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Auditory Occlusion Based on the Human Body in the Direct Sound Path: Measured and Perceivable Effects

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ABSTRACT

Audio plays a key role in the sense of immersion and presence in VR, as it correlates to improved enjoyment of content. We share results of a perception study on the ability of listeners to recognise auditory occlusion due to the presence of a human being in the direct sound path. We ran two-alternative forced choice trials to test for effects of occluder body type and distance from sound source on recognition of auditory occlusion. Results show that audio cues allow listeners to significantly detect the presence or absence of an occluder, and that position of the occluder relative to the listener and sound source, as well as occluder body type modulate detection rates. Synthesised audio achieved, in selected conditions, better occlusion detection than recorded audio. The work provides details on what filtering occurs across 26 1/3 octave frequency bands when a person comes between a listener and a sound source. This research will inform the recreation of auditory effects in virtual shared spaces aimed at music and dancing, due to the presence of other avatars.

CCS CONCEPTS

• **Applied computing → Sound and music computing**; • **Computing methodologies → Simulation evaluation**; **Simulation environments**.

KEYWORDS

Sound, auditory occlusion, presence, mixed reality, simulation

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1 BACKGROUND

This paper examines the effects of the interposition of a human body in the direct sound path between sound source and listener. It includes a study on the perceivable differences in occlusion as a result of position and body type. The presence of people affects the sound that a listener hears in a shared physical space, due to auditory occlusion. Reproducing these effects in shared online environments potentially improves the sense of presence and social connectedness. Especially in the context of music and dancing, where sound is a primary focal sensory point. Within virtual reality (VR) applications, audio plays a key role in the sense of immersion and presence [63]. Improving the sense of presence has been a long-standing goal in media [94]. Social connectedness has been recognised as having a positive effect on physical and mental health [89]. Online dancing is an activity which has been shown to effectively enable a sense of connecting with others [55] and reducing stress [40]. Research also points to the importance of users feeling embodied in virtual environments, particularly regarding auditory feedback from their movements [54].

The COVID-19 pandemic has highlighted the importance of digital social interaction in the mental resilience of individuals in combating loneliness [72]. VR interventions have also been shown to reduce psychological distress and anxiety amongst users [44, 79]. In real-world crowds, each individual contributes to the absorption of sound within a shared space, such as a theatre or concert hall [56]. People's position and clothing also affect this absorption factor. In VR shared experiences, this appears to be unexplored, yet acoustic shadows are an important auditory phenomenon which humans rely on to identify objects in a space which we cannot see [28]. Auditory feedback of the environment with regards to the acoustic shadows of individuals could provide another method of enhancing the sense of presence and connectedness of users.

Our research questions are:

(1) Can participants detect presence / absence of an occluder from audio input?
(2) Can participants correctly detect body type and position from audio input?
(3) Does audio type (synthesised or recorded) help detection of presence, occluder body type and occluder position?

This paper is organised as follows. We start with an exploration of related work in the fields of acoustics and computing, examining previous research on how sound is treated in interactive media such as video games and mixed reality (MR) applications, as well as the technical challenges therein. Then we provide the details of our data gathering methods on the auditory occlusion of a human body. We then discuss the online perceptual study which was conducted to test the perception of occlusion and the results of the measured human auditory occlusion. A discussion of the results is provided, followed by the conclusion of our findings.

2 RELATED WORK

Here we examine various approaches to the improved realism of audio in virtual environments and the need for a sense of presence and connectedness in online applications. We first examine past research in realistic acoustic environments. Then we highlight the potential need for enhancing remote social interaction. Finally, we explore what technical challenges arise when developing audio systems which try to replicate real-world sound interactions.

2.1 Absorption and Occlusion

There is considerable literature on the absorption coefficients of materials [52], sound propagation [77] and reflections [84] with regards to virtual spaces [53]. This research is of particular interest to the games industry, with demand for realism and natural sounding environments to enhance the immersive player experience [39]. With the increased availability of consumer VR products such as the Meta Quest [60] and HTC Vive [43], recent research has focused on methods of improved sound localisation using generalised Head-Related Transfer Functions (HRTFs) [4] and spatial audio techniques [49, 107]. While this research considers how sound emitting objects should be heard, they do not examine the changes to the environment due to the presence of other people.

Less is available on how dynamic occlusion objects may affect the auditory environment. Some, such as work by Raghuvanshi [76], develop methods on auditory changes to the virtual environment through portals. Russell and Brown [81] investigate the salience in the perception of occlusion of sound due to occluding objects. Some studies have been carried out on how people change the sonic characteristics of spaces [82] and the absorption of the body [17, 48], however there is a paucity of research which fully explores or measures the effect of people as occluding objects across the audible spectrum.

Avatars in interactive media such as VR can typically be altered via a number of physical attributes including height, weight, shape and gender. As such, when considering the audible changes a person could potentially make to a space, these traits are worth examining. We decided to use three basic body types (ectomorph, mesomorph and endomorph) as used in other research [24, 30, 35, 51], as a means of determining if any noticeable differences were measurable. Gender was also considered as a possible candidate for potentially noticeable measurement differences. Some other aspects were considered such as body fat content and more specific body types, but were determined to be outwith the scope of the initial study. Should a difference in body type become apparent in the measurements, this would present a case for further work.

2.2 Presence and Social Connectedness Online

As the worldwide lock-downs due to the COVID-19 pandemic demonstrated, social isolation exacerbates existing age-related health problems in elderly people, as well as detrimental effects on young people's mental well being [19]. Some social group activities such as dancing have been shown to improve the mental well being of participants [29]. By implementing an auditory feedback system that reacts intuitively as in real world scenarios, the user can be immersed more fully in the experience. This could aid in reducing user loneliness as they can feel more connected to the space and the users within it [72]. Around 15 percent of the world population are living with some form of disability [104]. Online discourse in recent years has led to the impetus for more accessibility in games, allowing those with a variety of disabilities to use and enjoy the medium [25]. A user focused approach to audio in virtual environments could result in the increased accessibility of MR applications in a broader sense.

Creating humanoid avatars in MR is also a technical challenge, both physically and technologically. Recreating precise movements of participants is difficult, particularly with regards to smaller details such as finger movement tracking [42]. Authentically portraying such experiences in a digital setting requires precision in the visuals, but also in auditory feedback for participants. Effective recreation of subtle, personal sounds of people could be a key factor in building an immersive virtual experience. Combining visual, audio and haptic feedback has been shown to aid in collaborative tasks [62], therefore a combination of these systems are often considered for group social activities. A sense of presence relies on the user believing themselves to be within a virtual space, and yet there is very little research on the sense of agency and body ownership with regards to personal sound i.e. the sound that your avatar makes in the virtual world [34]. While methods of procedurally generating footsteps and materials has been examined [97, 101], the effect on the user's experience has not.

Methods of measuring the sense of presence are plentiful, covering aspects from physical autonomic responses through to analysis of respondents feedback. In the case of the former, involuntary responses such as eye-movement can be used to measure salience of auditory events [47]. Examining the latter, a common method is the use of questionnaires, however the efficacy of such practice in virtual reality scenarios has been questioned [85]. Questionnaires however, are still common practice in the measurement of subjective feelings [46, 57, 100].

2.3 Technical Challenges

Audio in Mixed Reality. MR, as the next step in interactive media, builds upon what has been learned from traditional platforms. With video games in particular, accurate physics based on the ground truth has been a goal for many development studios and platforms [8, 59, 76]. However, focus on how a listener perceives their environment in a virtual space has been largely unexplored [9]. The proliferation of internet enabled applications, especially those with voice-chat capability, compounds this problem by including multiple users within a virtual shared space. Sound designers now should consider how to balance challenges such as realism and immersion, as well as adjusting the audio mix at run-time within the virtual space against what a user requires for the most engaging experience. In addition, spatialisation of audio for a VR user is more important than in traditional media, for example when important elements of the experience occur outside of the users field of view [88].

With the increased expectation of consumers for immersive virtual environments however, comes the need for more resource intensive audio feedback, such as implementation of real-time audio occlusion and reflections, versus baked-in alternatives [76]. With the popularisation of new virtual, mixed and augmented reality technology such as Meta's Quest 3 [60], Valve's Vive Pro [99] and budget friendly options such as Google Cardboard [36], this appears to be more important than in previous generations of products. While advanced systems such as desktop computers are less susceptible to these resource bottlenecks, less powerful systems can have trouble smoothly running intensive applications [102]. It would be beneficial to discover best-practices for the allocation and focus of those resources in order to prioritise crucial elements of the experience to avoid problems such as voice starvation [45].

Real Versus Synthesised Sound. It is possible to overlook a key difference in real-world versus virtual world auditory environments, that is using our ears rather than using some form of listening device such as headphones. Although advances have been made with HRTFs and acoustic modelling of virtual environments [13, 18, 69], technological constraints prevent real world interactions of sound with materials, other sounds, high order ambisonics and the listener themselves [50]. Auditory processing encompasses a wide range of acoustic and psychoacoustic phenomena including inter-aural time difference (ITD), inter-aural level difference (ILD), the Haas effect (also known as the precedence effect), masking, missing fundamental, just noticeable differences, equal loudness contours and even physical movement within the ear [90]. All contribute to understanding the surrounding environment. While some of these problems are simple to solve in a digital context, others require vast amounts of computation, and some are beyond the capabilities of today's technology. By understanding and utilising these phenomena, it may be possible to create systems for interactive media which could deliver an intended result while reducing the technical requirements.

A potential solution for these problems lies in the way the human brain handles the hundreds of sound sources, reflections and reverberations of daily life, known as the cocktail party problem [20, 61]. Similarly to how the eyes focus on a narrow band of our total visual field, humans are able to focus our hearing on a particular sound source, utilising top-down attention to group and segregate what we hear [32, 68]. This auditory selective attention allows us to process new and important information quickly by deprioritising unnecessary sound - for example the background dirge of traffic - so as to focus on the footsteps of someone approaching, or a singular voice in a group of people. These concepts could be applied to VR formats in order to emulate the real-world auditory experience with virtual sound sources.

It might also be beneficial to utilise systems which reduce the cognitive load of users [38]. Once such strategy could be the implementation of a system which occludes sound based on virtual avatar position in relation to virtual sound sources. Taking account of the process of auditory scene analysis [14], it may be possible for current technology to be utilised to provide audio feedback in a way which can convey this same information more effectively [41].

Shared Auditory Environments. In group social scenarios, particularly with a partner or crowds of people, it may be possible to create a more active listening experience for users in interactive MR applications, rather than the passive approach seen in today's media. For example, with music playing loudly in a club, it is often impossible to hear the speech from other individuals, even when in close proximity due to the overall volume within the space, often exceeding 100 dB [73]. In such cases, it is often necessary to shout loudly directly into the ears of someone in order to be heard; a situation which has been shown to lead to frustration [27]. Besides the risk of irreparable hearing damage, recreating such a scenario in virtual environments could also cause users to feel overwhelmed. Instead, MR technologies have the potential of creating new and better than real-world experiences [105]. One under-researched aspect of virtual environments is the auditory changes that occur as a result of people occupying a space. We know that objects and geometry affect sound-wave propagation [76], and different materials used also affect the absorption and reflections of spaces [3, 5], but there is limited information available on how people affect the acoustics of a space. Some research has been conducted into changes to absorption due to people in seated spaces [10, 96], however this does not aid in scenarios where people may be standing or moving around freely in a space, such as at a concert. This paper aims to provide information on this area.

3 EXPERIMENT 1: MEASURING HUMAN BODY SOUND OCCLUSION

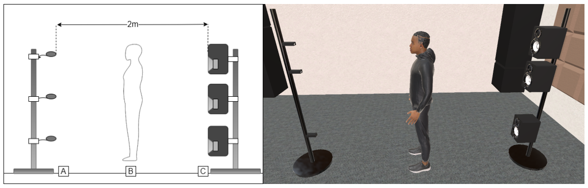
This section explains the method of gathering measurement data which would be used for the development of the follow-on perception study in the next section. We detail the setup and equipment used, as well as the process of gathering sound occlusion measurements for the variables of gender, body type and distance.

Participants. We invited 25 participants to take part in this measurement study (15M, 10F) from the Merchiston campus at Edinburgh Napier University. All participants were over 18 in accordance with University consent policy. Average age 31, min 18, max 55. After being shown an image to define clothing layers (see Fig. 1), participants were asked to wear only base and mid layers of clothing to avoid extraneous colouration of results due to heavy clothing materials or large garments which would affect their occluding silhouette.

Metrics including age, height, body type (ectomorph, mesomorph or endomorph [35, 51]) and gender were captured. Following Edinburgh Napier University's ethical guidelines, the participants were fully informed of the purposes of the experiment, and gave informed consent to take part. Earplugs were available, but the experiment measurements were taken at less than 85 dB(A) RMS, below the recommended level set by safety at work regulations in the UK [37], to prevent any possible hearing damage to participants. No participants chose to wear earplugs during the experiment.

Design. A suitable room, the Auralisation Suite at Edinburgh Napier University [74], was prepared. This room was chosen as it is partially acoustically treated to reduce reverberation, as well as prevent excessive noise from adjacent rooms and corridors. The

Figure 1: Participants during the measurement experiments were asked to wear only base and mid layers of clothing. [26]



(a) (b)

Figure 2: (a) Diagram of measurement equipment setup (not to scale). Microphone array on the left consisting of three AT831bs, loudspeaker array on the right consisting of three Genelec 8030As. Arrays were spaced 2 m apart. Participant stood at points A (0 m from microphone, referred to as the *close* position for experiment 2), B (1 m from microphone, *mid* position) and C (2 m from microphone, *far* position). Human outline [95]. (b) Mock-up of the configuration in Unity engine.

room measures 3.6 m x 3.1 m x 2.7 m for a total volume of 30.13 m^3. A loudspeaker array consisting of three Genelec 8030As [33] was set up at one side of the room, and a microphone array consisting of three Audio-Technica AT831bs [6] at the other (see Fig. 2). Positions for participants to stand were marked on the floor at distances from the microphone of 0 m, 0.5 m, 1 m, 1.5 m and 2 m. The distance between the loudspeaker array and microphone array was 2 m. All distances are given at distance from the microphone. Therefore 0 m measurements were taken with the participant directly in front of the capture microphone (without touching the capsule), and 2 m from the loudspeaker. Similarly, 2 m measurements positioned the participant directly in front of the loudspeaker, 2 m from the capturing microphone.

In order to minimise differences in height as a variable, the loudspeakers were adjusted for each participant to be at head (aligned with ears), chest (middle of the sternum) and leg (knee) height for each individual. The microphones were positioned in the same manner. This was determined the best way to examine the occlusion of the direct path between loudspeaker and microphone through the body and measure a complete picture of the individuals occlusion profile.

Participants self-recorded their body type from three basic somatotypes - ectomorph (thin, slender appearance), mesomorph (natural muscle tone and strength) and endomorph (soft, round body) - as explained by Giovanni and Valentina [35] and Lam et al. [51]. These criteria were chosen in order to determine if deeper investigation of these factors may be required in follow-on studies, but such research was deemed beyond the scope of this work.

Materials. The tests were conducted by playing a white noise burst for 500ms through each loudspeaker at 80 dB(A) RMS, measured at 1 meter from the loudspeaker, with one second of silence between each burst. Although pink noise is generally used when measuring acoustics, it presents a lower volume at high frequencies. With higher frequencies being shown to improve hearing challenges such as identifying speech in noise [64] and sound localisation [2] we therefore chose to use white noise due to expectations that higher frequencies would be most affected in the tests. In this way, we could compare the absolute change in dB across each 1/3 octave frequency band. It also provided an unweighted measurement that could be used for validation testing in other applications.

Procedure. A white noise track was used to capture the sound within the empty room, to establish a baseline unoccluded measurement. Then the participant was asked to stand at the first marked position. The measurements were repeated at each position, to determine the changes at the listener position due to the changing distance of the occluding person. Measuring different distances provides information regarding the changes in occlusion and transmission due to proximity to the loudspeaker and microphone.

The recorded results were then quantified via spectral analysis to determine changes in the propagation of sound between the sound source and the listener when occluded by a human. Analysis was carried out using MATLAB R2022b [58], where the audio data was then represented as 31-band graphic EQ bar charts, as well as extracting averaged dB levels for each 1/3 octave band for more precise comparison. By subtracting the values at each position from the empty room (unoccluded) signal values, it was then possible to illustrate the EQ profile of the occluded signals, and examine the precise values for each 1/3 octave band. Small rooms have known issues regarding low frequency phase, when combined with bass roll-off of near-field loudspeakers it was necessary for the EQ charts to be confined to 26 1/3 octave bands, starting at 63 Hz. Our measurements show the smallest range of variation across the endomorph measurements was in the 200 Hz band at approximately 2.7 dB, with the largest error range of approximately 10 dB in the 630 Hz band. For ectomorph, the lowest was approximately 5.1 dB in the 63 Hz band, with the largest of around 11.5 dB at 400 Hz.

4 EXPERIMENT 2: HUMAN AUDITORY OCCLUSION PERCEPTION STUDY

The following sections describe the details of the perception study, in which we tested conditions such as difference in distance, gender and occluder body type to examine which factors provide perceivable changes in auditory occlusion. The design of the tests and signals were based on the measurement data captured in the first experiment detailed in the previous section of the paper. This study involved two-alternative forced choice (2AFC) trials with visual elements, 2AFC trials with no visual element and a rating task.

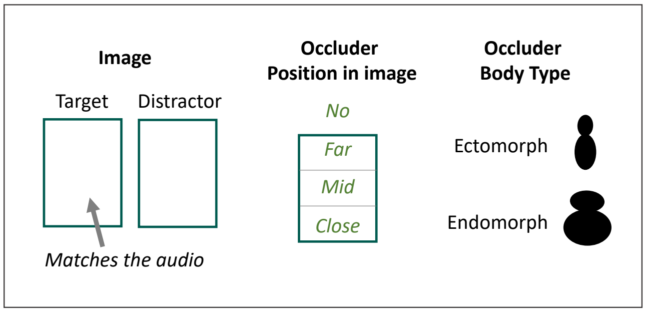


Figure 3: Variables in the two-alternative forced choice task.

Participants. After gathering measurement data, we then proceeded with a perception study. This was conducted online in order to reach a greater number of participants. For the study, 64 participants (44 male, 16 female, 4 did not disclose) were recruited both online and from Edinburgh Napier University, Merchiston campus (average age = 42, min = 21, max = 70). Following Edinburgh Napier University's ethical guidelines, all participants gave informed consent prior to taking part.

Design. We designed a virtual environment which allowed us to create images from a user perspective of facing an occluding object (a virtual avatar) and a sound source. Fig. 3 illustrates the variables examined during the 2AFC trials. We chose to make use of 2AFC tasks in order to easily examine one variable per trial [78, 87], and created a matrix which accounted for each dependent variable.

The variables for the scenarios included the distance of the occluder from the listener position (0m, 1 m or 2m), the audio signal occlusion method (real recorded occlusion or synthesised occlusion based on measurements in Experiment 1), the occluder gender and occluder body type. For example, if the occluder was 1 m from the participant, the signal would be a recorded or synthesised signal at 1 m from the microphones if it was aligned, or a different distance value signal if mismatched. We refer to the "correct" response in each trial as the *target* and the incorrect response as the *distractor*.

We tested three distances; 0 metres (directly in front of the participant) 1 metre and 2 metres from the participant (directly in front of the loudspeaker). We chose these particular distances to reduce the number of trials required, and as they showed the largest differences in occlusion. The 1 m scenarios were the midpoint between the microphone and loudspeaker, therefore we predicted a less perceivable occlusion effect than the 0 m and 2 m scenarios, and would be more likely to be confused with the no-occlusion scenarios. We also used three differing music tracks in order to check for consistency across sound sources.

In preparation for the online survey, "real" signals were recorded using a Neumann KU-100 binaural dummy head microphone [67], recorded at the participant head height, as was the loudspeaker. Recordings were taken at the same distances as the first experiment, using participants representative of each gender and body type. Synthesised signals were produced by applying EQ based on the average measurements taken in the first experiment. Our decision to do this, and to test for stereo files versus mono synthesised files was with regards to how game engines such as Unity handle 3D audio objects [93]. In such cases, audio sources are treated as a single point source, and therefore it is useful to understand how this process could be utilised to enhance the virtual experience. For representation in binaural experiences, HRTFs would be applied at the final stage of processing, with differing approaches and datasets in use [106].

After the two-alternative forced choice trails, the next set of trials were conducted as hearing tests, with no images shown to participants. A subset of the audio from the 2AFC trials was used. This set of trials was to determine if participants could identify the correct condition without a visual prompt.

Materials. The online survey was built using Gorilla [16]. Participants could complete the survey on any PC or laptop device with headphone output. Instructions for calibration of their device was given before the trials commenced, in order to ensure a suitable and safe listening volume. Images for the trials were captured from a virtual representation of the measurement room recreated in the Unity game engine [98]. Copyright free music was acquired via websites FreePD.com [31] and Uppbeat.io [65], which were then used for the real occlusion recordings and the synthesised occlusion clips. The track titles were "Camping" by Cruen [23], "Chronos" by Alexander Nakarada [66] and "Mood of Summer" by Abbynoise [1]. 10 second excerpts were used to reduce the time for each trial and to ensure each participant heard the same samples. To create the synthesised occlusion, the tracks were processed in Reaper [22] according to the measurement data taken in the first experiment.

Procedure. After giving informed consent to take part, participants were asked to complete a short demographic survey to allow examination of trends. They were then presented with instructions for setting up their device appropriately, including setting volume level and wearing headphones. This aimed to prevent effects of vastly differing volume levels which may affect perception due to loudness contours [21, 92] or masking caused by noise across participant environments [70, 83], as well as to reduce the risk of hearing damage to participants [37].

For the first task, participants were presented with a two-alternative forced choice (2AFC) setup. All trials were randomised to prevent any ordering effect in the results. Each screen presented the participant with an audio sample and two images, representing the occluding person between them and the loudspeaker (see Fig. 4). The audio samples were prepared from the previous measurements acquired during experiment 1. Trials were designed to include comparisons of all combinations of body type (endomorph and ectomorph); gender (male and female), and position of the occluder away from the microphone (close: 0m, middle: 1 m and far: 2m). Each combination was presented in a trial with a real recorded signal and in another with a synthesised signal, recreated in a digital audio workstation (DAW) based on the measurements taken in the first experiment. In total, each participant completed 120 2AFC trials. For each trial, they listened to a 10 second audio sample, then chose which of the two images was most appropriate to the audio. From this we can examine which occlusion scenarios presented the most noticeable occlusion and the perception of occlusion as it relates to the visual representation.

In the second task, designed to establish whether audio input can accurately convey a sense of presence, we presented audio clips to participants with no visual elements. The participants were asked to rate how sure they were that someone was present in the room

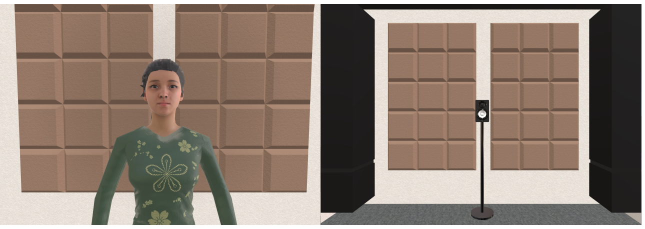

(a) (b)

Figure 4: An example of one of the 2AFC trials. This trial included two scenarios: (a) a female ectomorph occluder in close position and (b) no occluder. The participants task was to select the scenario they thought most appropriate to the audio clip being played.

using a slider from -100 (completely sure there was no-one in the room) to +100 (completely sure there was someone in the room). As well as this continuous measure of presence, participants were also asked to rate "I feel a sense of presence when listening to this audio." in a 7-point Likert scale (1 = Disagree, 7 = Agree). The trials for this task included no occluder, or an occluder with all combinations the three positions, two body types and two genders mentioned above. Each participant completed 24 presence trials. Again, trials were randomised for each participant. Finally, participants were debriefed and thanked for their participation.

5 RESULTS

The results of both of our experiments is detailed as follows. Firstly, the measurement data is provided, illustrating the various equalisation profiles based on body type and distance. Next we provide the results from the perception study which we conducted online. The initial 2AFC trials are broken down into analysis of effects including occluder body type and position, no occluder trials, occluders with position as the control variable, occluders with body type as the control variable and effects of synthesised versus recorded audio trials. We provide additional results pertaining to effects of practice, *distractor* presentation and effect of occluder gender. Finally, we provide analysis of presence trials which were presented without visual elements as a pure listening test.

5.1 Measurement data on body type, position and gender

An examination of the audio data capture suggests that there are potential differences in the degree of occlusion not only between male and female genders, but also body types. Distance however appears to be have the strongest effect. There was an expected drop off in high frequencies in all measurements, particularly above 2.5 kHz bands. Frequencies below 2 kHz are less effected, but we do see some increased response in bands around 250-315 Hz, particularly regarding the chest microphone measurements.

We also see from the measurements that the positions in closest proximity to the listener position and sound source create stronger attenuation at higher frequencies as well as intensification of responses in lower bands. The combined male versus combined female results appear to indicate this more strongly for female participants. The combined results are derived from three of each body type for both male and female, so nine male participants for the combined male reading and nine for female. This was to ensure equal weighting of the results. This is still a small sample size and further work could provide more statistically powerful measurements for these criteria.

For body type we compare a combined 18 total participants, three male and three female per type to ensure equal weighting of each result. Of the three types, mesomorph shows the flattest results across each measurement. Endomorph and ectomorph both show intensification of response around the 200-315 Hz at the head and chest measurements when not immediately at the listener position, as well as the 315-500 Hz bands in the knee results. At the closest to listener position (0m), the attenuation was noticeably stronger across all body types in the 200-315 Hz bands.

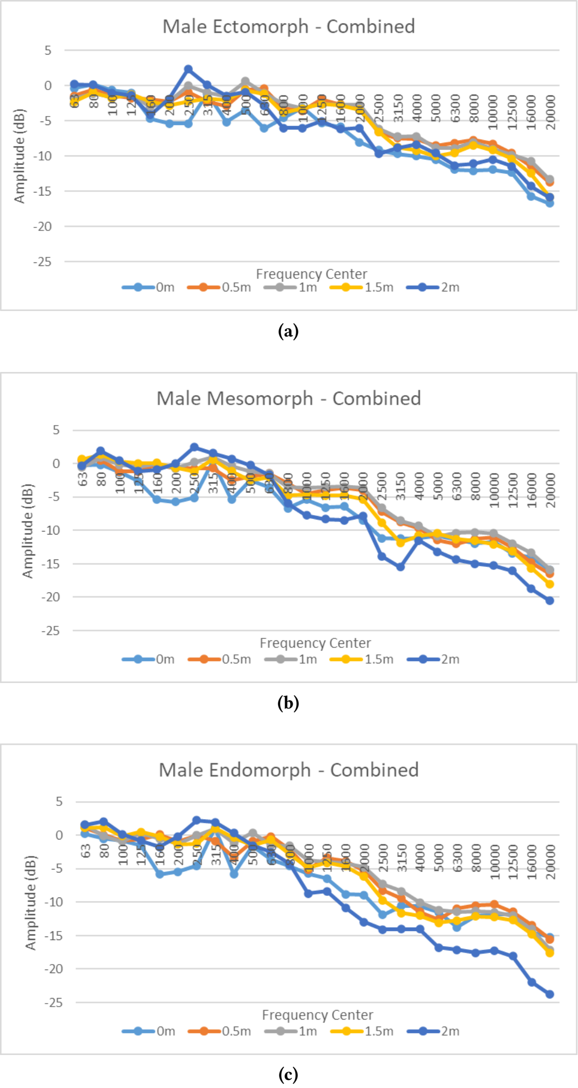
To investigate the nature of the changes across body type and distance, we also looked at averages across distance, body type and gender, such as with the male measurements in Fig. 5 and Fig. 7.

We also see from the combined male and female data some potential differences in the profiles for body types (see Fig. 8). Particularly in frequencies above 500 Hz we see some divergence between the profiles for body types. Noticeably, the 1 m readings are the most similar, but at 0 m (closest to the microphones) and 2 m (closest to the loudspeaker) we can see these results differ.

5.2 Online Perception Study

The following section reports the analysis of data from 64 participants in our Two-Alternative Forced Choice trials. *Target* refers to the correct alternative in the trial, i.e., the image that corresponded to the audio being played, while *distractor* refers to the other, incorrect image. Binomial models and binomial generalised mixed-effect models with the outcome variable being whether participants correctly identified the *target* image corresponding to the audio and variable, and participant as random effect were conducted. The package lme4 [7] in the software R [75] was used to fit the models. The dashed line in figures represents the response rate predicted by chance. We note the limitation in the online study of listening devices. Whilst we provided calibration instructions regarding volume level, different headphones do have varying frequency response profiles. However, as end users of XR products use a variety of headphones, we believe this aids in understanding the perception results. The perception study focused only on ectomorph and endomorph body types, as well as male and female genders in order to reduce the number of required trials. As such, we chose to focus on these variables at opposing ends of the spectra.

In the non-image trials, presence was measured in two ways. First, participants were asked to answer the question “I feel a sense of presence when listening to this audio” on a 7-point Likert scale from 1 = disagree to 7 = agree. (Fig. 9, left). Responses were not normally distributed, so a Wilcoxon test was conducted. It returned a significant effect of actual presence of an occluder correctly predicting Rated Presence (Likert) (W=932, p=0.000) with a moderate effect size (r=0.43). Second, participants rated confidence of their perception of another persons presence using a continuous slider with values from -100 (completely sure there was no-one in the



(a)

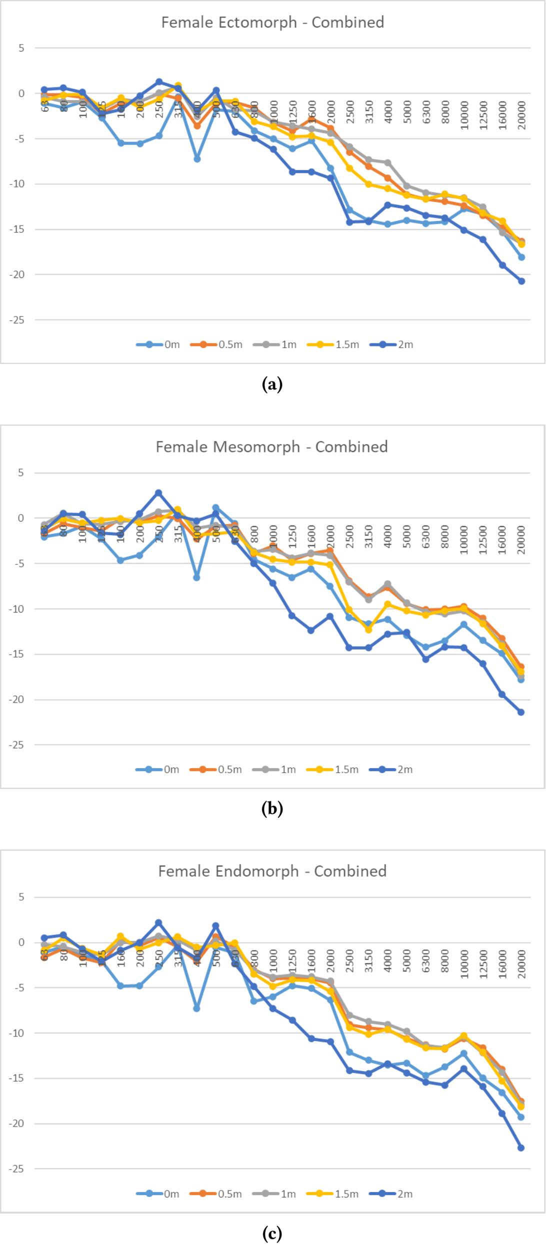
(b)

(c)

Figure 5: Measurement data of male occluders. Three body types are shown (Ectomorph, Mesomorph, Endomorph) with measurements taken at distances from the microphone. Points are combined averages of head, chest and leg microphone measurements.

room) to +100 (completely sure there was someone in the room) (Fig. 9, right)). Again, responses were not normally distributed. A Wilcoxon test returned a significant effect of presence on ratings (W=97552, p=0.000), with a large effect size (r=0.54). Both measures show that presence is clearly detected from audio.

Can participants correctly detect body type and position from audio input only? Descriptive statistics are shown in Fig. 10. In the remainder of this section, unless otherwise indicated, binomial models and binomial generalised mixed-effect models with participants as random effects were conducted, with proportion of correct responses as the outcome variable.



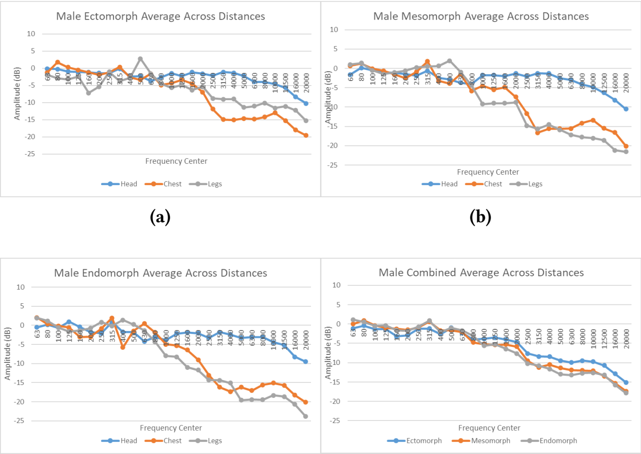
(a)

(b)

(c)

Figure 6: Measurement data of female occluders. Three body types are shown (Ectomorph, Mesomorph, Endomorph) with measurements taken at distances from the microphone. Points are combined averages of head, chest and leg microphone measurements.

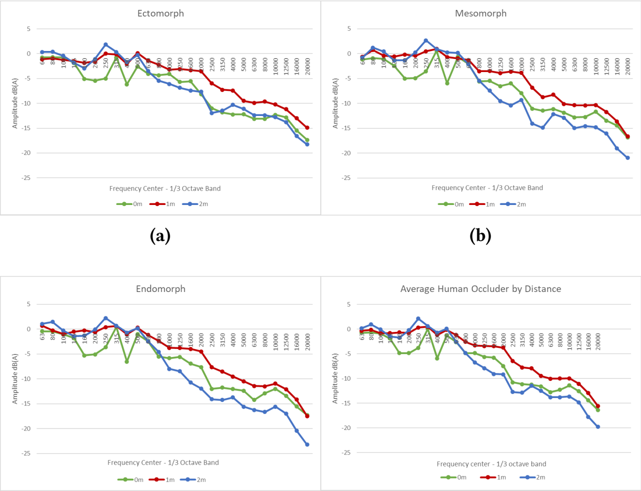
From this data we can extract a third measure of detection of presence, this time on correctness of response in the 2AFC trials with no visual elements. A linear model revealed that when an occluder was present in any position (*close*, *mid*, or *far*), responses were significantly less correct than when there was no occluder present (β=-1.18, p=0.000; R^2 = 0.06). As seen in Fig. 10 presence



(a) (b)

(c) (d)

Figure 7: Averaged values across all distance measurements for male body types at head, chest and legs. Images (a),(b) and (c) show average values across distance for each microphone in the array for the three male measured body types (Ectomorph, Mesomorph and Endomorph). Image (d) illustrates the combined average of the microphones for each body type.



(a) (b)

(c) (d)

Figure 8: Combined average of microphones for each body type (combined male and female). Images (a),(b) and (c) show average values across distance for the three measured body types (Ectomorph, Mesomorph and Endomorph). Image (d) illustrates the combined average for each distance measured.

of an occluder is the main influence on correctness of response. To examine in detail to what extent position and body type are correctly inferred from the audio, we analysed the trials with an occluder in the audio (positions *close*, *mid* and *far*) and without no occluder (position *no*) separately (Fig. 11).

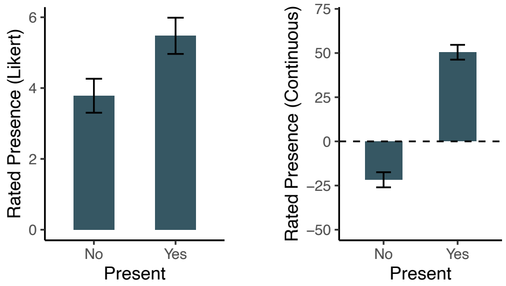


Figure 9: Presence ratings. Left: Sense of another person being present in the audio sample measured in a 7-point Likert scale. Right: Certainty of presence measured in a continuous scale from -100 to +100.

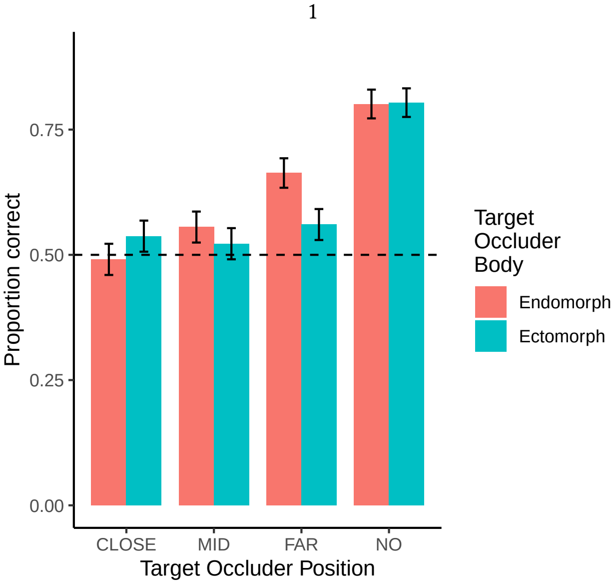


Figure 10: Proportion of correct answers by position and body type of the occluder in the *distractor* image. Significant results were recorded for *endomorph* in *mid, far* and *no* occlusion trials. *Ectomorph* was significantly correct in *close, far* and *no* occluder trials.

5.3 Trials when an occluder was present in the target image

Effect of occluder body type (controlling for position). Considering only trials in which there was an occluder in the *distractor* image, to isolate the effect of occluder body type, we analysed only the trials where the occluder was in the same position in the *target* and *distractor* images (Fig. 11, A1). A binomial regression with Body Type, Body Position (ordinal) and an interaction term as predictors and response Correctness as the outcome variable obtained a low $R^2 = 0.014$. Body position did not affect Correctness (β=0.25, p=0.13) (illustrated in Fig. 12, left). Occluder position (ordinal) had a significant effect (β=0.33, p=0.000) (Fig. 12, middle), and there was a

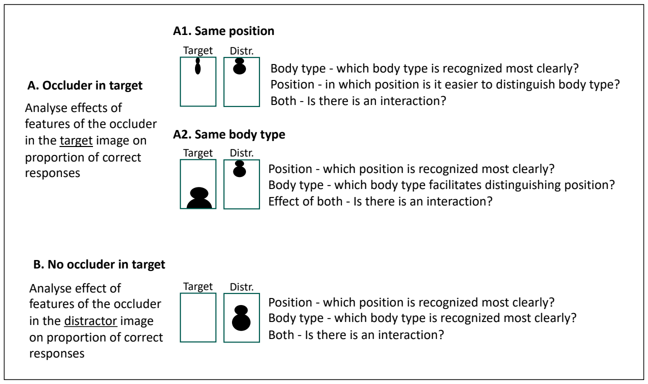


Figure 11: Analyses performed to determine to what extent occluder position and body type are correctly inferred from the recorded audio.

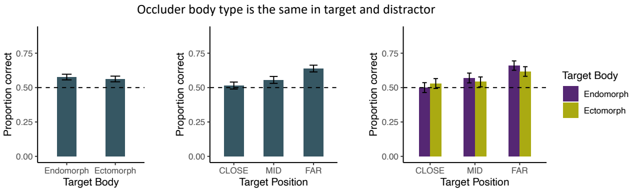


Figure 12: Proportion of answers correct in trials with same occluder position in the *target* and *distractor* images, broken down by features of the occluder in the *target* image. Left: By *target* occluder body type, significantly correct for both. Centre: By *target* occluder position, significant in *mid* and *far* positions. Right: By *target* occluder body type and position. Only *mid* and *far* position show significant results for both body types.

significant interaction between position and size (β=0.15, p=0.041) (Fig. 12, right), driven by a greater increase of correct detection of *endomorph* than *ectomorph* body type as distance from the listener increases (i.e. when the occluder is closer to the sound source).

Effect of occluder position (controlling for body type). Again, considering only trials in which an occluder was present in the *target* image, to isolate the effect of occluder position we analysed only the trials where the occluders in the *target* and *distractor* images had the same body type (Fig. 11, A2). A binomial regression with Body Type, Body Position (ordinal) and an interaction term as predictors and proportion of correct responses as the outcome variable obtained a low R^2 = 0.04, but significant effects of body type (β=1.22, p=0.000) (illustrated in Fig. 13, left), and ordinal position (β=0.43, p=0.000) (Fig. 13, centre), as well as a significant interaction between *position* and *body type* (β=0.77, p=0.000) (Fig. 13, right). This interaction is likely driven by a trade-off between body type and position. *Endomorph* body type was correctly identified more often when they were further from the loudspeaker, and *ectomorph* body types when they were closer to the loudspeaker. In particular, when placed in the *far* position, both body types tended to be identified as *endomorph* (Fig. 13, right).

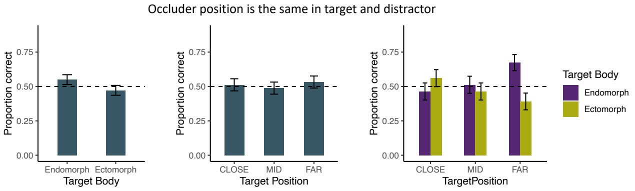


Figure 13: Proportion of answers correct in trials with same occluder body type in the *target* and *distractor* images, broken down by features of the occluder in the *target* image. Left: By *target* occluder body type, *endomorph* is correct at significantly better than chance. Centre: By *target* occluder position, no significant results. Right: By *target* occluder position and body type.

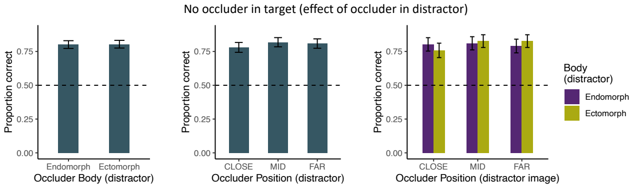


Figure 14: Proportion of answers correct in trials where the *target* image did not include an occluder, broken down by features of the occluder in the *distractor* image: Left: By occluder body type. Middle: By occluder position. Right: By occluder body type and position.

Trials when there was no occluder in the *target* image (effects of *distractor* image). Considering only trials with no occluder in the *target* (Fig. 11, B). A binomial regression with Body Type, Body Position (ordinal) and an interaction term as predictors and correctness of response as outcome variable returned a very low R^2 = 0.04, and no significant effects of body type (illustrated in Fig. 14, left), position (ordinal) (Fig. 14, centre) or interaction (Fig. 14, right).

5.4 Does audio type (synthesised or recorded) help detection of presence, occluder body type and occluder position?

To test the effect of audio type we considered trials from the presence study when there was an occluder present in the *target* only (in trials where there was no occluder, synthesised data was not tested).

Effects of audio type on detection of occluder presence. A Shapiro-Wilks test determined rated presence was not normally distributed, therefore a Wilcoxon test was used to determine the effect of audio type (Synthesised or Recorded) on correctness of Rated presence (continuous between -100 and +100). (W=29774, p=0.000) with a moderate effect size r = 0.47. Since an occluder was present in all trials, this result indicates that participants exposed to synthesised audio signals detected occluders more accurately than when exposed to recorded audio signals.

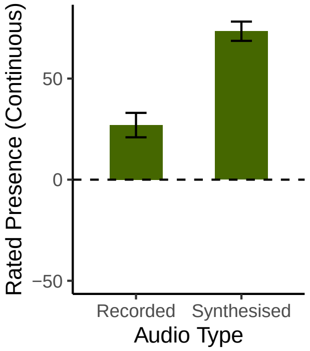


Figure 15: Rated presence (continuous) in trials where an occluder was present, by audio type.

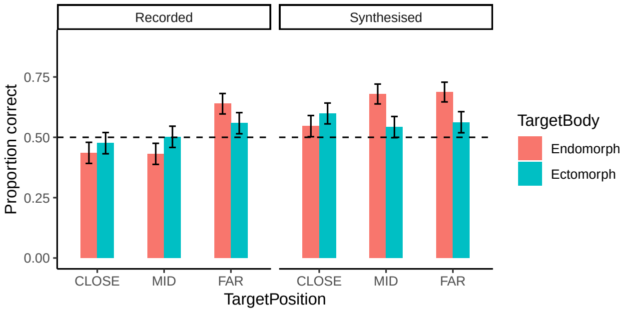


Figure 16: Proportion of correct responses by audio type, occluder body and occluder position. Recorded audio resulted in incorrect responses in *close* and *mid* position for *endomorph* body types. Synthesised audio resulted in higher correct response for all conditions.

Effects of audio type on detection of occluder body type and position. A binomial model with two interactions as predictors: audio type x occluder position (ordinal), and audio type x occluder body type, and with proportion of correct responses as the outcome variable returned R^2=0.02; a significant interaction between the audio type and occluder body type (β=-0.33, p=0.002); and a significant interaction between audio type and occluder position (ordinal) (β=-0.18, p=0.006). This indicates that with recorded audio, detection of position increases with distance of the occluder from the participant, and with synthesised audio it decreases, but only for the *ectomorph* body type (Fig. 16).

Overall, synthesised audio input obtained more accurate perceptions of occluder size and position than recorded input. This difference was most notable for *endomorph* occluders in *close* and *mid* positions. Indeed, *endomorph* in *close* and *mid* positions were predicted worse than expected by chance with the recorded signals, but better than chance with synthesised signals.

Effect of target position side (left or right). To test whether there was an effect of *target* position (left or right), a generalised linear model was conducted with Correct (yes or no) as the outcome variable and *target* position (left or right) as the predictor. The results indicate no effect of image position (β=-0.02, p=0.83).

Effect of occluder gender. To test whether there was an effect of gender of the occluder (male or female) a generalised linear model was conducted with correct (yes or no) as the outcome variable and occluder gender as predictor. The results indicate no effect of gender (β=-0.09, p=0.07).

6 DISCUSSION

Our measurements indicate that there is nuance to the attenuation of frequencies when a person acts as an occluder (Fig. 5). The results show potential differences across bands due to gender and body type, but particularly regarding distance from the listener and sound source. Of particular interest are the changes in close proximity to the listener. In scenarios such as crowded gig venues or more intimate virtual environments with a partner or small group of users, this sonic coloration of sound could have a noticeable impact on the listening experience, particularly for low frequencies [86]. We see that close proximity results in more severe attenuation at higher frequencies, but also typically the lower bands with frequency centers around 200 Hz.

Regarding our first research question, the results indicate that participants are able to detect the presence or absence of an occluder from the audio input. When asked to indicate perception of presence, participants indicated strong responses when someone was occluding the sound source (Fig. 15). There was less certainty in participant responses when no occluder was present. This indicates that participants could hear when someone is occluding a sound source and are more sure that there is occlusion taking place.

When no image was presented, participants were able to audibly perceive the presence of another person in the space between them and the loudspeaker. The results show a strong response to trials in which a person was present (see Fig. 9). The results for distance show higher accuracy of results at the *close* and *far* positions versus *mid*. This indicates that the occlusion effect was stronger at close proximity to listener or sound source, with less certainty in the *mid* position, potentially due to a higher mix of reflections from the room. The strongest indicator to a person causing occlusion was in the *far* position - closest to the sound source - indicating that this is where the strongest occlusion effect takes place.

The results appear to indicate that participants are able to correctly detect body type and position from audio input in some instances. However, the sample size for each body type upon which the measurements were taken in this study is small. In Fig. 11 we see that the most noticeably correct response is for *endomorph* body type at the position closest to the loudspeaker. We also see that *ectomorph* body type is the most often mistaken for the *endomorph* body type at the *far* position, possibly indicating bias due to the visual elements of the trials. *Ectomorph* body types are most accurate in the *close* position. This might indicate that the effect of occlusion is less obvious in this position, but participants are still able to determine that occlusion is occurring in that trial. The *mid* position trials show a chance close to random for both body types, indicating that this position causes the most confusion amongst participants. This implies a less clear effect of auditory occlusion at this midpoint.

Distance to sound source and listener show significant results (β=0.25, p=0.000) (Fig. 13), as well as in the case of having no occluder (Fig. 14). Scenarios with the occluder closest to the sound source had the most significant results, whilst the mid-point position had the lowest accuracy. This indicates that proximity to listener or sound source has significant impact on the listeners ability to discern occlusion.

In Fig. 12 we see that *endomorph* body type closest to the loudspeaker had the highest correct response rate, indicating a stronger effect than in other positions. At the *close* position (closest to listener), the *ectomorph* body type had more accurate responses. This suggests that the audio occlusion was more noticeable at the *far* position (closest to loudspeaker) which was possibly being conflated with the *endomorph* occluding body type, as indicated by the level of incorrect response for *ectomorph* in the *far* position. Fig. 13 indicates this position was most accurately judged when controlling for body type. Therefore body type of the occluder was not a significant variable for audio occlusion in these trials.

Regarding our third research question, audio type (synthesised or recorded) shows an effect on the accuracy of perceived body type and position. Synthesised input provided more accurate perceptions of occluder body type and position than recorded input (see Fig. 16). This could be due to some loss of complexity in the audio processing of the synthesised media, but this would require further study. The use of the Neumann microphone may have caused some confusion in real signal tests due to the effect of the dummy head ear canal. This difference was most notable for *endomorph* occluders in *close* and *mid* positions. Indeed, *endomorph* occluders in *close* and *mid* positions were predicted worse than expected by chance with the *recorded* input, but better than chance with *synthesised* input. We see that for *endomorph* in the *close* and *mid* positions, participants incorrectly identified the body type as *ectomorph* at worse rates than expected by chance (50% dotted line) when presented by recorded input. This means that participants were incorrectly identifying *endomorph* body types as *ectomorph* in the *close* and *mid* positions. This implies that the recorded audio caused the impression of weaker occlusion, but this is being partially corrected with the synthesised audio.

Gender had no effect on the results and was therefore shown to not impact the perception of audio occlusion. Participants were better able to recognise occlusion over time as they completed trials, indicating that participants are capable of learning what an occluded track sounds like, but the specific nature of what they are listening for in such cases was unclear and would require further study. The randomised nature of the *target* and *distractor* image positions was effective and showed no significant impact on the results. In Fig. 14 we can see that despite varying the *distractor* images between position and body type, there was no impact on correct responses for scenarios where no audio occlusion took place.

6.1 Further Work

The sense of presence, embodiment and spatial awareness in VR can affect the perception of the effects of occlusion. A future study would benefit from placing participants in a virtual scene with visible sound sources and occluders, allowing movement and correlation of visual and audio sensory information.

As the measured data shows that higher frequencies are the most heavily attenuated, it may also be reasonable to assess the perception of auditory occlusion against the background of presbycusis [103] where subtle changes in upper frequency content typically becomes more difficult to discern.

It could be argued that the stereo recorded audio caused confusion in the results as a result of the KU-100s HRTF profile due to listener mismatch [69]. It may be the case that the measurement data gave an exaggerated effect of occlusion and this presents a more noticeable effect for listeners versus recordings without an HRTF in the capture. Mono source capture may be advisable for future testing purposes. Further work may also include examining participant preferences in such cases.

We initially planned on testing if persons with highly trained listening skills such as professional musicians or other audio professionals were able to more accurately judge the effects of occlusion. Unfortunately, our sample data is heavily skewed in favour of those with a high level of audio expertise. It may be the case that audio professionals have better listening training versus the general population which therefore allows them to notice smaller shifts in frequency content [15]. Broader studies are needed to determine if this is the case.

7 CONCLUSION

The current work only explores auditory occlusion in the direct path of sound due to the human body. It would be beneficial to carry out similar work to examine changes in general absorption and frequency content for the human body. Such work should consider the full frequency spectrum, particularly changes to upper frequencies, rather than the common practice in room measurements which generally only measure up to 4 or 8 kHz [12, 71]. We plan to carry out such work in the next stage of this research. This is often difficult to conduct in occupied spaces, and previous work has focused on simulations to determine such estimates [10], particularly with regards to passive obstructions [91].

We conducted a survey examining the auditory occlusion caused by a human on the perception of someone being present in a shared space. Results indicate that listeners are able to correctly identify the auditory occlusion caused by someone positioned between them and a sound source with above chance accuracy. Based on our small sample size, it appears that gender of the occluding person had no significant impact on this perception in these trials, but body type in some instances shows potentially perceivable changes.

The occluders' distance from the listener or sound source does have a significant impact on accuracy. We show that in listening-only tests, participants were highly accurate in judging the presence of another person. In scenarios where the occluder was in close proximity to the listener or the sound source, the ability to judge the presence of another person in the room was more accurate than at the midpoint between listener and loudspeaker. Our results also provide evidence that synthesised audio occlusion effects, as measured and processed according to our mono capture source, are able to provide a degree of correction for confusion caused by binaural recordings of real occlusion with regards to occluder body type.

We conclude that listeners are able to determine the presence of an individual in a shared space due to their occlusion of a sound source. This ability to recognise when someone is in a shared space indicates a potential need for such systems in MR applications where users share a virtual space - such as concerts, social gatherings or multiplayer co-operative or competitive games. However, use of audio in MR for social experiences is under-researched [11]. We can determine from our results that while certain aspects of an avatar - such as gender and body type - should not make material changes to the sound occlusion, other aspects such as proximity to listener or sound source should be considered.

We argue that the sound occlusion caused by people is an important aspect of real world listening environments that should be replicated in MR applications for player and non-player avatars to improve the plausibility of shared virtual environments. The ability for listeners to recognise the presence of another individual in a virtual space through the effect of sound occlusion makes the case that such a system could aid in the improvement of immersion in MR. The specific effects of visual cues on auditory processing are unknown, with some work showing confusion due to mismatch of visual environments in VR [80]. Although precise localisation was not the purpose of this study, we do show that the auditory occlusion caused by a person was strongly recognised in both visual and non-visual tests. In reality, people are acutely attuned to the presence of other people through various sound cues. This work makes a strong case that auditory occlusion caused by humans is one such cue that should be considered and implemented in the development of MR applications in order to increase the plausibility of the space and the presence of others, be they player or non-player controlled avatars.

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