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Auditory environmental context affects visual distance perception

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Abstract

To perceive the distance to an object through the visual modality, an observer uses a variety of cues, many of which may not be directly related to the target. This is illustrated by the fact that in a well-lit environment (with multiple visual cues) visual distance perception (VDP) is relatively accurate, whereas in a dark environment (where the observer can only see the target) VDP becomes inaccurate. Besides, a number of recent studies indicate that VDP is not only affected by the availability and reliability of depth cues, but also can be influenced by the context even in the presence of multiple visual cues. Here we provide evidence that VDP is influenced by the auditory environmental context through reverberation-related cues. We conducted VDP experiments in two dark rooms with extremely different reverberation times: an anechoic chamber and a reverberant room. We first show that the distance to a visual object located in the reverberant chamber was perceived significantly farther than the same target located at the same distance in the anechoic chamber. The results also show that the maximum distance perceived by participants correlated significantly with the perceived size of the room. In addition, participants who performed the experiment in the reverberant room reported a perceived size greater than those who performed the experiment in the anechoic chamber although both rooms are of similar sizes. Secondly we note that by separating participants between musicians and non-musicians only the former group perceived differences in the size of the room through auditory modality; moreover, only this group perceived the distance to the visual object in the reverberant chamber farther than in the anechoic chamber. On the other hand, the group of non-musicians did not perceive differences in the size of both rooms or in the perceived distance in both chambers. These results show that the auditory environment can influence the VDP, presumably by reverberation cues related to auditory perception of the size of a room.

Keywords: visual distance perception, multimodal integration, auditory perception

Auditory environmental context affects visual distance perception

1 Introduction

To perceive the distance to an object through visual modality, an observer must use a variety of visual cues many of which may not be directly related to the target. For example, in well-lit environments (with multiple visual cues) visual distance perception (VDP) is relatively accurate, whereas in the dark, where the observer can only see the target, becomes very inaccurate. However, a number of recently published studies have brought evidence indicating that VDP not only depends on the availability and reliability of classical depth cues, but also can be influenced by the context even in the presence of multiple visual cues. For example, it has been shown that in order to estimate the distance to a visual object the observer integrates local patches of ground information into a global surface reference frame [1]. It has also been reported that visually perceived distance of familiar objects in natural settings are conditioned by the structure of the surrounding visual field. For example, Lappin et al. [2], showed that, both, the accuracy and the precision of distance judgments differed between three types of environments with multiple visual cues: a lobby, a hallway, and an open lawn. In the same context, Witt et al. [3] showed that, both in indoor and outdoor environments, the space beyond the target influences the VDP: the distance appears greater when the target is near the end of a hallway than when it is distant from its end. Finally, Stefanucci et al. [4] reported that VDP is influenced by the inclination of the ground. Their results showed that the participants perceived the distance of the targets at greater distances in steep terrain (both uphill and downhill) than in environments with flat ground.

Here we provide evidence that VDP is also influenced by the auditory environmental context through reverberation-related cues. Reverberation has a large impact on the perceived characteristics of a listening environment. The perceived "spaciousness" of a room increases with reverberation time, reverberation level, and/or the amount of decorrelation between left and right ear signals [5]. Experiments performed by Sandvad [6] showed that subjects could usually correctly match photographs of rooms with the corresponding binaural recordings made in that environment. Also, a number of experiments have found a direct relation between the perceived room size and the amount of reverberation [6, 7, 8, 9, 10]. Finally, results published by Kolarik et al. [11] show that judgments of apparent sound source distance and auditory perception of the size of a room (using auditory environmental cues provided by reverberation) are correlated.

We conducted VDP experiments in two dark rooms with extremely different reverberation times: an anechoic chamber and a reverberant room (Fig. 1). We first show that the distance to a visual object located in the reverberant chamber was perceived significantly farther than the same target located at the same distance in the anechoic chamber. Secondly, we note that the maximum distance perceived by participants correlated significantly with the perceived size of the rooms. In addition, participants who performed the experiment in the reverberant room reported a perceived size greater than those who performed the experiment in the anechoic

Figure 1: Details of the experimental setup. (a) View from above the subject in the anechoic room. (b) Lateral view in the reverberant room. The subject can be seen on the left. (c) View from the subject position in the reverberant room. The room is in darkness and all targets are lit. The shot was taken with a little displacement to the right, in order to avoid occlusion by the nearest targets.

chamber, although both rooms are of similar sizes. Finally, we note that by separating participants between musicians and non-musicians only the former group perceived differences in the size of the room through auditory modality; moreover, only this group perceived the distance to the visual object in the reverberant chamber farther than in the anechoic chamber. These results suggest that the auditory environment can influence the VDP through reverberation related cues.

2 Methods

The experiments were conducted in two rooms with very different reverberation times: (a) an anechoic chamber and (b) a reverberant room (T_{60} about 8 seconds for a 1/3 octave noise band centered at 1 kHz). A total of seventy-five volunteers (19 women and 56 men) participated in the experiments. None had prior knowledge of the experimental rooms or the setup, nor were informed of any characteristic of the rooms or of the experiment. Each participant was brought by the experimenter to the experimental room blindfolded and then seated at the zero position. Next the experimenter left the room and the lights were turned off, remaining so until the completion of the experiment. Before starting the experiment the participant was asked to remove the blindfold in order to be able to look at the targets. In order to expose the subject to the acoustic characteristics of the room, a recording with the instructions of the experiment was played through a loudspeaker located 70 cm in front of the listener at a height of 1 m. The setup also had a microphone in the room which allowed real-time communication between the experimenter and the participant. All communication between both was done in this way.

Visual stimuli were acrylic squares of size 5×5 cm. Each target was illuminated by four LEDs mounted in its back that provided diffuse light. Stimuli were placed in front of the participant (0º azimuth) at a height of 1.50 m (approximately the height of the subject's head, giving roughly 0º elevation). Before entering the room, participants were able to see and touch an identical model of the visual targets employed in the task. This gave participants a prior knowledge of the targets. The experimental setup consisted of a linear array of five visual stimuli, located at 2, 3, 4, 5 and 6 meters from the subject's position (Fig. 1). Each stimulus was mounted on a metal support. To avoid visual obstruction between stimuli, servomotors were used to rotate the targets beyond the line of sight of the participant. The targets were lit only when they reached their final position. White noise (500 ms of duration) were presented through the loudspeaker before each trial, in order to mask the sound produced by the servomotors. This also contributed to expose the subject to the acoustics of the room.

Participants were randomly assigned to two groups: subjects in Group 1 performed the experiment in the anechoic chamber (n = 37) while subjects in Group 2 performed it in the reverberant room (n = 38). After each presentation, participants were asked to express verbally the apparent distance to the visual target. Subject responses were recorded on a computer and manually transcribed into a data sheet. Each target was presented five times for each test distance (25 trials in total) in random order. Participants made only one verbal response by trial and did not receive any information about the accuracy of their responses. After the completion of the VDP experiment subjects were asked to report verbally (still in complete darkness) their estimation of the length, width and height of the room where the experiment was conducted. Finally, subjects answered a short questionnaire regarding their music expertise. Fifty-one subjects were classified as musicians, all of whom reported experience as professional players and/or composers.

3 Results

Fig. 2a shows the average perceived distance as a function of the target distance for both rooms (anechoic in red markers, reverberant in blue markers). Error bars indicate standard errors and the dotted line indicates the physical distance to the targets. The data shows that the group of participants who performed the experiment in the reverberant chamber perceived the visual targets at greater distances than those participants assigned to the anechoic chamber.

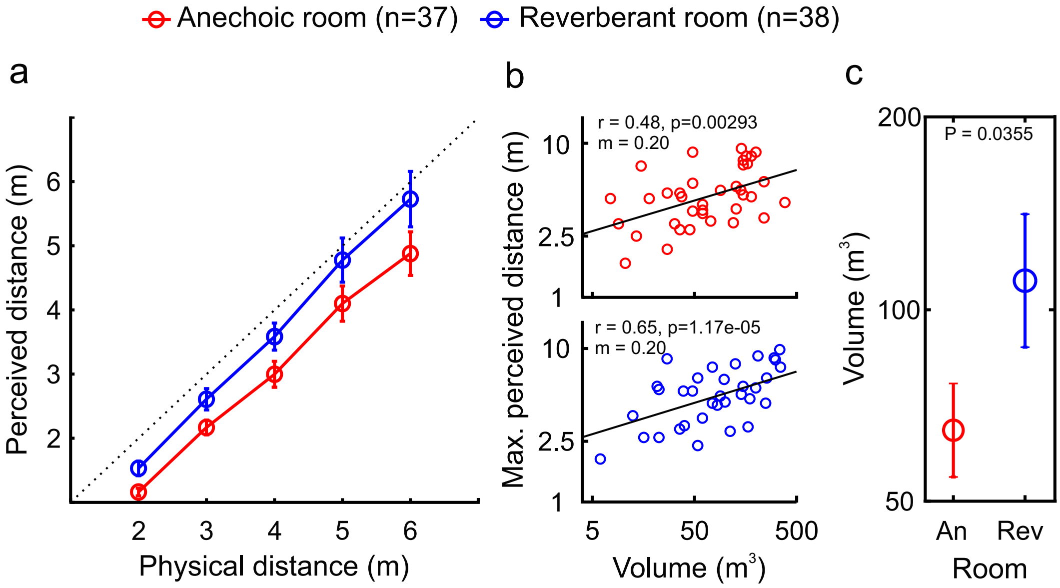

Figure 2: (a) Visual distance perception curves for all subjects in both rooms. (b) Maximum perceived distance vs. perceived room size. The linear correlation coefficient between both magnitudes (r) and its significance level are indicated in the upper-left corner of each plot. Black lines indicate the result of a linear fit between both magnitudes in log-log scale; the resulting slope (m) is indicated below the correlation coefficient. (c) Perceived room size averaged between subjects. The significance level of the difference is indicated in the upper side of the plot. See text for details on the statistical tests. In (a) and (b) error-bars indicate standard error.

The statistical significance of this difference was assessed by means of a repeated-measures ANOVA on the logarithm of the responses with factors “distance” (within-subjects) and “room” (between-subjects). The analysis yielded a significant effect of the room ($p = 0.0461$) and of the distance ($p = 4.51 \cdot 10^{-62}$) but not of the interaction; see Table 1 for details.

As previously mentioned, reverberation is a fundamental cue to perceive the environmental context through the auditory modality. Previous studies have shown that the reverberation time significantly influences the perception of the size of a room [6, 7, 8, 9, 10]. To study whether the response observed in our experiment could be explained by a relationship between VDP and the perceived size of the room we asked participants to estimate the room size after completing the VDP task (see Methods and [11]). Fig. 2b shows the correlation between the maximum distance perceived by the participants and the perceived volume of the room (anechoic in red markers, reverberant in blue markers) in log-log scale. The Pearson correlation coefficient and its statistical significance is indicated in each plot on the upper-left corner, along with the slope obtained after applying a linear fit to the data. Both groups (rooms) showed a significant positive correlation between the maximum target perceived distance and the perceived volume of the room.

Table 1: Results of analysis of variance on the distance curves, considering as factors the room and the source distance. Significant results (at the 5% level) are indicated in bold. Sphericity violations for the distance and for the interaction were corrected by means of the Greenhouse-Geisser correction, see below the table. Data were log-transformed before the analysis in order to improve normality.

	Room		Distance		Room×Distance Interaction	
	F	p	F	p	F	p
All subjects[a]	4.12	**0.0461**	627	$\mathbf{4.51{\cdot}10^{-62}}$	0.973	0.369
Musicians[b]	5.28	**0.0259**	482	$\mathbf{1.13{\cdot}10^{-49}}$	1.51	0.227
Non-musicians[c]	0.0106	0.919	149	$\mathbf{1.31{\cdot}10^{-14}}$	0.0158	0.951

[a] F(1,73) for room and F(4,292) for distance and interaction. ε_{GG} = 0.426.

[b] F(1,49) for room and F(4,196) for distance and interaction. ε_{GG} = 0.482.

[c] F(1,22) for room and F(4,88) for distance and interaction. ε_{GG} = 0.342.

The comparison between the volumes perceived by both groups of participants in the anechoic (A) and the reverberant (R) rooms is shown in Fig. 2c in log scale. Open circles indicate the mean response of subjects (error bars indicate standard error). Differences were assessed by means of a two-sample t-test on the logarithm of the perceived volume. We tested the null hypothesis that the reverberant room was perceived smaller than the anechoic room, based on the hypothesis reviewed in the Introduction; for this reason, we employed only one tail of the distribution. The test showed a significant difference (p = 0.0355, null hypothesis rejected).

Most of the participants in this study were students of music composition at the Universidad Nacional de Quilmes, which is the main reason of the high percentage of musicians. In order to study whether this condition influenced the responses, we divided the participants into two sub-groups, musicians and non-musicians (see Methods) and repeated the analysis for each sub-group. The resulting data is plotted in Fig. 3.

The distance curve corresponding to the musicians sub-group (Fig. 3a) shows that the observed effect between the two rooms was increased while data corresponding to the non-musicians sub-group (Fig. 3d) shows no apparent effect due to the room. This is reflected in the analysis of variance (see Table 1) whose results indicate that the "room" factor significantly affected the response for musicians (p = 0.0259) but not for non-musicians (p = 0.919). Interestingly, musicians perceived the volume of the reverberant room significantly bigger than the volume of the anechoic chamber ($p = 9.15{\cdot}10^{-3}$, same test as before, Fig. 3c), while non-musicians did not perceive differences between the two rooms (p = 0.728, same test as before, Fig. 3f).

Finally, we analyzed the correlation between the maximum perceived distance and the perceived volume of anechoic (red circles) and reverberant (blue circles) rooms for musicians (Fig. 3b) and non-musicians (Fig. 3e). All conditions showed a significant positive correlation

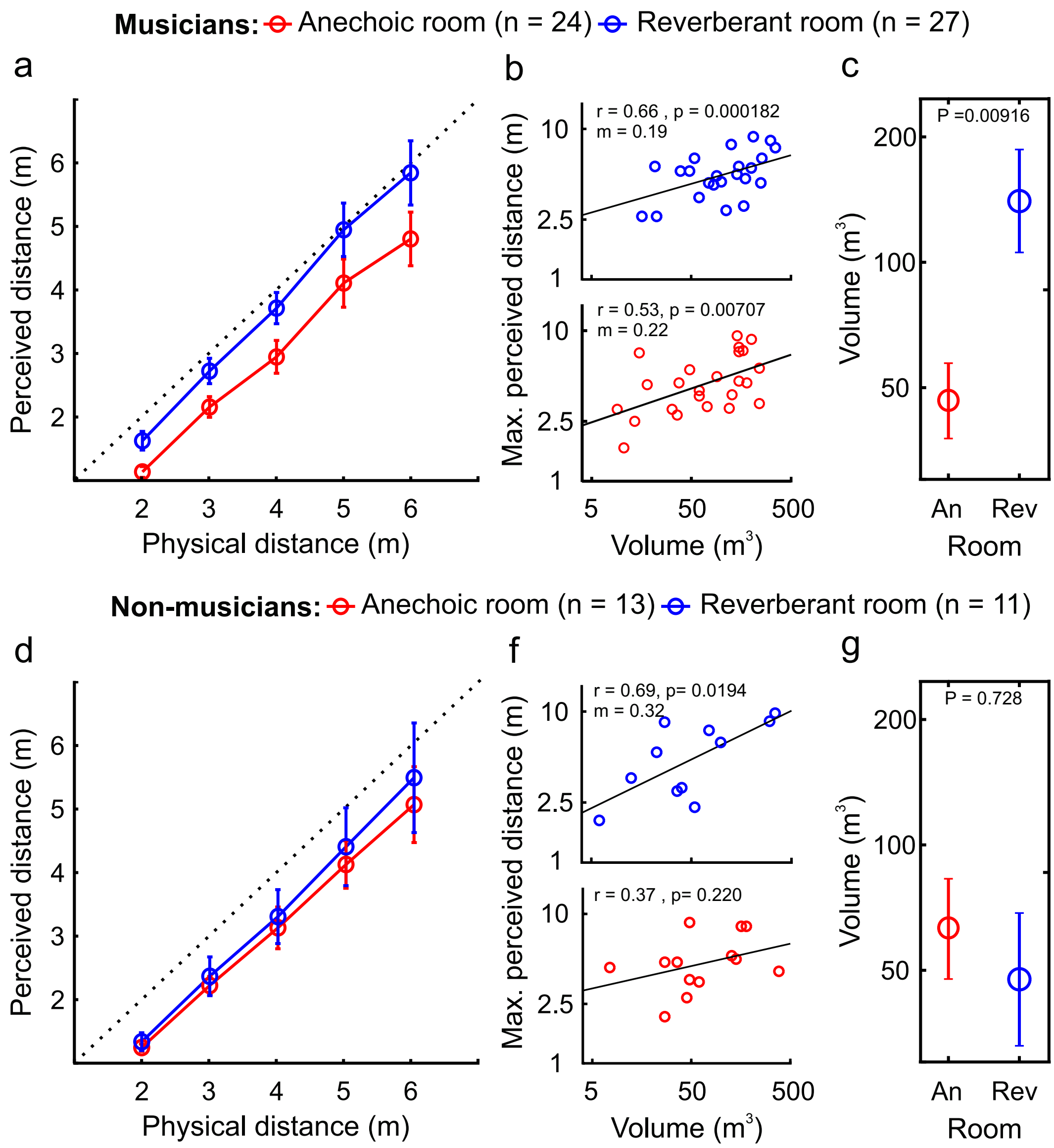

Figure 3: Results segregated by music expertise. Upper row shows (a) visual distance perception curves, (b) maximum perceived distance vs. perceived room size, and (c) perceived room size for musicians. Lower row shows the same (d, e and f, respectively) for non-musicians.

between the maximum perceived distance of the visual target and the perceived size of the room, with the exception of non-musicians when they performed the experiment in the anechoic chamber; see upper-left corner in each graphic.

4 Final remarks

The experiments reported here demonstrated that auditory environmental context significantly influences the visual distance perception of luminous objects located in the dark. Our results show that participants who performed the experiment in the reverberant chamber perceived the targets significantly farther than participants assigned to the anechoic chamber. Our analysis suggest that this effect could be due to a relationship between the perceived size of the room and the perceived distance to the visual object. We found that both magnitudes are positively correlated (Fig. 2b) and that the reverberant room was perceived as being bigger than the anechoic chamber (Fig. 2c). These facts combined could serve as explanation for the differences observed in the VDP curves between both rooms. Given that the only cues subjects could use in order to perceive differences in both rooms were of auditory origin, we conclude that the auditory context was the responsible for the observed differences in VDP.

This hypothesis holds when we turn to the segregated data. Only the musicians sub-group showed differences in VDP and room size (Fig. 3a and c), while subjects in the non-musicians group did not perceive differences in none of both magnitudes (Fig. 3d and f). The segregated data also showed a positive correlation between room size and perceived distance, the only exception being the non-musicians performing the experiment in the anechoic room (Fig. 3b and e). This discrepancy could be due to the relatively small sample size of this last sub-group (n = 13) combined with the comparatively high variability of their responses. The fact that the degree of music expertise could be an explanatory factor for the observed differences in both rooms is in line with the proposal that the auditory context had an influence on the VDP. It is reasonable to assume that professional players and composers have a higher degree of auditory awareness, and hence are more prone to sense auditory context and extract information from it.

Our results are consistent with those reported in previous studies showing that information related to the context influences the VDP [1, 2, 3, 4]. The novelty of our study is that the context information comes from auditory cues, while in the aforementioned works that information came from visual modality. Many previous studies have shown multimodal auditory-visual interactions. Most of them point to the influence of vision on the accuracy of auditory localization judgments (see King [12] for review). This is because spatial localization is more accurate in visual than in auditory modality. However, several authors have shown that when visual information is degraded, the auditory modality can influence the visual modality [13, 14, 15, 16].

In the majority of those works, multimodal information corresponds to the same physical object. In our work, however, auditory information corresponds to the environment, while visual information corresponds to the target whose position subjects had to estimate. In a room with adequate illumination, the spatial context is sensed mainly by visual cues. This cues contribute to the representation of the surroundings, and this representation in turn interacts with the performed task. Under the conditions of our experiment, visual cues are degraded to the point that vision gives no information about the spatial context. In consequence, subjects create a representation of the surroundings using auditory cues. Our results show that a spatial context constructed from auditory cues can also affect the response in a VDP task; in our particular case, this can be seen in the differences in perceived room size between both rooms. Our study is relevant because, in addition to supporting the hypothesis that context affects visual perception of distance, it also shows that this information may be obtained from other modalities as well.

Acknowledgements

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