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Using scale modelling to assess the prehistoric acoustics of stonehenge

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ABSTRACT

With social rituals usually involving sound, an archaeological understanding of a site requires the acoustics to be assessed. This paper demonstrates how this can be done with acoustic scale models. Scale modelling is an established method in architectural acoustics, but it has not previously been applied to prehistoric monuments. The Stonehenge model described here allows the acoustics in the Late Neolithic and early Bronze Age to be quantified and the effects on musical sounds and speech to be inferred. It was found that the stone reflections create an average mid-frequency reverberation time of (0.64 ± 0.03) seconds and an amplification of (4.3 ± 0.9) dB for speech. The model has a more accurate representation of the prehistoric geometry, giving a reverberation time that is significantly greater than that measured in the current ruin and a full-size concrete replica at Maryhill, USA. The amplification could have aided speech communication and the reverberation improved musical sounds. How Stonehenge was used is much debated, but these results show that sounds were improved within the circle compared to outside. Stonehenge had different configurations, especially in terms of the positions of the bluestones. However, this made inaudible changes to the acoustics, suggesting sound is unlikely to be the underlying motivation for the various arrangements.

1. Introduction

The purpose of Stonehenge and the activities that took place within the monument have been subject of much research (Whittle, 1997; Parker Pearson and Ramilisonina, 1998; Darvill, 2016). Understanding how the site responded to sound and how this might have influenced behaviour is an important aspect to study. Although the acoustics of current Stonehenge have been measured, (Scarre and Lawson, 2006) the sound is very different from the past because so many stones are now missing or displaced. Measurements at the Maryhill Stonehenge, USA, provide a better insight into prehistoric conditions (Fazenda and Drumm, 2013). However, this replica's concrete blocks are more regular than the real stones, and this alters how sound waves are diffracted and scattered, which is very important to the acoustics in a stone circle.

Computer simulations on prehistoric Stonehenge have utilized an industry-standard geometric room acoustic model (Till, 2019). But such algorithms produce at best plausible rather than accurate simulations in conventional rooms (Brinkmann et al., 2019*)* and stone circles are even more challenging because of the approximate modelling of diffraction and scattering (Cox and D'Antonio, 2017). (See supplementary data for a comparison of predictions from a geometric model to measurements). Wave-based models such as Finite Difference Time Domain can model reflections more correctly (Cox and D'Antonio, 2017), but prediction times would be very long for a large space like Stonehenge.

Acoustic scale models have been used since the 1930s to give room acoustic parameters for research and design (Barron, 2010). They have also been applied to investigate historic buildings (Katz et al., 2011) and amphitheatres (Farnetani et al., 2005). One motivation for our study was to apply the method to prehistoric stone circles for the first time. For Stonehenge a 1:12 scale model was built. Testing happened with sound waves at twelve times the frequency, as this preserves the relative size of the sound wavelength and stone dimensions. The model is shown in Fig. 1.

A key advantage of using physical scale models is that they can properly capture wave effects, such as interference and the complex reflections from the amorphous stones. Geometric room acoustic computer models can only ever do this approximately. There are practical problems with using physical scale models, however, such as the effort and cost required to construct them and compromises over the choice of sound sources (see below).

The research questions addressed are: (i) How would musical sounds and speech be altered by the stones, and what does this say about where

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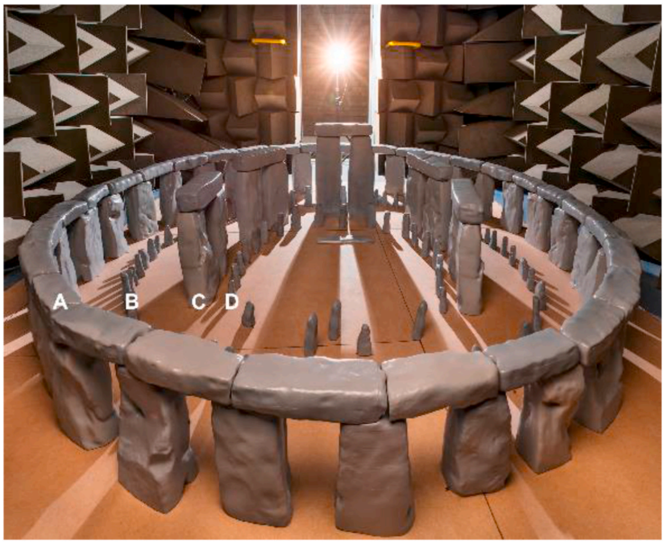

Fig. 1. The 1:12 Acoustic Scale Model of Stonehenge in the semi-anechoic chamber. This is the monument after the bluestones had been re-arranged, c.2200 BC. It is approximately 2.5 m wide. Text annotations: (A) outer sarsen circle; (B) outer bluestone circle; (C) inner trilithon horseshoe and (D) inner bluestone oval.

rituals might have taken place? (ii) How did the construction phases affect the acoustics, and how does this feed into debates on whether sound informed the design?

2. Materials and methods

Unless otherwise stated, all dimensions and frequencies below are given as full-scale equivalents.

2.1. *The model*

The model was based on laser scans of Stonehenge provided by Historic England (Abbott and Anderson-Whymark, 2012), and the latest archaeological evidence for the construction phases. The main configuration tested was stage 4 from Darvill et al.'s proposed sequence dating to shortly after 2200 BC (Darvill et al., 2012). It assumes that the outer sarsen circle was completed, although this is not accepted by all archaeologists (Field and Pearson, 2010).

The model was tested in a semi-anechoic chamber at the University of Salford. This room provides complete absorption for sound escaping the stone circle over the bandwidth of interest, simulating the acoustic effect of the open countryside that immediately surrounds Stonehenge both today and in prehistory. The modelling represents conditions where there is no significant sound refraction created by wind or temperature gradients.

1:12 scale was chosen because it was the largest model that could fit in the chamber. Using the largest possible model scale minimises corrections required when scaling for air absorption (Polack et al., 1992), thereby reducing errors associated with this. The smallest gap between a stone and the tip of the foam wedges on the walls was about 20 cm (model scale).

Based on Historic England's CAD reconstruction there were 157 different stones that made up this phase of Stonehenge. 27 stones that were representative of all the different shapes and sizes were printed. Silicon moulds of these were made and then casting used to create the 130 other stones. Time and resource constraints prevented printing each individual stone. Although this does not provide an entirely accurate replica, this did not make a significant difference to the acoustic measurements because our perception in a place with so many stones is about the combined effect of hundreds or thousands of reflections (Kuttruff, 2016). With 157 stones reflecting and scattering sound in Stonehenge, what matters is getting the distribution of stone sizes and general shapes correct. As discussed later, much larger changes in configurations, such as removing all the bluestones, make only a small difference to the acoustic. Finally, it is worth noting that there are only 63 complete stones and 12 others in fragments at Stonehenge today, and many are partially buried or fallen over. Consequently, the Historic England CAD model contains many stones that are partial or complete reconstructions.

For the outer sarsens, six copies of five extant uprights were made to create the 30 stones needed for the circle. A similar process was used for the outer sarsen lintels. In Fig. 2, the upright stones that were 3D printed and moulded are shown in grey; the lintels printed were the ones above the grey trilithons. For the inner trilithon horseshoe, the central trilithon is significantly taller than the others and so was 3D printed. For the others in the horseshoe, moulds were made of the three stones of the northern trilithon, and four copies made of each of these. The altar stone was 3D printed as it is unique. For the 81 bluestones, eight representative stones were moulded and used for casting. To choose these eight stones, a k-means cluster analysis of all 81 bluestones in the CAD model was undertaken. The data used for the clustering was the volume, surface area and height of the stones. Casts from the stone nearest to the centre of each cluster was then used to represent all the stones within that cluster – see Fig. 3. The standing sarsen stones and bluestones used for the modelling are not thought to have changed significantly in terms of shape, due to erosion or damage, since the Neolithic period.

The sound absorption coefficient of the model needs to match that of full-size materials, allowing for the different frequency ranges. For instance, the sound absorption coefficient of the model ground at 12,000 Hz (model scale) needs to be the same as real ground at 1000 Hz (full scale). Consequently, acoustic scale models use different materials to the actual site to get the right sound properties.

The model stones were made impervious and heavy to minimize sound absorption. Stone has a very low sound absorption coefficient (typically 0.01–0.02), and consequently in Stonehenge absorption is primarily due to sound waves escaping between the stones or into the

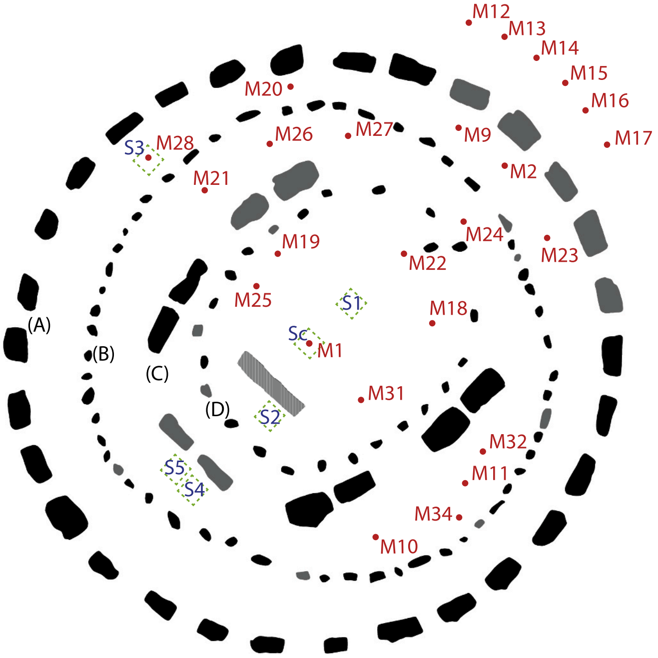

Fig. 2. Plan showing source (S) and microphone (M) positions. Labelled features are: (A) outer sarsen circle; (B) outer bluestone circle; (C) trilithon horseshoe and (D) inner bluestone oval. Grey stones were the ones printed and used for moulds.

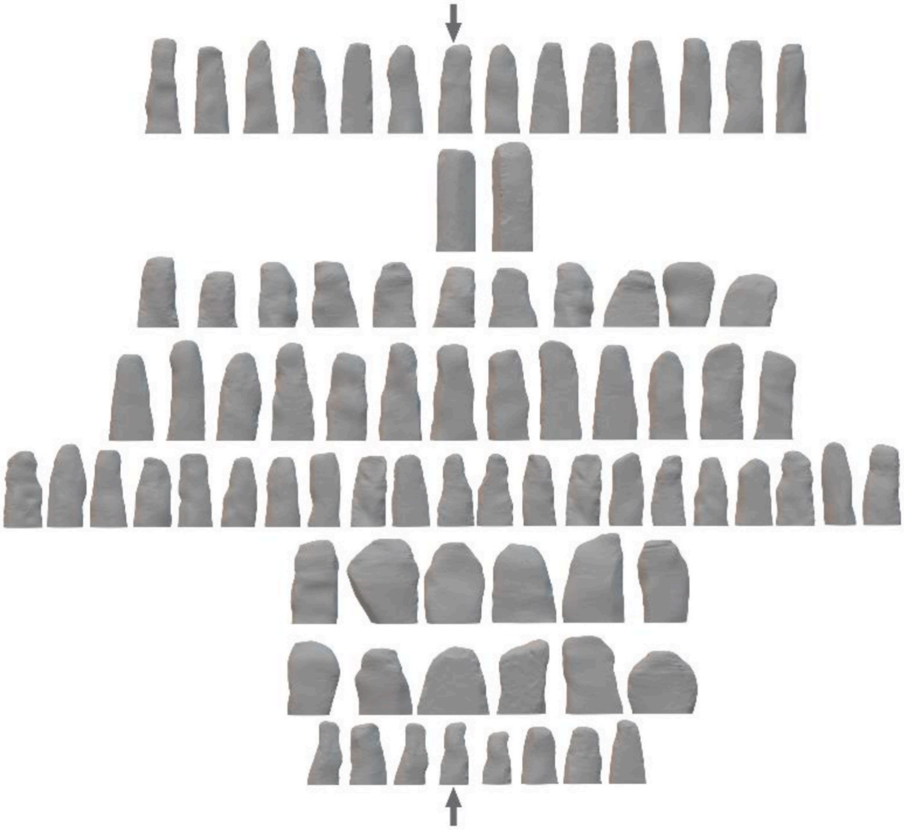

Fig. 3. Outcome from clustering of the bluestones, where each row is one cluster. The middle stones in each row (between the arrows) were 3D printed and moulded to represent the others in the row. For the cluster with only two stones, both were 3D printed.

sky. Some of the model stones were 3D hollow prints (1.5 mm thick plastic) with the cavity filled with an aggregate and plaster mix. Others were cast using a plaster-polymer-water mix; using a liquid acrylic polymer reduced porosity and made the stones more robust to handling. All stones were sealed with a cellulose car spray paint to stop sound getting into any surface pores to minimize absorption. Stones were joined with butt joints and gaps sealed with play dough to reduce sound absorption due to viscous losses in small crevices. No account was taken of the potential presence of people inside the circle, although it is possible to use model people in acoustic scale modelling (Choi, 2014).

One source of uncertainty in the modelling is the exact prehistoric ground conditions. It has been assumed that construction with stones that weigh up to 30 tonnes would lead to heavily compacted grassland over the chalk geology. The random incidence absorption coefficient for ‘compacted dense ground’ was calculated using data from Attenborough et al. (2016). The physical scale model used unvarnished Medium Density Fibreboard (MDF) for the floor because this gave similar absorption coefficients at twelve times the frequency (Jeon et al., 2009). For 125–1000 Hz the MDF absorption coefficient was within 0.03 of compacted dense ground. At 2000 Hz the absorption coefficient of the MDF was too small by 0.1 and at 4000 Hz too small by 0.2. The reduced absorption for the highest two octaves was not an issue because any vertical reflecting sound is lost to the sky. Furthermore, the source used naturally radiates less energy towards the ground at high frequency. The gentle undulations of the ground at the real site were not modelled; these are likely to have changed somewhat since prehistory in any case.

2.2. *Measurement method*

The source and receiver positions are shown in Fig. 2 and the pairs measured given in Table 1. These were chosen at random to cover a variety of positions within the stone circle. Some of these were chosen so the direct sound propagating between the source and receiver was blocked by a stone. A position at the centre was chosen because of a previous suggestion that focussing would occur from the outer sarsen circle (Till, 2019). There are more microphone positions towards the north-east and sources to the south-west, but this bias is less significant than might appear at first because of reciprocity. For example, the response for s4-m2 is the same as if the source was at m2 and the microphone at s4, if both are omnidirectional. The outside positions were close to the outer sarsen circle where communication from inside to outside would be best, as further away the speech would be quieter due to the inverse square law.

Impulse responses are the standard way to measure acoustics in rooms. They characterise what happened to sound waves as they propagate from source to receiver. Where possible, the measurement method followed standard methods (ISO 3382-1, 2009), but a few modifications were necessary to work at 1:12 scale. Measurements were carried out for the 125–4000 Hz octave bands (full-scale equivalents). A 1 s logarithmic sine sweep was used (Farina, 2007), sweeping from 800 Hz to 96,000 Hz

Table 1
Source-Microphone pairs measured.

Investigation	Source-microphone pairs used
Reverberation time, early decay time, definition and strength within circle	s1-m1, sc-m31, s1-m25, sc-m22, s2-s1, s2-m10, s2-m19, s1-m27, s1-m26, s2-m18, s5-m1, s4-m1, s1-m2, s2-m22, sc-m32, s2-m11, sc-m34, s2-m21, sc-m2, sc-m23, s1-m28, s2-m24, s2-m23, s2-m20, s2-m2, s2-m9, s3-m2, s5-m2, s4-m2
Speech communication inside to outside circle	s2-m12, s2-m13, s2-m14, s2-m15, s2-m16, s2-m17
Different stone configurations	sc-m2, sc-m22, sc-m23, sc-m31, sc-m32, sc-m34

(model frequencies) with a 0.01 s fade in. This was followed by 1 s silence. An RME Fireface UFX interface running at 192 kHz sampling frequency was used between the computer, the amplifier and the microphone. A loop-back signal direct from the output to the input of the interface was measured to quantify the delay due to the convertors in the soundcard.

The standard way of testing architectural acoustics is to use an omnidirectional source (ISO 3382-1, 2009). However, compact, omnidirectional, broadband ultrasonic loudspeakers are not available. To achieve approximate omnidirectionality, four Peerless XT25SC90-04 tweeters were arranged pointing outwards on a square with 10 cm side length (model scale). Two pairs were connected in parallel, and then these connected in series. The middle of the tweeters was 13 cm above the MDF boards (equivalent to 1.56 m full-scale). An unbranded laboratory amplifier was used. Fig. 4 shows the source and Fig. 5 the octave band polar responses in the horizontal plane. With the scale model having no roof, no attempt was made to create a source omnidirectional in the vertical plane. In the vertical plane, the -6dB beam width for the octaves from 125 to 4000 Hz was 180°, 180°, 127°, 67°, 27° and 19° respectively.

A GRAS 40BF 1/4″ free-field microphone was used because it can measure up to 100 kHz. It was connected to GRAS 26AA 1/4″ preamplifier and a GRAS microphone power module (settings: 40 dB gain, fast, high pass). The power module was outside the circle and covered in foam to absorb unwanted reflections from it. The microphone signal was further amplified by 20 dB by a Brüel & Kjær 2610 measuring amplifier (outside the semi-anechoic chamber). The microphone was pointing upwards to get an omnidirectional response in the horizontal plane, see Fig. 4, and the diaphragm was 13.5 cm (model scale) above the MDF boards; this is equivalent to 1.62 m full-scale, the average standing head height for the Neolithic period (Chandra and Jain, 2017)· Both source and microphone were on small metal supports that were covered in thin acoustic foam and fleece to reduce reflections.

The limited sound power level emitted by the loudspeakers, and the Stonehenge model being very open, meant that the measurement signal was affected by electrical noise from the microphone/preamplifier in the higher octave bands. To overcome this, the sweeps were repeated 128 times and subsequently averaged. A measurement with the source unplugged was made to determine the background noise level and to check that enough signal-to-noise ratio was achieved in each octave band.

Fig. 4. The microphone (left) and source (right).

2.3. Analysis

The impulse response was calculated via deconvolution using an inverse signal generated with Kirkeby regularization (Farina, 2007). Analysis was carried out in octave bands (3rd order bandpass Butterworth filters). Fig. 6 shows a typical impulse response and background measurement. All octave bands had at least 45 dB of decay before the noise floor was reached so a reliable reverberation time T_{30} could be calculated. Correction C in Equation (3) in ISO 3382–1 was used.

The loss of energy as sound waves go through the air does not scale linearly with frequency, with excess air absorption in the highest octave bands in the model compared to full-scale. Consequently, a correction curve was applied to the impulse responses in each octave band (Ismail and Oldham, 2005). Relative humidity and temperature were taken for each measurement to allow the correction curve to be calculated from air absorption per metre formulations (Bass et al., 1995).

As is normal in architectural acoustics, the impulse responses were then used to calculate a set of octave-band acoustic parameters that have been shown to correlate to perceptual response. The acoustic parameters were: Reverberation Time T_{30}, Early Decay Time EDT, Definition D_{50} and Strength G. To allow the calculation of Strength, the source was measured in anechoic conditions for different horizontal orientations to get the average level at 10 m (ISO 3382-1, 2009). No compensation for the directionality of the source in the vertical plane was made. For the calculation of amplification due to reflections, the inverse square law was used to remove the effect of attenuation due to spherical spreading.

3. Results

3.1. Reverberation

Reverberation is the prolonging of sound due to reflections and is a key characteristic of any room acoustic (Barron, 2010). Fig. 7 shows the average reverberation time from 29 measurements distributed across the monument, which are all within the outer sarsen circle. Surprisingly, despite there being no roof and many gaps between the stones, the model maintains reverberation through sound propagating horizontally. The reverberation times are different from previously reported measurements at Stonehenge itself and at the concrete replica at Maryhill, USA (Scarre and Lawson, 2006; Fazenda and Drumm, 2013). In interpreting room acoustic parameters, it is necessary to know what difference is needed to make an audible change. This is normally done via a Just Noticeable Difference (JND), which is about 0.06s for music for short reverberation times (Niaounakis and Davies, 2002). This means the differences in reverberation times between our model, Maryhill and current Stonehenge, would be audible.

The Early Decay Time (EDT) is a better measure of perceived reverberance for music and speech (Kaplanis et al., 2019). It is more influenced by early reflections and is therefore more sensitive to the measurement position. To analyse how reverberance parameters varied with position around the site, a clustering of measurement positions using a k-means algorithm was carried out. This was done on a vector of twelve parameters: the reverberation times and EDT for the six octaves measured at the measurement positions. The reverberation time varied little over the three obtained clusters, see Fig. 8, and so subsequent analysis focussed on EDT. Cluster A has the lowest EDT. This cluster corresponds to positions where the sources and receivers are close together and near the centre of Stonehenge. Consequently, the early decay is dominated by the properties of the source rather than stone reflections.

Where source and receiver were further apart, it was expected that whether the line of sight between the loudspeaker and microphone was blocked would be important. Cluster C with the largest EDTs included most of the cases where the line-of-sight between the source and receiver was completely blocked by a stone. In these obstructed cases, the direct sound from source to receiver is attenuated and hence the decay time

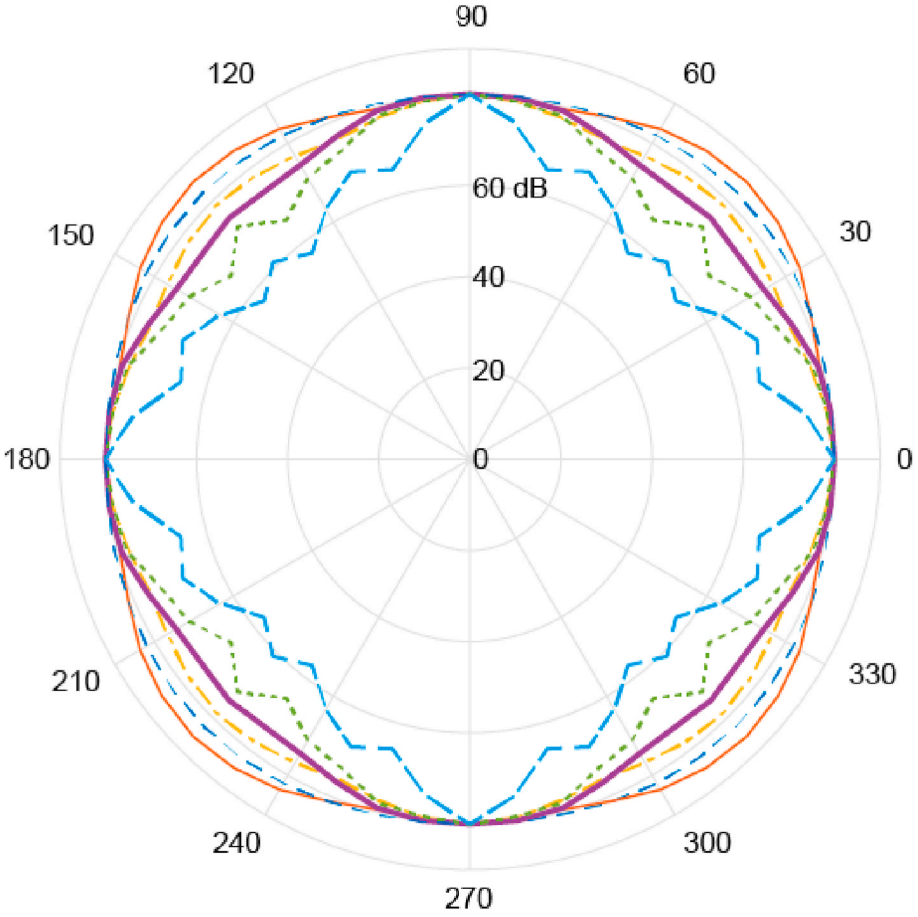

Fig. 5. Top: Free-field polar response of the source in the horizontal plane (dB). Measurements were carried out over one-eighth of the circle and symmetry assumed. - - - 125 Hz; —— 250 Hz; -·- 500 Hz; —— 1000 Hz; ········ 2000 Hz; — — 4000 Hz.

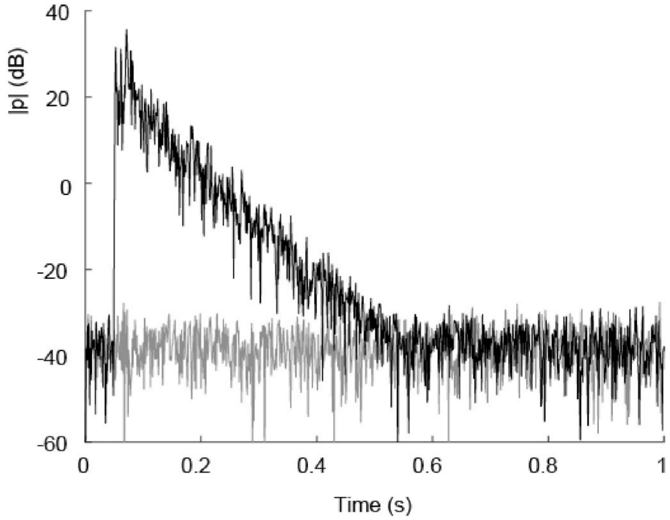

Fig. 6. —— measured impulse response magnitude and —— background noise. Shown for 4000 Hz frequency band where electrical noise from the microphone is the greatest.

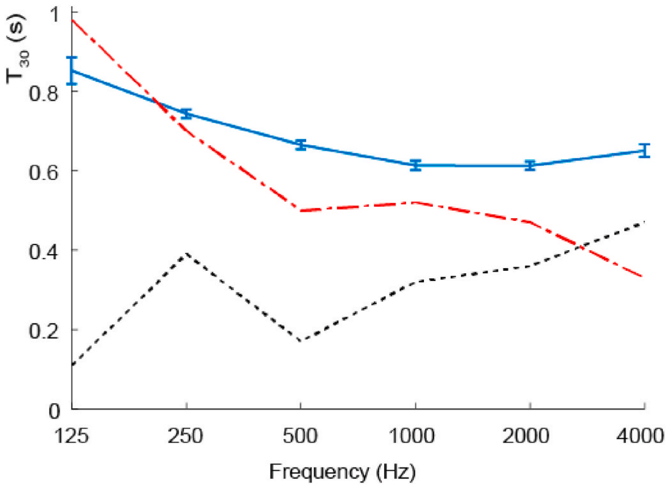

Fig. 7. Average reverberation time (T_{30}): ----- current Stonehenge; -·-· Maryhill Replica and the —— 1:12 acoustic scale model. Error bars are 95% confidence intervals.

increased. A test on the significance of blocking the direct sound was done by comparing the mean mid-frequency EDT (average of 500, 1000 and 2000 Hz octave bands) for the clear and fully occluded cases. These were: clear line of sight, EDT = 0.55 ± 0.06s and fully occluded, EDT = 0.67 ± 0.08. A Mann-Whitney *U* test showed a significant difference between these two data sets ($p = 0.046$, effect size $r = 0.4$, a medium effect).

The decay times measured are significantly less than recommended for current music (Barron, 2010), nevertheless even small amounts of reverberation are preferred to none at all (Cox, 2014). Moreover, reverberation has been shown to be desirable across current genres

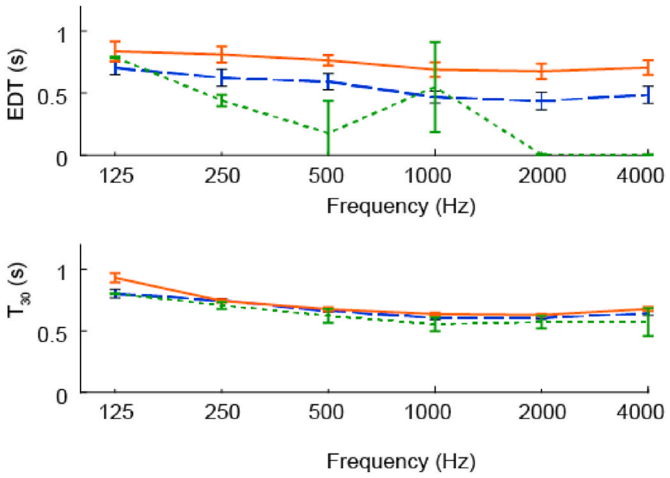

Fig. 8. Mean EDT and reverberation time for the three clusters with 95% confidence limits. Clusters: ········ A; — — B; —— C.

including: classical (Barron, 2010), rock and pop (Adelman-Larsen et al., 2010) as well as traditional instruments such as gamelan (Nitidara et al., 2014). Although it is impossible to know what sounds might have been played during rituals at Stonehenge, if any of them were like music, then the stone reflections within the circle would have enhanced the sound. Musical instruments including bone flutes, wooden pipes, animal horns and drums are likely to have been used in Neolithic Britain (Wyatt, 2009), their usage dating back to the Upper Palaeolithic period in Europe (Conard et al., 2009). An example of a flute made from a crane bone was found in an early Bronze Age barrow at Wilsford, just to the south of Stonehenge (Wiltshire Museum collection, 2020).

3.2. *Speech*

For speech, analysis began by checking whether reflections arrived sufficiently early to aid rather than hinder intelligibility. This was done using *Definition* (D_{50}) (ISO 3382-1, 2009). The range of D_{50} values was from 0.45 to 0.97, with a mean of 0.77 and standard deviation of 0.13. Only one measurement had a value $D_{50} < 0.5$; this was for the source hidden right behind a tall trilithon (s4). For the other 28 measurements, we would anticipate 90% syllable intelligibility provided the speech was audible above any background noise (based on Figure 7.11 in Kuttruff, 2016).

In cases where speech would otherwise be a few decibels quieter than any background noise, speech communication would have been aided by amplification due to reflections. On average the level in the model is (4.3 ± 0.9) dB higher than would be the case in free-field (omnidirectional source, average of 500 and 1000 Hz octave bands). To illustrate, consider someone talking at a normal level facing away from the listener at 25 m (i.e. talking from one side to the other within the outer sarsen circle) when the background noise level is 30 dB(A). (This background level is typical of quiet levels found in US national parks away from anthropogenic noise.) For normal speaking, the speech sound pressure level with no stone or floor reflections is estimated to be 24 dB(A) (Monson et al., 2012). Using data from Fig. 11 of Rhebergen and Versfeld (2005), the number of sentences that would be heard correctly would be just 33%. Based on our impulse response, the addition of the reflections from the stones and floor is estimated to amplify the level of the speech from 24 to 34 dB(A). That would raise the number of sentences heard correctly to 100%. This shows that the stone reflections are particularly useful when the talker is not facing the listener or is partly obscured by a stone.

A set of measurements was made with microphone positions just outside the circle of sarsens. The estimated level of speech for these positions was compared to that at microphone positions m2, m9 and m23 (which are just inside the sarsen circle). A correction for the inverse square law was applied to account for the interior microphones being somewhat closer to the source. For outer microphones m12, m14 and m16 where there was a clear line of sight to the source, on average speech was 3 dB quieter than the interior microphone positions (with inverse square law correction). For microphones m13, m15 and m17 where the line of sight is blocked, the average attenuation was 7 dB.

It is not known if speech intelligibility was important to rituals undertaken by users of Stonehenge. More recent history suggests that intelligibility is not always important. For example, before the reformation, Christian services were in Latin and so incomprehensible to most of the congregation (Cox, 2014A). If it is assumed that understanding speech was important, however, then communication would have been easier if any activities or rituals took place with everyone inside the circle, where speech is amplified. Furthermore, this amplification could have other likely effects, as louder talkers tend to be judged by modern listeners as more powerful and competent (Peng et al., 1993).

3.3. *Discrete echoes*

Several authors have suggested that acoustic aberrations might have been exploited at ancient sites. For example, Waller found a correlation between the location of Palaeolithic ungulate drawings and carvings and the level of reflected sound (Waller, 1993). At Stonehenge, Till (2019) has written about discrete echoes, a distinct repetition of the original sound, suggesting these could be caused by focussed reflections from the concave outer sarsen circle.

To test for discrete echoes, a method described in Kuttruff (2016) is used. First, a smoothed impulse response envelope is formed. The bottom graph in Fig. 9 shows an example for the most critical case with the source and receiver near the focal point at the centre of the circle. An echo would appear as a clear step-up in the smoothed envelope, but none is seen. Next the echo criterion (EC) of Dietsch and Kraak was calculated from the smoothed envelope. No measurement produced an EC value greater than the test thresholds, indicating no echoes would be present for speech or music. As a final check, the impulse responses were convolved with an anechoic balloon burst and auditioned to listen for discrete echo effects; none were heard. The lack of echoes is due to the bluestones and inner trilithons obscuring and scattering reflections from the outer sarsen circle.

3.4. *Configurations*

The model was tested in different configurations to explore the acoustic importance of the various parts of the structure. The stones at Stonehenge were placed in several different arrangements and altered

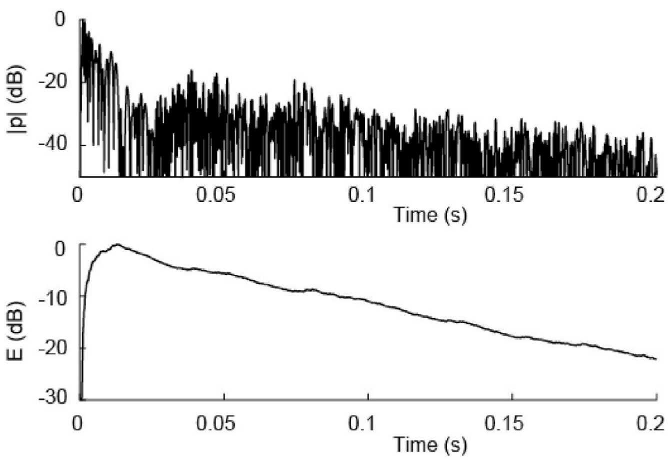

Fig. 9. Top: Magnitude of impulse response for source and receiver close to the centre of Stonehenge; bottom: smoothed envelope.

over a period of at least 500 years (Darvill et al., 2012). Once erected, the sarsen horseshoe and circle were not moved but the bluestones were placed in at least one prior configuration, the double bluestone arc, before being moved to the positions shown in Fig. 2. Although the position of this double arc has been excavated, without knowing more detail of which bluestones stood in these sockets and how they were arranged, it is not possible to exactly model the acoustics of this phase of the monument. Therefore, the configurations tested were based on the final major phase of Stonehenge, as it appeared in c.2200 BC.

The configurations tested are given in Table 2. Fig. 10 shows the average reverberation time for the five arrangements tested. Configuration (i) which consists of only the inner trilithon horseshoe is very different to the other cases. It is usually assumed that for practical reasons this horseshoe was constructed before the outer sarsen circle, although the two elements may have been constructed in rapid succession. With just these inner trilithons, the acoustic is dominated by the direct sound and strong discrete reflections. Because the stones are arranged in a horseshoe, there is at least one strong reflection to all measurement positions, except when the microphone was placed right behind one of the stones. The effects of these reflections are subtle and amplify the voice. The amplification is 2.8 dB (average of 500 and 1000 Hz octave bands) for five of the microphone positions. The occluded microphone position (m32) had an attenuation of 5.6 dB.

The four configurations with the outer sarsen circle uprights in place have roughly similar reverberation times. There are significant differences, as confirmed by a repeated measures one-way ANOVA (using a separate test for each octave band). Mauchly's test of sphericity was only significant for the 4000 Hz octave, and so the Greenhouse-Geisser correction was used for that frequency. All frequencies had a significant and large main effect for 'configuration' with $p < 0.001$. The range of the F-statistic across the octave bands were $71 \leq F(4, 20) \leq 166$ and the effect size range was $0.94 \leq \eta^2 \leq 0.97$. Results for the post-hoc pairwise comparison with Bonferroni correction are given in Table 3.

The significant differences in the various octave bands can mostly be explained by scattering created by diffraction and reflection from angled surfaces. For example, the reverberation time for (v) the 2200 BC model with all components present, is lower than the other three cases (ii, iii and iv) at 250 and 500 Hz. Reverberation is mostly created by sound propagating horizontally in the model. The bluestones in (v), the 2200 BC model, reflect some of the sound vertically into the air and this energy is then lost from the circle lowering the reverberation time. This scattering of sound is frequency dependent, being greatest when the bluestone height is similar to the sound wavelength. The addition of lintels also significantly alters the reverberation time in a frequency-dependent manner (comparing cases (ii) and (iii)). There are significant differences at 125 Hz, 2000 Hz and 4000 Hz.

The effects between these four configurations (ii, iii, iv and v) are only slightly larger than accepted perceptual just noticeable differences (JND) for reverberation time. But these published JND values came from laboratory measurements where sound samples with different reverberation times were juxtaposed for testing. This would have made very small changes audible. As the reorganisations of stones may have taken place over many years, Stonehenge users could not have noticed these small changes.

Table 2
Different structures present in the five configurations tested. Configuration (v) is the 2200 BC model of bluestones and sarsens.

Structures present	Configuration				
	(i)	(ii)	(iii)	(iv)	(v)
Inner trilithon horseshoe	✓	✓	✓	✓	✓
Outer sarsen circle uprights	–	✓	✓	✓	✓
Outer sarsen circle lintels	–	–	✓	✓	✓
Outer bluestone circle	–	–	–	✓	✓
Inner bluestone oval	–	–	–	–	✓

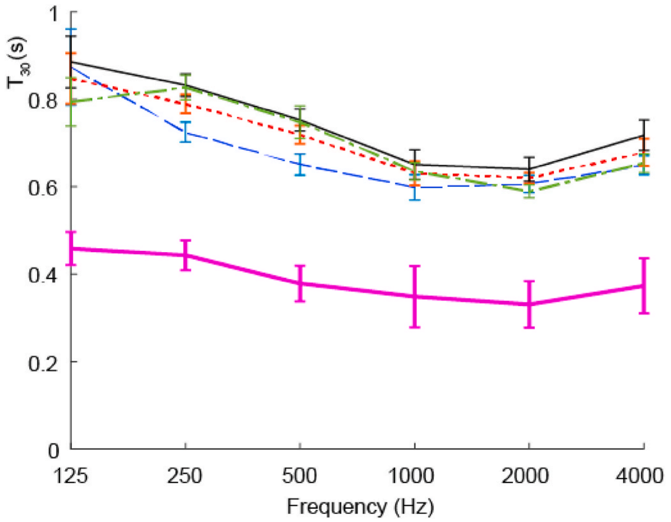

Fig. 10. Average reverberation time (T_{30}) for different configurations with 95% confidence limits. —— (i); -·-· (ii); —— (iii); ······ (iv), and – – – —— (v).

Table 3
Octave bands (Hz) where post-hoc pairwise comparisons of reverberation times showed a significant difference between the model configurations.

	(i)	(ii)	(iii)	(iv)	(v)
(i)	–	125–4000 Hz†	125–4000 Hz†	125–4000 Hz†	125–4000 Hz†
(ii)	–	–	125*; 2000*; 4000†	2000*	250*; 500*
(iii)	–	–	–	500*	250†; 500†; 1000*
(iv)	–	–	–	–	500*
(v)	–	–	–	–	–

†$p < 0.01$; *$0.01 \leq p < 0.05$.

4. Discussions and conclusions

In this paper, it has been shown how scale modelling can quantify prehistoric acoustics. Stonehenge in 2200 BC had a small but noticeable reverberation of 0.6 s, which provided useful amplification of the voice and enhanced musical sounds for those standing within the stone circle. The monument does not facilitate the projection of sound out into the surrounding area, for example to an audience standing outside the stone circle but within the henge enclosure. Nor were sounds created outside the stone circle readily heard by those within the central setting. If participants were to benefit from the enhancement provided by stone reflections during rituals, then that would apply to a relatively small and restricted audience, within the sarsen circle.

Although it is not known what sort of rituals, ceremonies or activities took place at Stonehenge in the Neolithic period, nor whether these included the playing of musical instruments or speech, the results suggests that any sounds created within the stone circle were best intended for others within the same relatively intimate setting, rather than to be broadcast more widely to those outside, whose view into the stone circle would also have been obscured. This evidence once again emphasises the contradiction between the large numbers of people required to transport the stones and construct the monument, with the small number of people able or allowed to fully take part in, and witness, activities within the stone circle.

The most significant change to the acoustics during the various historic configurations examined was when the outer sarsen uprights were added. This would have increased the reverberation time by a noticeable amount. With the outer sarsen uprights in place, the introduction and various rearrangements of the bluestones only make subtle changes to the acoustics, which would have been inaudible to people in prehistory. Moreover, no echoes were audible in the 2200 BC model. Overall, it seems improbable that sound was a primary driver in the design and arrangement of the stones at Stonehenge. Other considerations were more likely to be important, including the astronomical alignments, the incorporation of two different groups of stones, the replication of similar timber monuments and the creation of an impressive and awe-inspiring architectural structure.

Data

The octave band impulse responses and a table of acoustic parameters from the measurements are available at http://doi.org/10.17866/rd.salford.12687554.

Author contributions

The project was conceptualized, and methodology developed by TJC and BMF. TJC and BMF supervised the measurements, did the data curation and formal acoustic analysis. SG provided the archaeological analysis. The paper was written, reviewed and edited by TJC, BMF and SG.

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Declaration of competing interests

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Susan Greaney is employed by English Heritage, the charity who run historic properties under care of the state, including Stonehenge. The authors can think of no reason why this would bias the research, but following best practice for competing interests, this employment is declared.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jas.2020.105218.

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