THE INFLUENCE OF SUBWOOFER FREQUENCIES WITHIN A MULTI-CHANNEL LOUDSPEAKER CONFIGURATION ON THE PERCEPTION OF SPATIAL ATTRIBUTES IN A CONCERT-HALL ENVIRONMENT[1][2]

Robert Sazdov
Digital Media and Arts Research Centre (DMARC)
Computer Science and Information Systems
University of Limerick
Limerick City
Ireland

ABSTRACT

This paper considers the use of subwoofers in a multi-channel loudspeaker configuration. Subwoofers are regularly used in multi-channel electroacoustic music because they are generally considered to contribute to spatial attributes. Research in the perception of spatial attributes of subwoofers is reviewed, establishing that there is little research in the perception of spatial attributes of subwoofer perception in a concert-hall environment. Further, literature is lacking in perceptual research of the effects of combined use of subwoofers and loudspeakers on spatial attributes. This paper reports an experiment concerning judgments of the spatial attributes envelopment, spatial clarity and engulfment using a subwoofer within a multi-channel loudspeaker configuration run in a concert-hall environment.

1. INTRODUCTION

1.1. Subwoofers and effects on judgements of spatial attributes

Using the low-frequency component of looped rhythmic sections of jazz, funk, pop and rock music, Martens [12] found that two decorrelated subwoofers resulted in participants reporting a wider spatial imagery when compared with one subwoofer. This was essentially Apparent Source Width (ASW) and was achieved when using two forward positioned subwoofers placements at ±30°. Regardless of the relatively narrow displacement of ±30°, which would produce minimal ITDs, forward placement of subwoofers can contribute to the perception of spatial attributes; in the experiment run by Martens [12], the spatial attribute affected was ASW. However, the influence of the amplitude envelope of the rhythmic loops must be regarded as a cue and most likely contributes to the perception of the subwoofers. The sharp rise and fall of the volume envelope present in many rhythmic loops of jazz, funk, pop or rock music should be considered as a perceptual cue. The amplitude envelope of a complex sound such as a rhythmic loop is considered to be a 'real-world' or ecologically valid application of the subwoofer and was implemented in the current study. Martens et al. (2005) found that two subwoofers positioned at ±110° resulted in a significant increase in the perception of envelopment over the use of only one subwoofer for decorrelated octave-band noise signals at 63 and 125 Hz, but not at 31 Hz. The results suggest that there is a cut-off point at which subwoofer frequencies do not contribute to spatial attributes, in this case the perception of envelopment.

Hiyama et al. [11] found that frequencies as low as 100 Hz contribute to the perception of 'diffuseness' which is regarded by Braasch et al. [4] as closely related to listener envelopment. Griesinger [8] concluded that for 'world class' listener envelopment in concert halls the lateral perception of frequencies lower than 300Hz is needed. Soulodre suggests that two subwoofers positioned laterally are required for listener envelopment [5]. Griesinger further suggests that four subwoofers would be needed if listeners are permitted to move their heads by up to 90°, with subwoofers placed at the 0° and 180° azimuth positions [5].

It can be concluded from the research that has used two subwoofers that: (a) the use of two subwoofers leads to an increase in LEV perception; (b) ASW is possible with subwoofers positioned at the ±30° locations; and (c) subwoofer frequencies as low as 63 Hz lead to an increased perception of LEV. Of importance to the current study is whether these results achieved in a listening room environment would also be seen when

[1] This paper reports on an experiment discussed in [16] as a 'further research' recommendation. Therefore, the current experiment utilised the same experimental equipment, set-up, and subwoofer stimuli stated in [16] Also, the experiment refers to [15] for the definition, discussion, as well as the creation of frequency ranges, musical layers, and spatial scenes.

[2] This experiment tests only one subwoofer, as it was not know what the result would be in a concert hall environment, since studies have only taken place in either listening rooms or anechoic chambers. Further and as will be discussed below, it was not known how subwoofer frequencies would interact with higher (non-subwoofer) frequencies in a multi-channel configuration as previous studies have not tested this combination.

using a multi-channel setup in a concert-hall acoustic, as practiced with most electroacoustic music performances. It is generally accepted that listener envelopment is achieved with lateral and late-arriving reverberation in a concert hall [2]. The importance of low frequencies (< 300 Hz) in concert halls is considered important by Griesinger [8] and suggestions that frequencies as low as 60 Hz contribute to the perception of envelopment. Also, it is generally accepted that reverberation increases with the use of subwoofer frequencies in concert halls [5]. Therefore, it is likely that the results achieved in listening rooms might be different to those obtained in a concert-hall environment.

1.2. Perception of spatial attributes using subwoofer and loudspeakers

Most relevant research is concerned with the perception of subwoofers only; there seems to be a lack of literature that examines the combined effect on spatial attributes of subwoofer and broad-range frequencies produced by loudspeakers. As discussed previously [16], there are two general approaches when using subwoofers in a multi-channel configuration, as an LFE channel or as a subwoofer. In both approaches, the use of the subwoofer would normally be accompanied with the use of loudspeaker frequencies (> 100 Hz). The strategic placement and use of only subwoofers can lead to the perception of envelopment and similarly the use of loudspeakers, considered full range (generally stated as 20 Hz–20 kHz). Stimuli above 100 Hz can lead to the perception of envelopment, but what would be the perceptual effect of simultaneously using both types of loudspeakers? This would be more ecologically valid, as in electroacoustic music the use of the subwoofer is usually accompanied with higher frequencies produced by the loudspeakers.

2. RESEARCH QUESTIONS FOR EXPERIMENT 4

Even though envelopment is largely considered an attribute related to the lateral and therefore horizontal plane, there is evidence that elevated loudspeakers contribute to a greater perception of envelopment [7, 10]. The first research question in Experiment 4 is: would the use of a subwoofer further contribute to a greater perception of envelopment in spatial scenes when used with loudspeakers in both the horizontal and elevated planes when compared to spatial scenes that do not use a subwoofer? Based on the results of previous experiments [15], there is evidence to suggest that engulfment is a unique spatial attribute produced using elevated loudspeakers. The second research question in Experiment 4 is: would the use of a subwoofer further contribute to the perception of engulfment? Finally, the attribute of spatial clarity was examined in previous experiments and the results suggest that spatial scenes with more musical layers had less spatial clarity (two layers vs. eight layers), as well as spatial scenes that used elevated loudspeakers (Horizontal vs. Elevated) [15]. The final research question in Experiment 4 is: would the use of a subwoofer contribute to the perception of spatial clarity? These questions motivated the design of Experiment 4.

3. EXPERIMENT 4

The main aim of Experiment 4 was to investigate whether the use of complex subwoofer frequencies can contribute to the perception of envelopment, spatial clarity and engulfment when used in a multi-channel loudspeaker configuration setup in a concert-hall environment that includes horizontal and elevated loudspeaker locations. To address all of the above questions, the design criteria for Experiment 4 were that the experiment:

a) be run in a concert-hall environment;
b) use both subwoofer and loudspeaker frequencies;
c) consist of a loudspeaker configuration with both horizontal and elevated plane positions;
d) use complex stimuli with an amplitude envelope;
e) consist of varying degrees of sonic complexity in the form of music layers (two, four, and eight layers).

Experiment 4 was a 2 × 2 × 3 design which resulted in 12 conditions[3]. The design consisted of subwoofer/no subwoofer spatial scenes (2), elevated/horizontal spatial scenes (2), and two-, four- or eight-layer spatial scenes (3). All conditions used in Experiment 4 are stated in Table 3.1.

Subwoofer	No Subwoofer
Horizontal	Elevated

plus

2 Layers	4 Layers	8 Layers

Table 3.1. The 12 conditions tested in Experiment 4. The design was a 2 (subwoofer/no subwoofer) × 2 (elevated/horizontal) × the third factor of 3 (two-, four, or eight-layers).

3.1. Participants

In total 16 participants, 14 male and 2 female, with self-reported normal hearing and a mean age of 26 years ranging from 21 to 35 years (SD = 3.74 yrs), participated in the experiment. All were deemed to be expert listeners studying music, audio engineering, sonic arts, or a multidisciplinary combination including the mentioned areas. The participants were all engaged in a course of study at SARC, Queens University, Belfast; ranging

[3]A single subwoofer was used for the reasons outlined in Section 3.4

from B.Sc. (Music Technology) through to PhD levels. The mean years of study was 11.8 with a range of 4–27 years (SD = 4.79 yrs), with eight participants studying multi-channel sound or composition for a mean of 3.25 years with a range of 1–8 years (SD = 2.64yrs). Further, 10 participants engaged in multi-channel composition, and four participants indicated they had composed 3D music. It should be noted that participants regularly attended 3D multi-channel concerts of electroacoustic music in the Sonic Lab at SARC. The participants volunteered their time and were not paid to undertake the experiment. This was the fourth and final experiment the participants were involved in[4].

3.2. Stimuli

All of the spatial scenes and therefore the stimuli used in Experiment 4 were previously used in [15] and [16]. For the Two, Four and Eight Musical Layer conditions, the LM_Lm1, All Mixed Four Layer and All Mixed Eight Layer spatial scenes were used, respectively. The stimuli of Low (L), Low–Mid (LM), Low Mid 1 (Lm1) High–Mid (HM) and High (H), used to construct All Mixed spatial scenes were those used in Experiment 1 (see [15] for further discussion). The reason for the selection of these spatial scenes is that they were rated highest for the perception of envelopment, spatial clarity and engulfment [15]. For the horizontal plane conditions, the loudspeakers used for the Two Musical Layers were the rear 135° and the 225° positions, the Four Musical Layer spatial scene used the 45°, 135°, 225° and 315° positions, with the Eight Musical Layer using the 0°, 45°, 90°, 135°, 180°, 225° 270° and 315° Floor Level-positioned loudspeakers. For the elevated spatial scenes positions, the High Level loudspeakers were used. The rear two loudspeakers at approximately the 135° and 225° azimuth positions were used for the Two Musical Layer Elevated spatial scene and the front two loudspeakers at approximately 45° and 315° azimuth positions were included for the Four Musical Layer Elevated spatial scene. It should be made clear that the Eight Layer Elevated spatial scene consisted of four horizontal loudspeakers at the 45°, 135°, 225° and 315° positions along with the four High Level loudspeakers used for the Four Layer Elevated spatial scene. Therefore, the Eight Layer Elevated spatial scene uses both horizontal and elevated loudspeakers. Even though the Sonic Lab contains eight High Level loudspeakers, the original configuration was used as for [15]. The Eight Layer Elevated spatial scene thus uses a multidimensional loudspeaker setup.

The subwoofer stimulus used in Experiment 4 was originally used in [16]. It should be noted that the same vocal phrase manipulation was used for all loudspeaker stimuli and the subwoofer stimulus. Therefore the amplitude envelope was identical for all stimuli ranging from subwoofer though to High, eliminating any perceived motion and trajectory within in the spatial scene. The use of a subwoofer amplitude envelope is similar to that of [12]; even though a vocal phrase would not have the same repetitive rhythmic pattern as drum loops, there would still be rise and fall of the amplitude envelope.

[4]The participants undertook a total of four experiments totaling 70 minutes

3.3. Stimuli

The experiment was run in the Sonic Lab at the Sonic Arts Research Centre, Queens University Belfast. It is the identical setup to that used for Experiment 1 (See [15] for discussion of the experimental setup).

3.4. Subwoofer setup and placement

The results of [16] suggest that the localisation of subwoofers is not possible in off-horizontal plane locations. Therefore an elevated subwoofer location is not necessary for the experimental loudspeaker configuration. Martens et al. [13] found that the ±110° positioned subwoofers produced the most enveloping results and Welti [17] as part of his ideal subwoofer set-up included a subwoofer placed at the 180° position. Therefore, it was decided to use the rear Floor level subwoofer of the Sonic Lab configuration and not the front subwoofer. Only one subwoofer was used in the experimental design, as it was not known what the effect of a subwoofer placed in a concert-hall environment would be; essentially how it would react with the reverberation, the room nodes, and the other frequencies produced from the loudspeakers. Using two or more subwoofers would have potentially further increased the effects and unnecessarily complicated the experimental design.

3.5. Equipment and calibration

Equipment in the Sonic Lab was used for the experiment. It consisted of Digidesign ProTools Version 7 software with multiple HD3 192 kHz interfaces running on a Mac G5 computer. The 24-bit, 96kHz audio files were first compiled using MOTU Digital Performer 4 and the AIFF files were then transferred and loaded onto the Sonic Labs setup. Using the Terrasonde Audio Tool Box Sound Level Meter, all loudspeakers and subwoofer were calibrated with pink noise at the centre sweet spot position at 70 dB SPL C weighting and Slow response. The levels were adjusted from within ProTools so that all loudspeakers and the subwoofer individually delivered 70 dB SPL (±0.1dB). `

3.6. Procedure

The participants were seated in an area deemed to be the sweet spot area for surround sound listening, i.e. in the centre of the loudspeaker configuration. The experiment was run in one session as this would best replicate concert conditions, with some participants seated slightly off the central sweet spot position. The spatial attributes ‘envelopment’, ‘spatial clarity’ and ‘engulfment’ were explained in both written form and verbally. Participants were given an explanation of the possible advantages of head movements and instructed to move their heads if needed. Apart from this, very little information was relayed to the participants; they were not informed of the nature of the experiment. There were three repeats of the 12 conditions; therefore the participants rated 36 randomly ordered spatial scenes for their level of envelopment, spatial clarity and engulfment. A five-level Likert scale was used and participants were free to mark X anywhere, not just on the indicated points (Fig. 3.2). Each scene was played once and there was a 7 s interval for participants to indicate their rating. The experiment was run in one session and the experiment lasted just over 10 minutes.

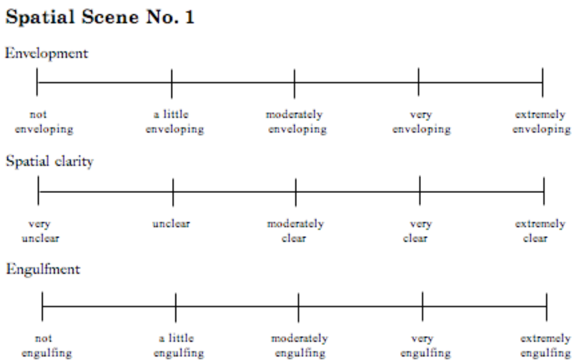

Figure 3.2. The five-level Likert scale used in Experiment 4. The participants were asked to mark X anywhere along the scale, not just at the five labelled anchors.

4. RESULTS

The experimental design will be used as the basis for reporting the results. This will start with reporting on Subwoofer/no subwoofer spatial conditions, horizontal/elevated loudspeaker positions, and 2-, 4-, or 8-layers; all rated for the perception of envelopment, spatial clarity and engulfment. Multiple *t*-tests were ran on the mean data, with all data reported as significant having a $p<0.05$ value.

4.1. Subwoofer vs. no subwoofer: all conditions

Analysis of data for the contribution of the subwoofer for all conditions and for all spatial attributes showed a significant difference $t(15) = 6.026$, p = 0.004. (See Tables 4.1–4.3 for means). This result suggests that the subwoofer does influence the perception of spatial attributes; however, it does not indicate how it influences each specific spatial attribute. An analysis of the contribution of the subwoofer on the perception of envelopment, spatial clarity and engulfment was carried out to consider this more specifically.

4.2. Subwoofer vs. no subwoofer: envelopment, spatial clarity, and envelopment

4.2.1. Envelopment

The participants rated envelopment $t(15) = 3.72$, p = 0.041 as significantly different with the subwoofer active. Please refer to Figures 4.1 – 4.3 for graphs of all conditions. This suggests that for all conditions with subwoofer, participants rated them to be more enveloping when compared to the no-subwoofer conditions.

4.2.2. Spatial Clarity

There was no significant difference for spatial clarity between subwoofer and no subwoofer conditions: $t(15) = -1.38$, p = 0.285.

4.2.3. Engulfment

There was also no significant result for engulfment $t(15) = 2.68$, p = 0.096 between the subwoofer and no subwoofer conditions.

4.3. Elevated vs. horizontal

4.3.1. Envelopment

Analysis of data comparing all elevated loudspeaker conditions and all horizontal loudspeaker conditions resulted in no significant difference for envelopment $t(15) = 0.48$, p = 0.4.

4.3.2. Spatial clarity

No significant difference for the spatial attribute of spatial clarity $t(15) = -2.76$, p = 0.093 was seen between horizontal and elevated locations.

4.3.3. Engulfment

There was, however, a significant difference for engulfment $t(15) = 9.36$, p = 0.000 between elevated locations and horizontal locations.

The results suggest that the loudspeaker dimension does influence the perception of engulfment. Participants rated the elevated conditions as more engulfing than the horizontal conditions.

4.4. Musical Layer: two vs. four and eight musical layers

Analyses of the data for the influence of musical layers on the perception of the spatial attributes of envelopment, spatial clarity and engulfment between two music layer vs. four and eight musical layers were conducted.

4.4.1. Envelopment

Comparison between two music layers vs. four and eight musical layers showed a significant difference for envelopment $t(15) = 8.68$, p = 0.001.

4.4.2. Spatial Clarity

No significant difference was obtained for spatial clarity $t(15) = -2.08$, p = 0.157 comparing two musical layers vs. four and eight musical layers.

4.4.3. Engulfment

A significant difference was seen between two musical layers vs. four and eight musical layers and for engulfment $t(15) = 6.08$, p = 0.004.

The data suggests that when comparing subwoofer and no subwoofer conditions between two musical layers vs. four and eight musical layers, there is no significant perceptual difference for spatial clarity. The data suggests that envelopment and engulfment were rated higher for the four and eight musical layer conditions when compared to the two musical layer conditions.

4.5. Musical Layer: four music layers vs. eight musical layers

4.5.1. Envelopment

Comparison between four musical layer and eight musical layer conditions showed that there was a significant difference for envelopment $t(15) = -4.28$, p = 0.024.

4.5.2. Spatial clarity

No significant difference was seen for spatial clarity $t(15) = 1.28$, p = 0.269, between four musical layer and eight musical layer conditions.

4.5.3. Engulfment

No significant difference was obtained comparing four musical layer and eight musical layer spatial scenes for engulfment $t(15) = -0.742$, p = 0.358.

Therefore, the only significantly different spatial attribute for four musical layers vs. eight musical layers was envelopment, with eight musical layer spatial scenes rated higher.

4.6. Elevated vs. horizontal: subwoofer vs. no subwoofer

4.6.1. Envelopment

Analysis of data for the two-way interaction between elevated vs. horizontal loudspeaker conditions and subwoofer vs. no subwoofer conditions showed no significant interaction for the spatial attribute envelopment $t(15) = 0.568$, p = 0.39.

4.6.2. Spatial Clarity

There was a significant difference seen for spatial clarity $t(15) = -3.81$, p = 0.037 for the two-way interaction between elevated vs. horizontal loudspeaker conditions and subwoofer vs. no subwoofer conditions.

4.6.3. Engulfment

There was also a significant difference between the two-way interaction between elevated vs. horizontal loudspeaker conditions and subwoofer vs. no subwoofer conditions for engulfment $t(15) = 4.54$, p = 0.013.

The results for the two-way interaction between elevated vs. horizontal loudspeaker conditions and subwoofer vs. no subwoofer conditions suggest that conditions which used the horizontal loudspeakers and had no subwoofer were rated higher for spatial clarity than those which were elevated and included the subwoofer. Also, the participants rated the elevated conditions with subwoofer more engulfing than those in the horizontal plane without a subwoofer.

Spatial Scene	Mean	SD	Spatial Scene	Mean	SD
Horizontal 2 Layer	2.48	0.79	Horizontal 2 Layer + Subwoofer	2.71	0.93
Horizontal 4 Layer	2.85	0.9	Horizontal 4 Layer + Subwoofer	2.93	1.03
Horizontal 8 Layer	2.9	0.97	Horizontal 8 Layer + Subwoofer	3.14	0.93
Elevated 2 Layer	2.1	1.02	Elevated 2 Layer + Subwoofer	2.34	0.89
Elevated 4 Layer	2.7	0.78	Elevated 4 Layer + Subwoofer	2.98	1.05
Elevated 8 Layer	3.28	1.03	Elevated 8 Layer + Subwoofer	3.42	1.21

Table 4.1. Ratings for envelopment in the two-way interaction between elevated and horizontal conditions, as well as subwoofer and no subwoofer conditions.

Spatial Scene	Mean	SD	Spatial Scene	Mean	SD
Horizontal 2 Layer	3.48	0.52	Horizontal 2 Layer + Subwoofer	3.18	1.1
Horizontal 4 Layer	3.23	0.82	Horizontal 4 Layer + Subwoofer	3.28	0.75
Horizontal 8 Layer	3.35	0.68	Horizontal 8 Layer + Subwoofer	2.98	0.87
Elevated 2 Layer	3.12	0.77	Elevated 2 Layer + Subwoofer	3.1	0.76
Elevated 4 Layer	2.98	0.75	Elevated 4 Layer + Subwoofer	3.07	0.95
Elevated 8 Layer	2.82	0.82	Elevated 8 Layer + Subwoofer	3.03	0.84

Table 4.2. Ratings for spatial clarity in the two-way interaction between elevated and horizontal conditions, as well as subwoofer and no subwoofer condition

Spatial Scene	Mean	SD	Spatial Scene	Mean	SD
Horizontal 2 Layer	1.75	0.72	Horizontal 2 Layer + Subwoofer	2.76	1.05
Horizontal 4 Layer	2.57	0.92	Horizontal 4 Layer + Subwoofer	2.57	1.04
Horizontal 8 Layer	2.6	1.06	Horizontal 8 Layer + Subwoofer	2.62	1.13
Elevated 2 Layer	3.06	1.29	Elevated 2 Layer + Subwoofer	3.17	0.98
Elevated 4 Layer	3.34	0.78	Elevated 4 Layer + Subwoofer	3.54	0.99
Elevated 8 Layer	3.67	0.8	Elevated 8 Layer + Subwoofer	3.39	1.22

Table 4.3. Ratings for engulfment in the two-way interaction between elevated and horizontal conditions, as well as subwoofer and no subwoofer conditions.

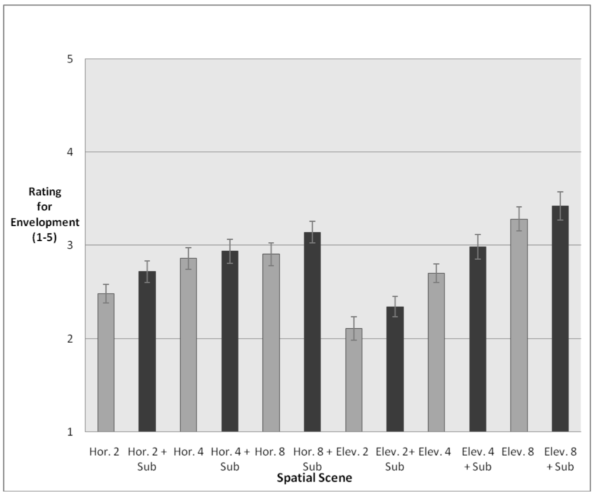

Figure 4.1. Envelopment: two, four, and eight layers, with and without subwoofer. The dark coloured column is the subwoofer condition. Error bars indicate standard error of the mean.

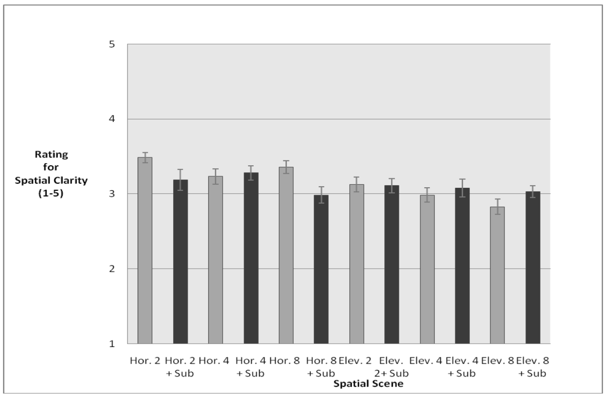

Figure 4.2. Spatial Clarity: two, four, and eight layers, with and without subwoofer. The dark coloured column is the subwoofer condition. Error bars indicate standard error of the mean.

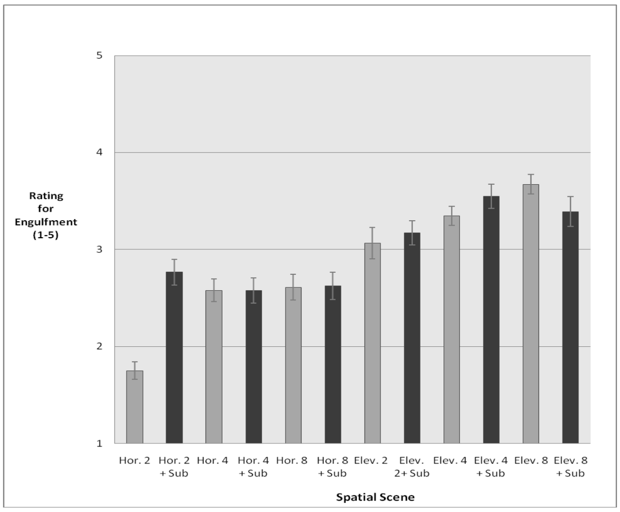

Figure 4.3. Engulfment: two, four, and eight layers, with and without subwoofer. The dark coloured column is the subwoofer condition. Error bars indicate standard error of the mean.

4.7. Subwoofer vs. no subwoofer: two music layers vs. four and eight music layers

Another two-way interaction analysing conditions with subwoofer vs. no subwoofer, and two music layers vs. four and eight musical layers was performed.

4.7.1. *Envelopment*

The results showed no significant different result for envelopment $t(15) = 0.33$, $p = 0.435$ for the subwoofer vs. no subwoofer, and two music layers vs. four and eight musical layer conditions.

4.7.2. *Spatial clarity*

A significant difference was obtained for spatial clarity comparing the subwoofer vs. no subwoofer, and two music layers vs. four and eight musical layers, spatial clarity $t(15) = -3.64$, $p = 0.044$.

4.7.3. *Engulfment*

Significant results were seen for engulfment $t(15) = 3.86$, $p = 0.005$, for the two-way interaction for subwoofer vs. no subwoofer, and two music layers vs. four and eight musical layers.

The four and eight music layer subwoofer and no subwoofer conditions were rated as being more engulfing than the two music layer subwoofer and no subwoofer conditions. Also, the two music layer subwoofer and no subwoofer conditions were rated higher for spatial clarity than the four and eight music layers with subwoofer and without subwoofer conditions.

4.8. Subwoofer vs. no subwoofer: four musical layers vs. eight music layers

4.8.1. Envelopment

An analysis of the two-way interaction between subwoofer and no subwoofer conditions for four musical layers and eight musical layers showed no interaction for envelopment $t(15) = 2.4$, $p = 0.124$.

4.8.2. Spatial clarity

No significantly different results were seen for spatial clarity $t(15) = 0.128$, $p = 0.478$ for the two-way interaction of subwoofer and no subwoofer conditions for four musical layers and eight musical layers.

4.8.3. Engulfment

Similarly, no significantly different results were seen for the two-way interaction of subwoofer and no subwoofer conditions for four musical layers and eight musical layers for engulfment $t(15) = 0.341$, $p = 0.433$.

5. DISCUSSION AND CONCLUSIONS

The discussion and conclusions for Experiment 4 are structured around the research questions.

5.1. Research Question 1: Would the use of a subwoofer further contribute to a greater perception of envelopment when used with loudspeakers in both the horizontal and elevated planes?

There were no significant differences to suggest that the use of a subwoofer with horizontally positioned loudspeaker or the use of a subwoofer with elevated positioned loudspeakers would lead to a greater perception of envelopment. Most research (i.e. [4], [5], [13]) in the perception of envelopment using only subwoofers has suggested that the use of two subwoofers is more enveloping that one subwoofer. The current experiment used only one subwoofer positioned directly behind the listener (180° azimuth), whereas the subwoofer positions for most related research has been at lateral locations, at either ±90° or ±110° (i.e. [11], [13]). Therefore, two factors are proposed to have contributed to the current result: (i) using only one subwoofer instead of two or more subwoofers, and (ii) the position of the subwoofer not being at a lateral location, i.e. ±90°. Further research should incorporate a minimum of two subwoofers positioned at ±90° in the setup of the experimental loudspeaker configuration, however the use of four subwoofers in an experimental design would better reflect recent discussions on ideal subwoofer configurations [16]. Research Question 2: Would the use of a subwoofer further contribute to the perception of engulfment?

Even though there was a significant difference for engulfment between the all-horizontal vs. all-elevated conditions, this could be largely the effect of the elevated loudspeakers positions contributing to the perception of engulfment, rather than the subwoofer. As no significantly different results between the subwoofer vs. no subwoofer conditions were obtained, the contribution of the subwoofer cannot be considered to be the main contributing factor to the perception of engulfment. The subwoofer location used in the current study cannot be ruled out as a contributing factor, and as discussed above in Section 3.4, the use of two subwoofers positioned at ±90° should be tested in further perceptual investigations into engulfment, as well as those discussed in [16].

5.2. Research Question 3: Would the use of a subwoofer contribute to the perception of spatial clarity?

The use of a subwoofer did not significantly affect the perception of spatial clarity within a concert-hall environment when compared to spatial scenes without a subwoofer. However, the two-way interaction between elevated vs. horizontal loudspeaker conditions and subwoofer vs. no subwoofer demonstrated a significant difference. This result for spatial clarity was similar to that of Guastavino and Katz [9], who suggest that three-dimensional spatial scenes were less clear or muffled when compared to two-dimensional spatial scenes. Even though the current experiment was run in a concert-hall environment, whilst Guastavino and Katz [9] was run in a modified listening room standard, the data suggests that spatial scenes consisting of elevated loudspeakers will not be perceived as clearly as spatial scenes with only horizontally placed loudspeakers. This is contrary to Brant's [6] and Barrett's [1] assumption that the extra dimension presented by using elevated sound or loudspeakers would result in more sonic clarity. A possible explanation for why horizontally placed loudspeaker perception was rated as clearer than elevated loudspeaker perception could be the human hearing mechanism. With elevated loudspeaker localization, the dominant cue would be spectral or pinna cues which are not considered to be as robust as ITDs or ILDs, resulting in greater localization blur [3, 14].

6. ACKNOWLEDGMENTS

This research was funded by a UWSPRA Scholarship and Top-up Stipend. The experiment was funded by a MARCS Auditory Laboratories Travel Fund and would not have been possible without the support of students and staff at the Sonic Arts Research Centre, Queens University – Belfast. Special thanks to Professor Michael Alcorn, Dr. Pedro Rebelo, Dr. Eric Lyon, Mr. Chris Corrigan and Mrs. Pearl Young.

7. REFERENCES

[1] Barrett, N., (2002). “Spatio-musical Composition Strategies” *Organised Sound*, Vol. 7, no. 3

[2] Barron, M., Marshall, A., (1981). “Spatial impression due to early lateral reflections inconcert halls: the derivation of a physical measure.” *J.Sound and Vibration*, 77(2):211–232.

[3] Blauert, J. (1997). Spatial Hearing – The Psychophysic of Human Sound Localization, Cambridge: MIT Press

[4] Braasch, J., Martens, W. L., and Woszczyk, W. (2004). “Modeling auditory localization of subwoofer signals in multi-channel loudspeaker arrays”, in *Proceedings of Audio Engineering Society 117th Convention*, San Francisco, USA

[5] Braasch, J., and Martens, W.L., “Low-frequency content in music reproduction: Is one sub-woofer enough?” (2005). *Echoes*, Vol. 15, No. 3.

[6] Brant, H., "Space as an Essential Aspect of Musical Composition," (1967). Contemporary Composers on Contemporary Music, ed. E. Schwarz and B Childs, New York

[7] Furuya, H., Fujimoto, K., Wakuda, A., & Nakano, Y. (2005). The influence of total and directional energy of late sound on listener envelopment, *Acoust. Sci. & Tech.* vol. 26, no.2, pp. 208-211.

[8] Griesinger, D. (1997). “The psychoacoustics of apparent source width, spaciousness and envelopment in performance spaces.” *Acustica,* vol. 83, no. 4 pp. 721-731.

[9] Guastavino, C., and Katz, B., (2004). “Perceptual Evaluation of Multi-dimensional Spatial Audio Reproduction”, *J. Acoust. Soc. Am.*, 116 (2).

[10] Hanyu, T., and Kimura, S., (2001). “A new objective measure for evaluation of listener envelopment focusing on the spatial balance of reflections”, *Applied Acousitcs*, vol. 62. pp. 109-124.

[11] Hiyama, K., Komiyana, S., and Hamasaki, K., (2002). The minimum number of loudspeakers and its arrangement for reproducing the spatial impression of diffuse sound field. In *Proc. 113th Conv. Of the Audio Engineering Society*, Los Angeles, Ca, USA, Preprint 5696

[12] Marten, W. L., (1999). “The impact of decorrelated low-frequency reproduction on auditory spatial imagery: Are two subwoofers better than one?” In *Proceedings of the Audio Engineering Society 16th Int. Conf. on Spatial Sound Reproduction*. pp. 67-77, Rovaniemi, Finland.

[13] Martens, W.L., Braasch, J., and Woszczyk, W., (2004). “Identification and discrimination of listener envelopment percepts associated with multiple low- frequency signals in multichannel sound reproduction,” in *Proceedings of Audio Engineering Society 117th Convention*, San Francisco, USA

[14] Mills, A., (1958). “On the Minimum Audible Angle”, *J. Acoust. Soc. Am.* 30, 237-246.

[15] Sazdov, R., Paine, G, and Stevens, K., (2007). “Perceptual Investigation into Envelopment, Spatial Clarity, and Engulfment in Reproduced Multi-channel Loudspeakers” in *Proceedings of Audio Engineering Society Conference 31st Conference*, London, UK

[16] Sazdov, R., (2009). “Localisation of subwoofers in a concert hall environment”, in *Proceedings of the International Computer Music Conference 2009*, Montreal, Canada

[17] Welti, T., “How many subwoofers are enough,” in *Proceedings of Audio Engineering Society 112th Convention*, Munich, Germany, May 2002.