us to determine the acoustic response of the space to a directive source similar to the one of interest.

A Soundfield ST350 microphone was employed to record the response. The Soundfield microphone was chosen as it allows us to measure the sound pressure (known as the W channel) and particle velocity in three dimensions (X, Y and Z channels) at the microphone position. This is known as the Ambisonic B-format representation of the soundfield. Both source and receiver 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. A MOTU Traveler mk3 and an HP laptop were used for running Pro Tools 9 [41] and for signal acquisition and playback. A second Genelec 8040A was mounted on a dolly track and it was used to playback noise sources. A rope was attached to the speaker to allow the simulation of sound source movement.

The sources of noise chosen for the experiment were selected due to their presence in Stonegate: ambience, York Minster Bells, speech, footsteps and footsteps+speech (referred to here as F+S). The average frequency content of each noise source is specified in Figure 2. 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 near field. Position C was in the diffuse field, approximately 12 meters away from the speaker. The fourth position was a mobile position: the speaker on the dolly tracks was moved 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 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.

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

Sine Sweep (90 seconds)	Sine Sweep (15 seconds)
86.5 dB(A)	86.5 dB(A)

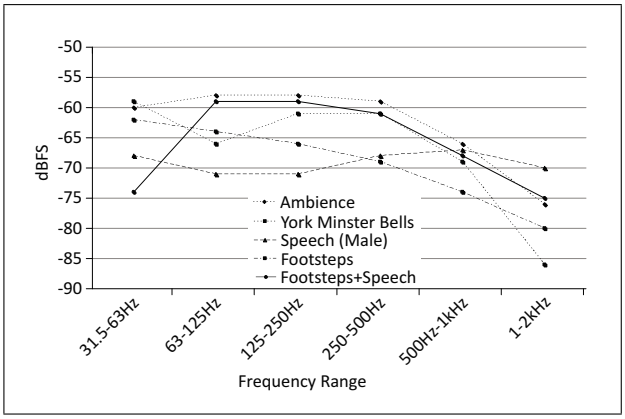

Figure 2. Average frequency content of noise sources.

In this particular experiment difficult test conditions in relation to the SNR were purposefully chosen in order to be able to analyse how the measurement methods performed in challenging noise conditions. For this reason, the reference output level of the loudspeaker was set to 73.5 dB(A) at 1m using a -20 dBFS pink noise signal. The levels at which the excitation signals and noise sources were played are specified in Tables III–IV, whereas the level of the noise sources at the microphone position are included in Table V.

The excitation signals were generated with the Aurora plug-ins [42] and the measurements were deconvolved using a Voxengo Deconvolver [43]. The analysis of the results is focused on the W channel of the B-format microphone. Three acoustic parameters related to reverberation time were calculated: T20, T30 and EDT. Whereas T20 calculates the reverberation time from the decay curve ranging from -5 to -25 dB, requiring the decay curve to start 35 dB above the background noise level, T30 considers the -5 to -35 dB range and the decay curve needs to start 45 dB above the background noise level [38]. Both T20 and T30 were considered in order to compare their results and determine whether it is possible to calculate T30 in environments such as Stonegate. The EDT (Early Decay Time), which calculates reverberation time considering the first 10 dB of the decay curve, was considered as it has been proven to be the parameter more closely related to the perception of reverberation [44]. Clarity is an early-to-late arriving energy ratio expressed in decibels, which

Table V. Long-term average SPL dB(A) of the noise sources at the receiver position.

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

can be calculated using C50. C50 considers the division between early and late energy as 50 ms and gives an indication of speech intelligibility and definition in a space.

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. 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 T20, T30 and EDT was considered as 5% [45] 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 [46]. The JND for C50 was considered to be 1.1 dB [47].

4.2. Analysis of results

The results of the measurements with no noise disturbances for both methods were very similar (Figure 3). 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 C50. No inaccurate results were found for this parameter with the introduction of noise sources, demonstrating the reliability of the results of C50 even in the presence of unfavourable circumstances during the measurements.

Regarding the parameters related to the reverberation time both methods were affected by the noise sources. Table VI 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 F+S samples which had the greatest negative effects from 125–500 Hz due the high spectral density of those noise sources at those frequency bands (Figure 2). 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 250 Hz to 1 kHz due to the presence of harmonics at these frequency bands.

It was the positions in the near field that had the greatest impact on the results of the three methods. There was very little impact of noise sources at 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.

Table VI. Highest deviations from results in optimum conditions calculated in JNDs.

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

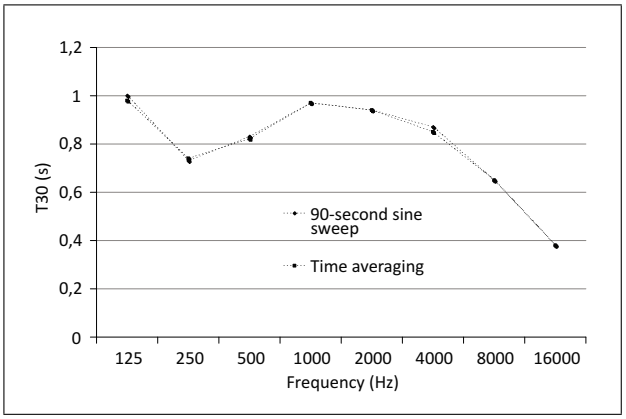

Figure 3. Mean values and standard deviation of the two measurements of T30 in a setup with no noise disturbances.

The experiment here presented was specifically conducted to arrive at a better understanding of what the most suitable method might be for measurements in Stonegate, taking into considerations the characteristics and restrictions of the site. The results here presented indicate that the 90-second sweep is the best choice for the site in question, confirming the findings reported in section 2. However, further studies on the effects of noise sources on the methods tested need to be carried out before arriving at generalisations on the most robust method for outdoors acoustic measurements.

5. Measurements in Stonegate

5.1. Setup

A set of IR measurements was carried out in Stonegate using the ESS method with a 90-second exponential sine sweep with a frequency range of 22–22000 Hz and 10s of silence after each measurement, allowing the high frequencies to decay completely. The sound source utilised was a Genelec 8040A Monitoring System and the re-



Figure 4. IR measurements in Stonegate (February 2012).

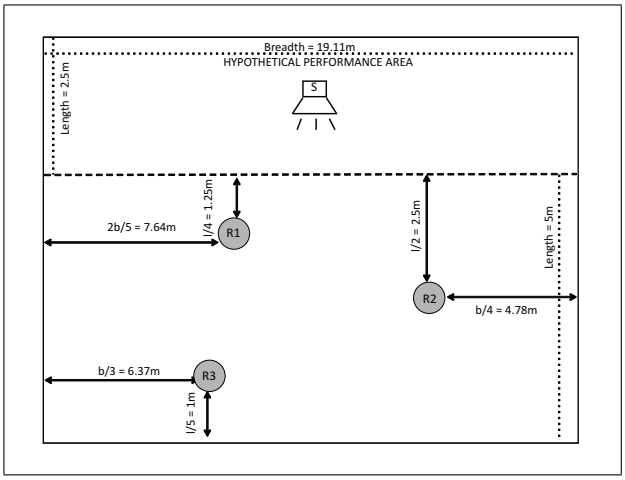

Figure 5. Positions of source and receivers in Stonegate.

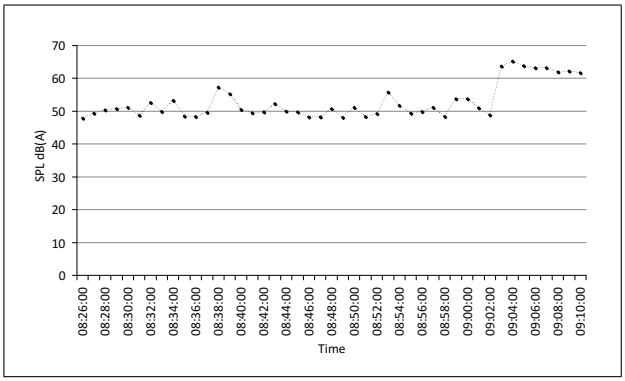

Figure 6. Measurements of SPL dB(A) taken in Stonegate on July 15th, 2012 from 8:26–9.10am.

ceivers used were a Soundfield SPS422B microphone and a Kemar dummy head. The latter provided binaural impulse response measurements, which were used to calculate the Interaural Cross-Correlation Coefficient (IACC). The soundcard used was a Fireface 800 while Pro Tools 9 [41] was employed for loop playback and recording.

The location chosen for the measurements is the Mulberry Hall area of Stonegate (Figure 4) which coincides with the location of the playing station of the *York Cycle* [21]. The objective of the measurements was not to determine the soundfield of the whole street, but more specifically to further our knowledge on the acoustic characteristics of this particular portion of the space used for these drama performances.

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 space. The measurements were conducted without including the presence of a wagon but instead considering the performance as carried out at street level, which is thought to have been an option at the time of the plays [48]. Therefore, source and receivers were positioned at a person's ear height (1.65 m). The effects of the presence of a wagon will be studied at a later stage using the virtual model of the medieval urban space. The setup used for the measurements consisted in one source position, which represented a performer at the centre of a hypothetical performance area. This performance area was delimited by taking the breadth of Mulberry Hall and the approximate depth of a medieval wagon [49] as a guideline for setting the boundaries of the performance area at street level. Moreover, the performance area was also delimited considering that the actors and singers might have performed to the side of the street rather than towards one of the ends. Therefore, the source was positioned towards Mulberry Hall and three receiver positions, which were positioned towards the speaker, were selected following the indications made by Gade [50] (Figure 5) and followed the recommendations of ISO 3382 by positioning the microphones more than half a wavelength from each other and at least a quarter of a wavelength from any reflecting surfaces [38].

The temperature recorded at the time of the measurements was approximately 2°C.

A determining factor of the choices 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 (Figure 6), consequently measurements taken closer to 9am are more likely to present low SNR and being affected by passers-by. Another complicated 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.

The limitations imposed by the site 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 [45]. Furthermore, although it would

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

Measurement (S-R)	Number 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*

have been of interest to position source and receivers considering the possibility of actors performing towards the side of the street and towards the end of the street, only the former was selected for the measurements.

The reference output level for the excitation signal was recorded using pink noise and it was 88 dB(A) at 1m from the source. The background noise was measured as 58 dB(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 individuals, 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 (Table VII). Deconvolution was implemented using a Voxengo Deconvolver [43] and the IRs were analysed using the Aurora plug-ins [42].

The energy decay curves for the three receiver positions at 1kHz (Figures 7–9) indicate the higher SNR achieved in the acoustic measurements for receivers 1 and 2 in comparison to receiver 3. The significant difference is related not to the distance of the microphone from the source, but 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 6 there is a tendency to an increase in background noise levels with the passage of time that can affect the calculation of T30.

5.2. Analysis of results

The measurements in Stonegate were analysed through parameters related to reverberation time, clarity and spatial impression. Although reverberation time is mostly considered when studying fully enclosed spaces it was deemed of importance to allow the fast comparison of the performance space studied with other enclosed spaces used for theatre performances, as well as those used for the performance of medieval music. Both T20 and T30 were calculated in order to analyse the way in which background noise affected the measurements, and to determine whether it is possible to calculate T30 in this particular site and with the limitations mentioned; the EDT was also

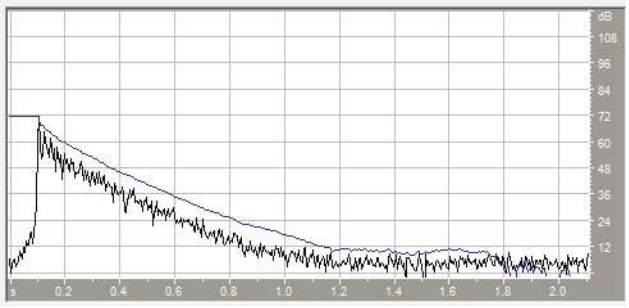

Figure 7. Energy decay curve corresponding to S1–R1 at 1 kHz.



Figure 8. Energy decay curve corresponding to S1–R2 at 1 kHz.

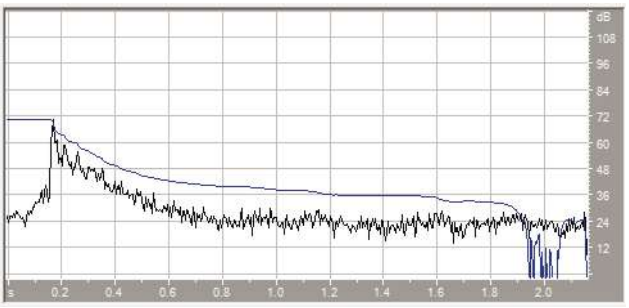

Figure 9. Energy decay curve corresponding to S1–R3 at 1 kHz.

calculated.Clarity was measured through the C50 and C80 parameters. C50 was chosen due to the relevance of speech intelligibility in the plays, whereas C80 is more suitable for the analysis of music and considers the division between early and late energy as 80 ms. The reverberation time and clarity parameters were calculated considering the responses recorded with the Soundfield microphone.

Spatial impression refers both to the Apparent Source Width (ASW) and the Listener Envelopment (LEV). The ASW is associated with the sense of spaciousness, that is, the perceptual broadening of the sound source related to the presence of early lateral reflections, whereas the LEV is associated with the late lateral reflections [51]. In the present paper the ASW has been analysed using the parameters $IACC_E$ and LF (Early Lateral Energy Fraction). The $IACC_E$ parameter measures the dissimilarity of signals arriving at both ears considering the first 80 ms 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 [52, 53], indicating a greater sense of spaciousness. This

parameter has been measured using the KEMAR dummy head and torso. The LF parameter is the ratio between early lateral energy (5–80 ms, early reflections) and early omnidirectional energy (0–80 ms, 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 [54]. In the present paper this parameter was calculated using the W- and Y-channels of the Soundfield microphone.

The LEV was studied considering the $IACC_L$ parameter which takes into account the sound arriving 80 ms 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 [55].

Both the $IACC_E$ and $IACC_L$ parameters can be calculated as $IACC_{E3}$ and $IACC_{L3}$ when the results are the mean across 500 Hz–2 kHz [54]. These frequencies are used due to the fact that the wavelength at those frequencies is similar or smaller than the dimensions of the head of an average listener [56].

5.2.1. Reverberation time

The reverberation times (T20, T30, EDT) measured from 125 Hz–4 kHz are within the range that Barron indicates is present in several theatres (0.7–1.2 s) and that is appropriate for speech intelligibility [1]. However, it is also necessary to consider that the plays included the performance of plainchant items. These 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 T30 of 6.1 s at 1 kHz [57]. The short reverberation time of Stonegate in comparison to the York Minster is of relevance when considering 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 (cathedrals, abbeys) they were composed for [58]. Furthermore, although they are monophonic pieces, when performed in reverberant spaces they benefit from the harmony produced when a note is sung at the same time than the reverberation from the previous note [1]. This effect is lost when performed in a space such as Stonegate. Beranek [59] also comments that the musical pieces lose their impact when performed in spaces with low reverberation times.

Regarding the singers, some of them would have been trained performers, and might have been part of the York Minster choir [17, 60], therefore 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.

It is possible that the wagon structures (the stages) built for the performances and positioned in the street would have also affected the acoustics of the space and even provided a higher reverberation time and therefore would have been more suitable for the performance of plainchant items. With the aid of computer models research will be carried out to determine whether this would have been possible.

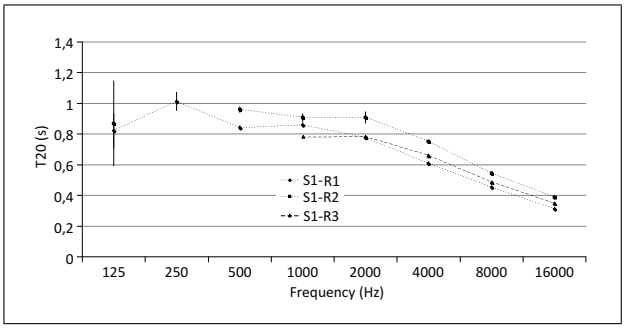

Figure 10. Mean T20 and standard deviation.

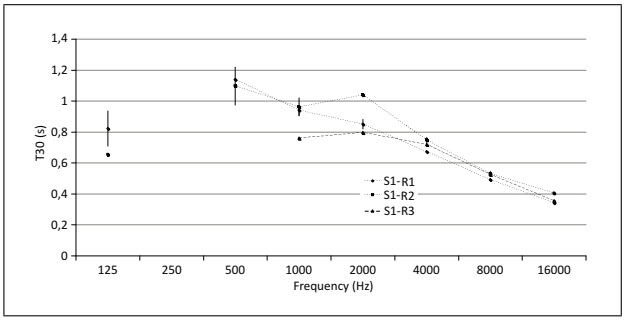

Figure 11. Mean T30 and standard deviation.

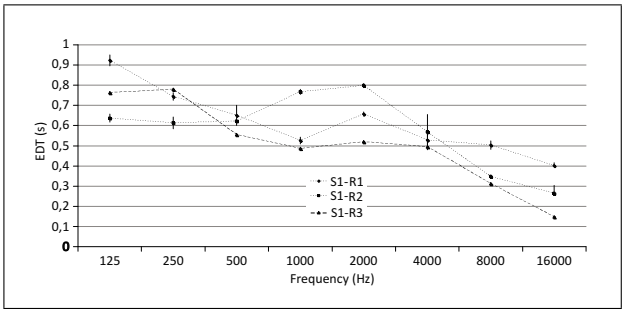

Figure 12. Mean EDT and standard deviation.

EDT values measured range from 0.15–0.93 s, the highest value being present at S1–R1. Most of the values recorded are below the suggested range of reverberation time for theatres as well as below the values suggested for concert halls 1.8–2.2 s [61]. Due to the fact that the EDT parameter is more closely associated to the actual perception of reverberation a deviation from the optimum range is considered of greater importance than a deviation of T20 or T30 [61]. Although these values are likely to produce good intelligibility, Barron suggests that values below 0.5 s would produce discomfort to listeners [1].

5.2.2. Clarity (C_{50})

The mean clsrity (C50, C80) values across all S-R combinations show results that are higher than the optimum clarity values for concert halls, which range from −2 dB to +2 dB [1]. The highest values are present at S1-R1 and S1-R3. These high values were expected due to the greater amount of early energy in comparison to late energy as

Table VIII. Mean Values of T20 and T30 across all S-R combinations.

Parameter	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
T20	0.85 s	1.01 s	0.90 s	0.85 s	0.82 s	0.67 s	0.50 s	0.35 s
T30	0.74 s	–	1.12 s	0.89 s	0.90 s	0.71 s	0.52 s	0.37 s

Table IX. EDT values at all S-R combinations.

	Parameter	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
S1-R1 Mean Values	EDT	0.93 s	0.74 s	0.65 s	0.53 s	0.66 s	0.53 s	0.50 s	0.40 s
S1-R2 Mean Values	EDT	0.64 s	0.61 s	0.62 s	0.77 s	0.80 s	0.57 s	0.35 s	0.27 s
S1-R3	EDT	0.76 s	0.78 s	0.56 s	0.49 s	0.52 s	0.50 s	0.31 s	0.15 s

Table X. Mean C50 and C80 values across all S-R combinations.

Parameter	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
C50	3.03 dB	5.20 dB	6.75 dB	6.62 dB	5.40 dB	7.76 dB	9.79 dB	11.35 dB
C80	6.24 dB	7.92 dB	9.53 dB	9.53 dB	8.51 dB	10.67 dB	14.64 dB	17.14 dB

Table XI. $IACC_E$ results at all S-R combinations.

	Parameter	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
S1-R1 Mean Values	$IACC_E$	0.91	0.89	0.73	0.45	0.27	0.48	0.31	0.24
S1-R2 Mean Values	$IACC_E$	0.98	0.89	0.69	0.35	0.26	0.16	0.17	0.22
S1-R3	$IACC_E$	0.96	0.84	0.79	0.64	0.36	0.52	0.27	0.18

Table XII. $IACC_{E3}$ values at all S-R combinations.

S-R Combination	$IACC_{E3}$
S1-R1	0.48
S1-R2	0.43
S1-R3	0.59

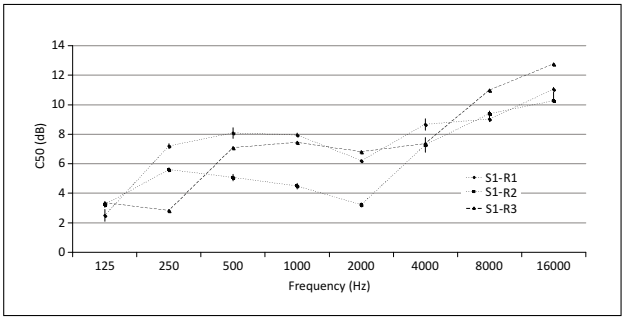

Figure 13. Mean C50 and standard deviation.

a consequence of the space being semi-open, sound dispersed quickly and the reverberation times short. Although high clarity is preferable for spaces with speech applications, when considering the performance of plainchant items this presents a problematic situation, since the items were composed for spaces with low clarity values [59]. The York Minster counts with a C50 of −3.44 dB and C80 of −2.77 dB at 1 kHz [62].

5.2.3. Spatial Impression ($IACC_E$, LF, $IACC_L$)

The highest sense of spaciousness was recorded at S1-R2. At 1 kHz the optimum values of $IACC_E$ for concert halls are in the range of 0.27–0.42 and when considering $IACC_{E3}$ they range from 0.36–0.46 [56]. The results for the S1-R2 combination at Stonegate are within the optimum range whereas the other two combinations present lower levels of spaciousness.

The results for LF indicate a low sense of spaciousness at receiver 1 from 250 Hz–4 kHz when considering the optimum values for concert halls as 0.1–0.35 [1, 54]. Such low values are related to the proximity of the receiver to the sound source [54]. Receiver 2 presents the highest values of LF, corroborating the results of $IACC_E$.

The $IACC_{L3}$ values for concert halls rated as "excellent" and "very good" are in the range of 0.10–0.22 [55], whereas spaces rated as "good" range from 0.15–0.28. The results of the measurements in Stonegate demonstrate an optimum level of envelopment at receivers 1 and 3 but a lower level of LEV is measured at receiver 2, nevertheless this is still within the range found in "good" concert halls.

6. Conclusions

The experiment conducted in the Black Box Theatre demonstrated the greater robustness under the test conditions of the ESS method when used with a sine sweep of 90 seconds of length. Subsequently, this method was

Table XIII. LF values at all S-R combinations.

	Parameter	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
S1-R1 Mean Values	LF	0.12	0.06	0.05	0.06	0.08	0.09	0.16	0.22
S1-R2 Mean Values	LF	0.13	0.08	0.12	0.14	0.20	0.31	0.30	0.51
S1-R3	LF	0.16	0.13	0.08	0.13	0.13	0.40	0.30	0.43

Table XIV. $IACC_L$ values at all S-R combinations.

	Parameter	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz	8 kHz	16 kHz
S1-R1 Mean Values	$IACC_L$	0.92	0.81	0.14	0.13	0.19	0.13	0.21	0.13
S1-R2 Mean Values	$IACC_L$	0.92	0.66	0.36	0.25	0.20	0.14	0.12	0.38
S1-R3	$IACC_L$	0.61	0.53	0.15	0.30	0.11	0.16	0.10	0.46

Table XV. $IACC_{L3}$ values at all S-R combinations.

S-R Combination	$IACC_{L3}$
S1-R1	0.15
S1-R2	0.27
S1-R3	0.18

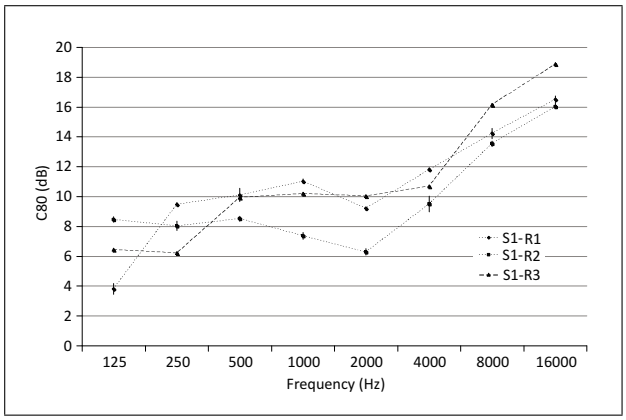

Figure 14. Mean C80 and standard deviation.

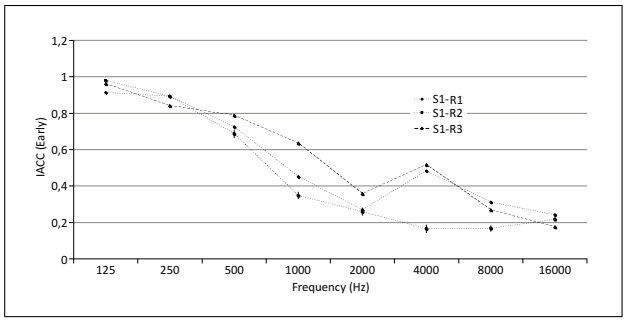

Figure 15. Mean $IACC_E$ and standard deviation.

used to carry out measurements in Stonegate. The measurements recorded a T20 of 0.85s at 1 kHz and a value of T30 of 0.89 s. The clarity was calculated as 6.62 dB (C50) and 9.53 dB (C80) at 1 kHz. Furthermore, the EDT values presented results at 1 kHz ranging from 0.49–0.77 s.

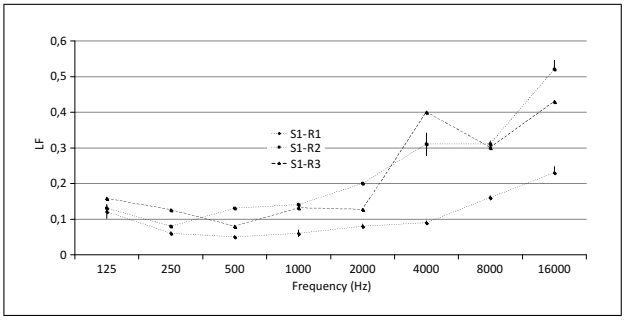

Figure 16. Mean LF and standard deviation.

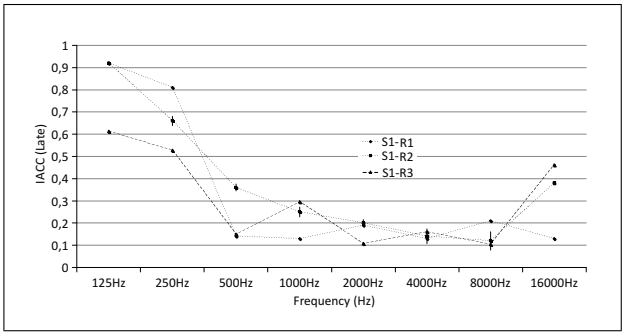

Figure 17. Mean $IACC_L$ and standard deviation.

The combination of these values indicates low reverberation times and high clarity, which are beneficial to speech intelligibility but less appropriate when considering the performance 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. In relation to spatial impression, Stonegate presents values of $IACC_{E3}$ (0.43) and LF (0.14) at 1 kHz at S1-R2 that are within the optimum range for concert halls. The calculation of the listener envelopment through $IACC_{L3}$ demonstrated that the space presents values within the range found in top ranked concert halls when considering receivers 1 (0.15) and 3 (0.18), and presents lower values at receiver 2 (0.26). High levels of

listener envelopment would have proven beneficial to the perception of the musical items of the plays.

It is possible that the physical characteristics of Stonegate in the Middle Ages, which meant it was a narrower space and presented more prominent jetties [20, 21] might have made it a more suitable space for the performance and perception of plainchant items than it is today. It is also likely that the guilds that organised the performance of the plays constructed the wagons used in the streets in such a way as to better suit the performance of plainchant items. In order to verify this hypothesis future work will include the simulation of Stonegate in the Middle Ages through the use of a virtual model which will employ as a starting point a simulation of Stonegate as it stands today, validated through the results of the measurements here presented.

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