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A case study investigating the interaction between tuba acoustic radiation patterns and performance spaces

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ABSTRACT

Previous work suggests that instrument directivity patterns can interact in interesting ways with their acoustic environments. This paper describes a case study of the tuba, an instrument that possesses a particularly directional radiation pattern, in the context of a small recital hall. We perform our acoustic simulations using ODEON room acoustics software [1], a CAD model of the recital hall [2], a recorded impulse response function [3], and an empirical tuba directivity pattern from a recently published database [4]. We conduct simulations at listener locations spread throughout the hall for two different performer configurations: one where the tuba player faces directly towards the audience, and one where the tuba bell points directly towards the audience. We show that several objective acoustic parameters – C_{80} (clarity index), LF_{80} (lateral fraction) and BR(SPL; bass ratio$_{SPL(dB)}$) – are substantially affected both by performer orientation and by listener position. Our results show how tuba players need to be particularly sensitive to decisions about performance configurations, as they are likely to influence the listening experience substantially.

1 Introduction

Experienced music performers and audiences alike are aware that a room's acoustics influence the musical experience. Performers recognise that some rooms have more supportive acoustics, that give them more active feedback on their playing across the frequency spectrum and reduce the perceptual salience of any blemishes or mechanical action noises [5]. Experienced audience members similarly appreciate that some acoustics provide a better acoustic balance of clarity and reverberation [5], both of which can enhance the listening experience when balanced well.

A less well recognized fact among performers and audiences is that room acoustics can interact in a complex manner with the instrument itself. In particular, certain instruments radiate sound in a directed manner, such that particular frequency ranges are represented particularly strongly or weakly at different angles [6] [7] [8]. Simulations suggest that this directivity can interact with the physical layout of a room, producing a situation where placing the instrument in different locations or orientations can materially affect the listeners' acoustic experience [9] [10] [11] [12]. However, this phenomenon is still little studied and hence little understood.

Here we study an instrument for which these effects might be expected to be particularly strong: the tuba. In a natural performing position, the tuba bell points diagonally upwards (Figure 1), and tuba sound radiation becomes more concentrated on the tuba bell axis as frequency increases from around 80 Hz upwards [6] [7] [8]. This leads to quite a focussed radiation pattern (as illustrated in Figure 2) and varied sound picture (as observed in the Results below).

Fig. 1: Natural performing angle of tuba.

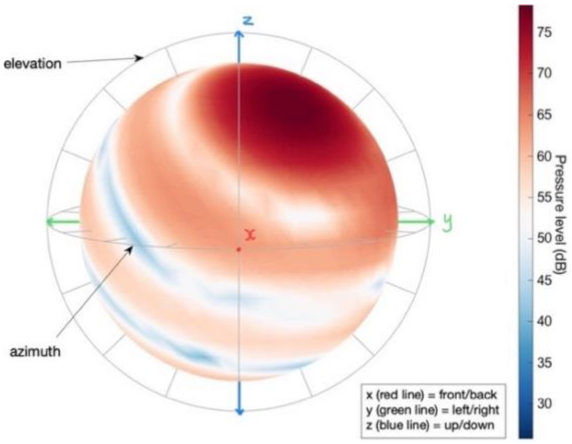

Fig. 2: Tuba directivity pattern for the frequency band 1414-1782 Hz. Data from [4].

We model the directivity pattern of the tuba using a recently published empirical directivity database [4], and we simulate how this interacts with an example performance space, the West Road Recital Room. The Cambridge University Music School (which includes the West Road Recital Room) and the West Road Concert Hall were designed by Sir Leslie Martin and built in the mid-1970s [13]. The West Road Recital Room is used for solo and chamber music rehearsals and performances (Figure 3). Using objective measures of perceptually important acoustic parameters, we test the extent to which performer and audience seating configurations are likely to affect the subjective listening experience in this performance space.

Fig. 3: West Road Recital Room (photo taken 16th November 2021).

2 Methods

The Weinzierl et al. [4] tuba directivity patterns used in this paper were captured using a spherical array of 32 microphones located on the faces of a truncated icosahedron at a fixed 2.1 m radius, recording pressure values for the 4th-order spherical harmonics domain at 31 different third-octave frequency bands [14]. We converted this data to the full-octave frequency bands required by ODEON [15] using linear interpolation.

We modelled the tuba player as a point source, placing them in a standard concert location in the middle-front of the hall (Figure 4). We consider two possible orientations: one where the tuba player faces directly towards the audience, and one where the player is rotated by 54 degrees azimuth such that the tuba bell points directly towards the audience. We then model three candidate listener (receiver) locations (labelled R1, R2, R3), which we place 1 m from the back wall, similar to a standard audience configuration.

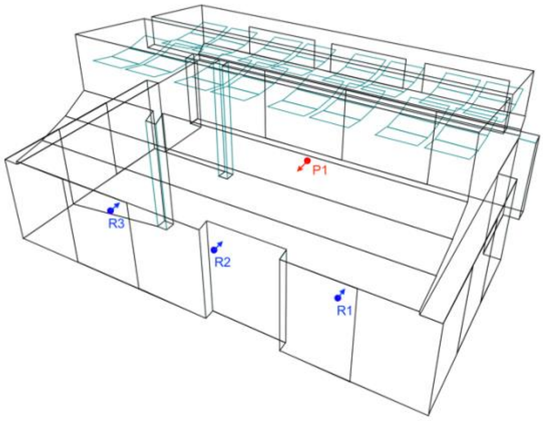

Fig. 4: West Road Recital Room model with point source and three receivers [2]

The ODEON room acoustics software [1] uses ray tracing to estimate different global and localised room acoustic parameters in a given room model depending on the inputted directivity characteristics of a sound source as well as the basic geometry of the room model. This gives the user a close estimate of the acoustic properties in a given space and the acoustic trends evoked by a given sound source in that space.

We used the following parameters for the simulations: transition order 2 (reflections including > 2 surfaces = calculated as late reflections), 1500 late rays, 1400 ms for room impulse response length (based off Wilkie's West Road Recital Room impulse response recording [3]), receivers and point source all 1.5 m off ground, approximate materials assigned to the model surfaces with their corresponding absorption coefficients using ODEON's Global Material Library, room acoustic parameters standardised according to ISO 3382–1 [16].

We compute two sets of simulated acoustic parameters. First, we compute *point response* measurements for the three receivers with their specified locations and orientations (Figure 4). Second, we compute *grid response* measurements, which give acoustic parameters for all locations on the floor plan, and are measured in a non-directed fashion (unlike the point response measurements). All results are averaged in the following octave bands: 63, 125, 250, 500, 1000, 2000, 4000, 8000 (Hz) [15].

3 Results

In this report we focus on three particular room acoustic parameters that are known to be perceptually important for the music listening experience: C_{80} (clarity index), LF_{80} (lateral fraction) and BR(SPL; bass ratio$_{SPL(dB)}$). We will consider each in turn.

C_{80} (clarity)

C_{80} is calculated as the early-to-late arriving sound energy ratio, with 80 ms as the early time limit [16]. Its perceptual correlate is clarity [17]. Recommended values for C_{80} in (larger) concert halls have been reported variously as: -4 to 0 dB [17], -4 to 1 dB [18], and -1 to 3 dB for symphonic music [19]. The Just Noticeable Difference (JND) for C_{80} has been measured to be approximately 1 dB [16]. For brevity, our C_{80} grid responses focus on the 250 Hz frequency band, which demonstrates particularly strong directivity effects in our analysis.

The results for the forward-facing tuba player simulations indicate that clarity varies substantially for different listener positions (Figure 5, Figure 7). Figure 7 shows how greatest clarity is achieved for listeners sitting towards the back left of the recital room, where the tuba bell is pointing. In contrast, listeners in the back right have relatively low clarity. The differences here clearly exceed the JND, so should be clearly perceptible to the listener.

Rotating the tuba player, so that the tuba bell points directly forward, drastically affects these patterns (Figure 6, Figure 8). In particular, we see that the location of greatest clarity for the 250 Hz band is now in the middle of the audience seating, and the back left position now receives the lowest clarity.

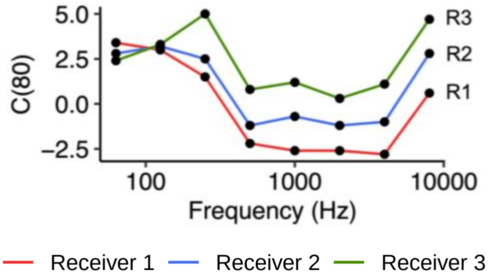

Fig. 5: C$_{80}$ (dB) 'clarity' across the frequency spectrum (front-facing configuration)

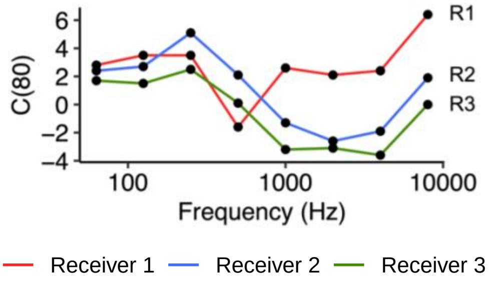

Fig. 6: C$_{80}$ (dB) 'clarity' across the frequency spectrum (angle-adjusted configuration)

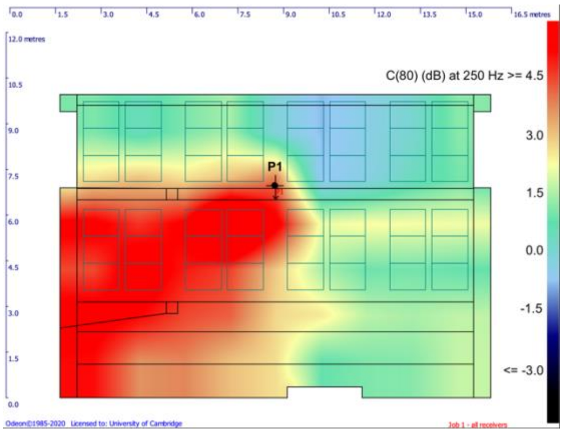

Fig. 7: C$_{80}$ (dB) 'clarity' grid response at 250 Hz (front-facing configuration)

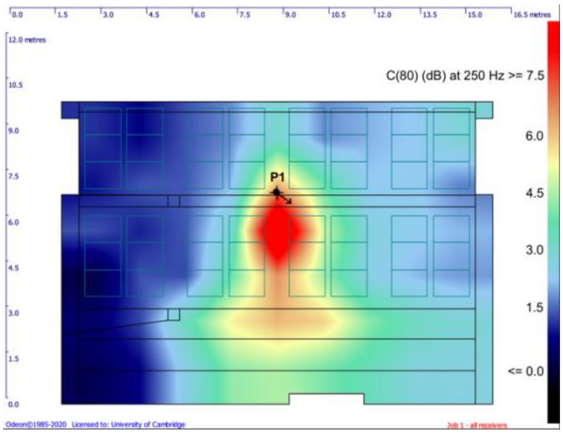

Fig. 8: C$_{80}$ (dB) 'clarity' grid response at 250 Hz (angle-adjusted configuration)

LF$_{80}$ (spaciousness)

LF$_{80}$ is calculated as the fraction of energy arriving from lateral directions within the first 80 ms [16]. Its perceptual correlates are spaciousness and envelopment [18]. Recommended values for LF$_{80}$ in (larger) concert halls have been proposed as c. 0.2 [18] and > 0.25 [19]. The JND for LF$_{80}$ has been measured to be approximately 5% [16]. Here we plot grid responses for the 500 Hz frequency band, which seemed to be particularly sensitive to directivity effects.

Figures 9 and 10 show that LF$_{80}$ (spaciousness) is lowest for receivers located directly in front of the tuba bell. This happens because listeners in these locations receive most of their sound directly from the tuba bell, rather than from reflections. As a result, rotating the tuba player (Figure 10) also rotates the LF$_{80}$ pattern, meaning that centrally located audience members' LF$_{80}$ levels drop from very good levels (c. 0.4 in Figure 9) to very poor levels (< 0.2 in Figure 10). This change clearly exceeds the JND for LF$_{80}$, so we can expect it to be perceptually salient.

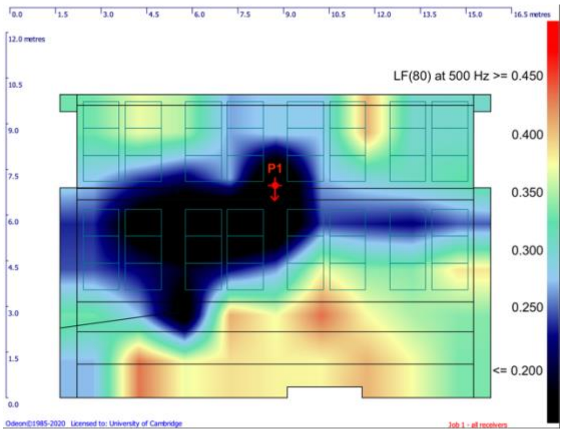

Fig. 9: LF_{80} 'spaciousness' grid response at 500 Hz (front-facing configuration)

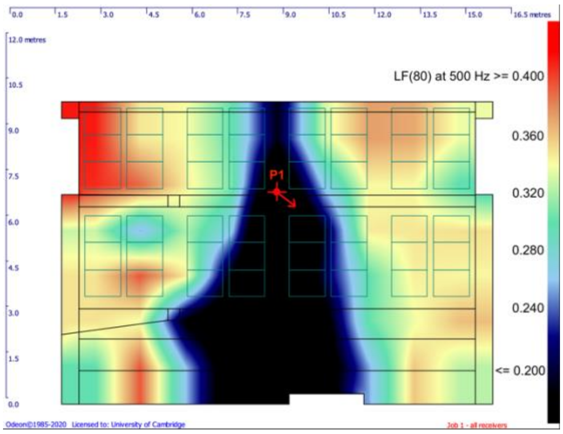

Fig. 10: LF_{80} 'spaciousness' grid response at 500 Hz (angle-adjusted configuration)

BR(SPL) (warmth)

BR(SPL) is calculated as the ratio of reverberation times in the 125 Hz and 250 Hz frequency bands to those in the 500 Hz and 1000 Hz bands [18]. Its perceptual correlate is 'warmth' of sound [17] [18]. Wilkie's West Road Recital Room impulse response recording indicates a complex reverberation time (T_{30}) of 1.415 secs [3]; recommended values for BR(SPL) in concert halls with reverberation times less than 1.8 secs are reported as 1.1–1.45 dB [20].

Figures 11 and 12 both exhibit a BR(SPL)) 'hotspot' of >= 1.3 dB located directly on top of the sound source with surrounding levels ranging from 1.1 to 0.0 dB. Both figures also exhibit a secondary hotspot that is likely produced by 1^{st}-order reflections from the angled ceiling reflector in front of the tuba player. In both performer orientations there are listener locations in front of the performer which exhibit Bass Ratios that almost reach the recommended BR lower limit (between c. 0.8 and 1.1), but many other locations fall far below it (as low as 0.0). This implies that perceptions of 'warmth of sound' in the West Road Recital Room are likely to be substantially varied based on listener locations relative to the tuba sound source.

It is interesting to note that rotating the tuba player causes the BR(SPL) hotspot to rotate in the *opposite* direction to the tuba player. This clearly stems from an idiosyncratic interaction between the tuba's directivity and the hall's design.

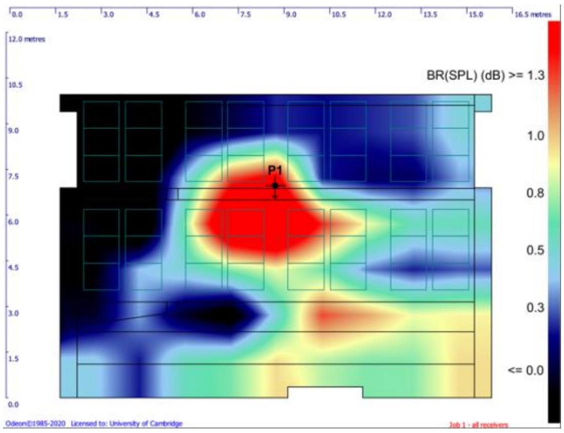

Fig. 11: BR(SPL) 'warmth' grid response (front-facing configuration)

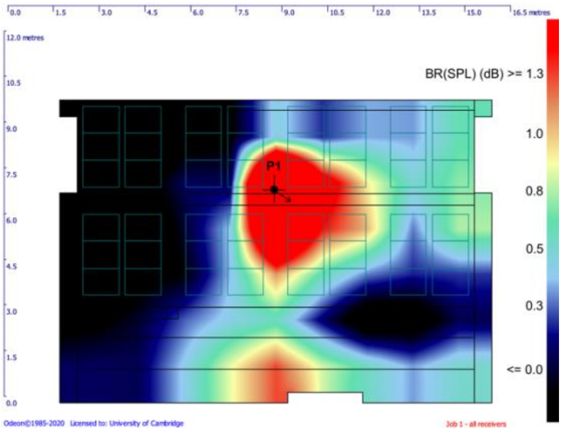

Fig. 12: BR(SPL) 'warmth' grid response (angle-adjusted configuration)

4 Discussion

In this paper we investigated the sensitivity of various acoustic parameters (in particular, clarity index C_{80}, lateral fraction LF_{80}, and bass ratio BR(SPL)) to (a) the orientation of a tuba player and (b) the location of audience members within the West Road Recital Room. Using acoustic simulation of a tuba sound source in the West Road Recital Room, we showed that simulated room acoustic parameters are drastically affected by both the orientation of the tuba bell and the listener's seating position. These effects clearly exceed perceptual JNDs, so we can be confident that they have a real effect for listeners; in many cases, the effect corresponds to the difference between 'acceptable' and 'poor' acoustics.

These results have important implications for music performers. Musicians need to be aware that the directivity of their instruments can interact very strongly with the listening experience across a performance space. This is particularly relevant to brass instruments and any other instruments which radiate their sound from a focussed opening like the flared horn with its point source-like radiation characteristics [7].

We found that clarity (C_{80}) is particularly responsive to the angle of the tuba bell (as evidenced in Figures 5-8). Tuba players performing music in a style or manner that demands high clarity control (e.g., lots of short articulations) should therefore be careful to adjust their playing style [6] (e.g., play with even shorter note lengths, or lower the maximum dynamic) and position themselves and their audience so as to maximise intended acoustic quality within and across a given acoustic environment.

Rotating the performer might achieve some positive effects on room acoustic parameters, but one should bear in mind that rotating the performer may also negatively affect the visual connection between performer and listener. Any decision to change performer orientation relative to the audience must therefore balance these acoustic and visual concerns.

Here we only analysed one musical instrument in one performance space. However, our methods would generalise easily to other instruments and spaces. In particular, other work could take advantage of the many directivity patterns recorded in the Weinzierl et al. database [4] to explore similar effects for other instruments.

Our analyses depend on acoustic simulation rather than real-world measurements. This has the disadvantage of potential inaccuracies but allows us to achieve a much higher granularity of analysis than would be practical in real-world measurements. Nonetheless, it would be interesting to record these acoustic parameters in the room itself, using a real tuba and recording from microphones at different listener locations; it would also be worthwhile to complement these acoustic measurements with a subjective listening experiment.

It would be useful to explore how alternative performance configurations of the West Road Recital Room affect the distribution of acoustic quality across the audience differently, to determine whether there might be a more preferable room configuration than the current one. For example, adopting the traditional 'shoebox' concert hall arrangement (with the tuba at one of the short ends of the hall) could situate more audience members within the area of most concentrated tuba sound radiation (for better or for worse).

We have shown that, in the case of a relatively small recital hall, room acoustic parameters can vary drastically as a function of tuba orientation and listener location. It is currently unclear how far these findings generalise to larger performance spaces, where the performer may be further away from the nearest reflectors and listeners. Future work could apply our same methods to different CAD models to explore this question.

Acknowledgement

We would like to thank Tom Mullock for creating and supplying a CAD model of the West Road Recital Room and Hannah Wilkie for recording and supplying a West Road Recital Room impulse response function for this dissertation project.

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