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REVERBERATION MAKES INTERIOR SPACES APPEAR LARGER

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ABSTRACT

The perceived width, depth, and height of interior spaces depend not only on the actual dimensions of the rooms but also on the brightness of room surfaces and other visual factors. Here, we measured the effect of the acoustic properties of the room surfaces on perceived size. Simulated rectangular rooms (light gray surface textures, no windows) with varying width and depth were presented on an HTC Vive Pro with head-tracking. For each combination of width and depth, one version with reverberant acoustics (mean RT_{60} = 1.03 s) and one version with damped acoustics (mean RT_{60} = 0.19 s) were simulated by varying the absorption coefficient of the surfaces. Binaural room impulse responses were generated using the room simulation software RAVEN (https://www.virtualacoustics.org/RAVEN/). Twenty-two participants viewed the rooms on the HMD and listened to speech and sounds of musical instruments inside the simulated space, using dynamic binaural synthesis with head-tracking. Participants estimated room width and depth in units of centimeters. As expected and compatible with previous studies, the estimated width and depth were significantly higher for the reverberant compared to the damped version of the simulated rooms. The mean increase in estimated width and depth was 1.1% (Cohen's d_z = 0.849) and 1.6% (d_z = 0.854), respectively.

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1. INTRODUCTION

Visually, the perceived height, width, and depth of an interior space can be increased by choosing bright colors for the room surfaces [1-3], or by painting the walls with a dense stripe pattern [4]. Is it also possible to make a small room appear more spacious by manipulating its acoustic characteristics? Speaking more generally, how are visual and auditory cues combined in judgments of the layout of interior spaces? Previous research has shown that when only auditory, but no visual information is available, the acoustic characteristics of a room affect its perceived size. When the acoustic properties of a real or simulated room were varied while the size of the room remained constant, room size ratings were reported to depend on the reverberation [5, 6]. The reverberation time seems to be more important than the direct-to-reverberant ratio [7]. When the room size was varied but the acoustic properties of its surfaces remained constant, room size judgments were found to correlate with the changes in actual room size [8, 9]. In studies where binaural room impulse responses (BRIRs) from real rooms were used so that both the room size and the reflectance properties varied, a few studies reported that the room size judgments depended on the actual room size [10-12], while other studies found no correlation with room size, but instead reported that the size ratings depended on the reverberation time [13] or the energy of the room-reflected sound [14]. However, there is only rather sparse evidence of whether room acoustics also have an effect when full visual information is available. Previous studies indicating that acoustic characteristics do influence the audio-visually perceived size of interior spaces [8, 12, 15] have some limitations, such as only parts of the rooms being visible. To further our understanding of the perceptual principles underlying the perception of room size and the interactions of hearing and vision, we conducted an experiment presenting audiovisual simulations of interior spaces varying in size (width and depth) as well as in their acoustic characteristics (acoustically reflective versus absorbent surfaces, resulting in a dampened vs. reverberant condition). The rooms were presented in a high-fidelity virtual-reality environment, enabling full 360° of exploration of the simulated rooms using head-tracking. Based on the findings of previous studies, we hypothesized that given a specific combination of width and depth, a room would be judged to be deeper and wider when its surfaces are acoustically reflective (resulting in longer reverberation time) compared to when they are absorbent (resulting in shorter reverberation time).

2. METHODS

2.1 Participants

Twenty-two volunteers (16 women and 6 men, age 20 - 34 years) with normal hearing, normal visual acuity, and normal visual stereoacuity participated. Before the experiment, potential risks were explained to them, after which they gave their written informed consent according to the Declaration of Helsinki. Participants were not informed about the hypotheses under test.

2.2 Stimuli and Apparatus

The stimuli were simulations of shoebox-shaped interior spaces, varying in width (3.913, 4.5, 5.175 m) and depth (5.217, 6.0, 6.9 m), but not height (2.9 m). Visually, the rooms had gray walls, white ceilings, and the floor was covered with a fine-grained, gray carpet. They were illuminated by an invisible light source in the middle of the room, but no shadows were simulated. Figure 1 shows a screenshot of one of the rooms presented in the experiment (6.9 × 5.2 × 2.9 m). Auditorily, for each room size (width × depth), two room-acoustical conditions were simulated. In one condition, the absorption coefficient α of all room surfaces was set to 0.1 at all frequencies ("reverberant"; mean RT_{60} = 1.03 s). In the other condition, α was set to 0.5 ("dampened"; mean RT_{60} = 0.19 s). The scattering coefficient was set to 0.2 in all conditions and for all room surfaces. In the virtual rooms, participants were positioned 1.0 m in front of the simulated back wall and shifted either 0.75 m or 1.25 m to the right from the horizontal center between the simulated left and right-side wall, depending on the experimental condition. The visual simulations were presented stereoscopically using an HTC Vive Pro head-mounted display with head-tracking. Participants were standing upright and able to explore the virtual rooms by moving their heads freely. The head tracking of the Vive ensured that the virtual eye height matched participants' real eye height [16].

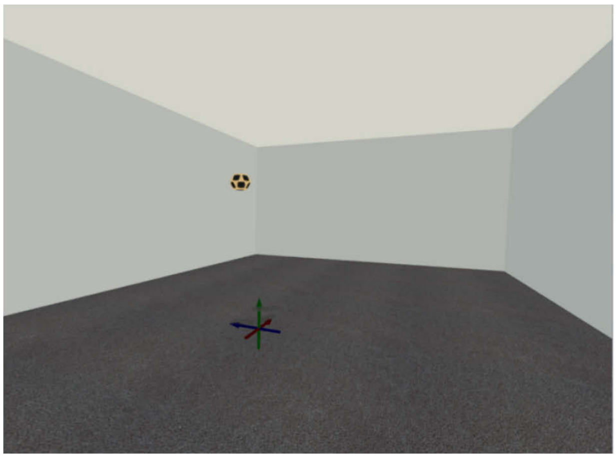

Figure 1. Screenshot of an example visual simulation of a room viewed from the participant's perspective and showing the sound source.

Inside the simulated space, participants listened to brief audio clips of speech (male and female talker), sounds of musical instruments (conga, cello), and hand claps produced by a single sound source with omnidirectional directivity, which was visualized by an octagon speaker (see Figure 1). The sound source position relative to the receiver was fixed, so that the distance between sound source and receiver did not provide a cue to the simulated room size. The sounds were presented in an endless loop, with pauses between sounds to make the reverberation tail audible. The sounds were auralized using dynamic binaural synthesis linked to the head-tracking of the HMD. The anechoic recordings were convolved with binaural room impulse responses (BRIRs) in real time, using the rendering software Virtual Acoustics (http://virtualacoustics.org/), within custom virtual-reality software based on the Unity game engine, and pre-generated BRIRs. The BRIRs were generated with the room acoustics simulation software RAVEN [17]. Head-related impulse responses (HRIRs) from the FABIAN head and torso simulator database [18] were used. The acoustic stimuli were presented on Sennheiser HD 650 headphones. On each trial, the position of the binaural receiver in the simulated space matched the position of the participant in the visual simulation (i.e., the position of the virtual cameras).

2.3 Design and Procedure

In a four-factorial within-subjects design, each participant received each of the 36 combinations of 3 room widths, 3 room depths, 2 room acoustics, and 2 observer positions. The experiment consisted of a short training block and four experimental blocks. Each experimental block began with a reference room (9 × 6 × 3.5 m), after which the 36 different experimental conditions were presented in randomized order, resulting in a total of four presentations per condition. As dependent measures, participants were asked to estimate the width and depth of the rooms in units of meters and centimeters. Apart from the very first trial in the training block, the experimenter did not provide any feedback concerning the correctness of the estimates. Within each participant, the estimated width and depth were averaged across the four trials presented per condition. The estimations for the reference room and trials from the practice block were not included in the data analysis.

3. RESULTS

Figure 2 depicts the mean depth estimates as a function of simulated room depth and room acoustics. On average, participants slightly overestimated the depth, but the estimations increased linearly with the simulated depth. Importantly and as expected, the main effect of room acoustics on the depth estimates was significant, $F(1, 21) = 16.055$, $p < .001$. The statistical effect size was relatively large ($d_z = 0.85$), indicating that this effect was observed consistently across participants. On average, reverberant rooms were estimated to be 10.78 cm (1.6%) deeper than their damped counterparts. The depth × room acoustics interaction was not significant.

As shown in Figure 3, the estimated width showed a similar pattern. Again, the effect of room acoustics was statistically significant, $F(1, 21) = 15.856$, $p < .001$, $d_z = 0.85$. On average, the reverberant rooms were estimated to be 6.1 cm (1.1%) wider than their dampened counterparts.

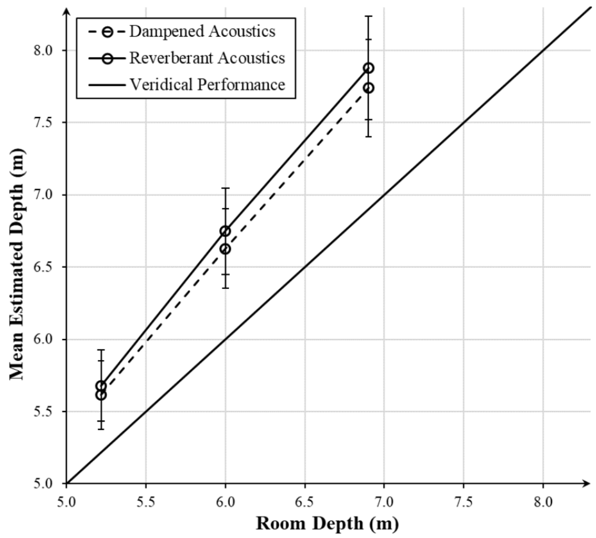

Figure 2. Mean estimated depth as a function of simulated room depth and room acoustics. The diagonal represents veridical judgments. Error bars show ± 1 standard error of the mean (SEM) across the 22 participants.

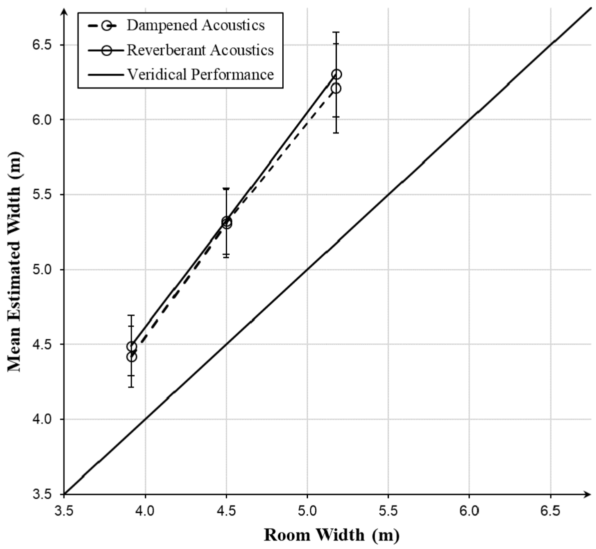

Figure 3. Mean estimated width as a function of simulated room width and room acoustics. Error bars show ± 1 SEM across the 22 participants.

4. DISCUSSION

As expected, the results showed that rooms in the reverberant room-acoustical condition were perceived to be significantly deeper and wider than their dampened counterpart. This demonstrates an influence of room acoustics on audio-visually perceived room size a condition where full stereoscopic and interactive visual information about room size was available, complementing previous studies presenting less realistic visual simulations. From an applied perspective, our results indicate that if one seeks to maximize the perceived size of a room, choosing acoustically reflecting materials for the boundary surfaces could be considered.

While this study provides evidence for an effect of room acoustics on audio-visual room size perception, it does not yet offer a sophisticated theory of how the acoustic characteristics might have led to the reverberant rooms being judged to be larger. We assume that the reverberation time plays an important role, but additional analyses and data are required to test this hypothesis. Another limitation pertains to the fact that, due to the nature of the task and the experimental design, the research hypothesis was likely transparent to participants, which might have resulted in an influence of demand characteristics.

Because we collected estimations for perceived room width and depth only, it remains to be demonstrated if a similar effect can be observed on perceived room height, or on perceived spaciousness and other more qualitative ratings. Future research could explore whether the effect can be generalized to interior spaces of all shapes and sizes, such as non-rectangular rooms or larger rooms. It could also be interesting to investigate how the effect of room acoustics depends on the quality and level of detail of the visual simulations provided. It seems possible that the impact of room acoustics would decrease with increasing visual simulation quality, as participants might pay less attention to auditory aspects.

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