*Short Report*

PERCEPTION

# Relationship Between Auditory Context and Visual Distance Perception: Effect of Musical Expertise in the Ability to Translate Reverberation Cues Into Room-Size Perception

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**Abstract**
In a recently published work by our group [*Scientific Reports*, 7, 7189 (2017)], we performed experiments of visual distance perception in two dark rooms with extremely different reverberation times: one anechoic ($T \sim 0.12$ s) and the other reverberant ($T \sim 4$ s). The perceived distance of the targets was systematically greater in the reverberant room when contrasted to the anechoic chamber. Participants also provided auditorily perceived room-size ratings which were greater for the reverberant room. Our hypothesis was that distance estimates are affected by room size, resulting in farther responses for the room perceived larger. Of much importance to the task was the subjects' ability to infer room size from reverberation. In this article, we report a postanalysis showing that participants having musical expertise were better able to extract and translate reverberation cues into room-size information than nonmusicians. However, the degree to which musical expertise affects visual distance estimates remains unclear.

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## Introduction

Several studies have demonstrated that, in addition to the classical cues (relative size, interposition, angular declination, perspective, motion parallax, binocular disparity and convergence, among others), visual distance perception (VDP) is influenced by information related to the visual environmental context such as ground information (He, Wu, Ooi, Yarbrough, & Wu, 2004; Wu, Ooi, & He, 2004), the space beyond the target (Witt, Stefanucci, Riener, & Proffitt, 2007), and ground inclination (Stefanucci, Proffitt, Banton, & Epstein, 2005), among others (Iosa, Fusco, Morone, & Paolucci, 2012; Lappin, Shelton, & Rieser, 2006).

In a recently published work by our group (Etchemendy et al., 2017), we found evidence that VDP is also affected by the auditory environmental context. We performed VDP experiments in two dark rooms with extremely different reverberation times: one anechoic ($T \sim 0.12\,\mathrm{s}$) and the other reverberant ($T \sim 4\,\mathrm{s}$). Subjects assigned to the reverberant room perceived the visual targets farther, and auditorily perceived the room size larger, than subjects assigned to the anechoic chamber. Our hypothesis, supported by the data, was that distance estimates are affected by room size, resulting in farther responses for the room perceived larger.

This hypothesis has been previously proposed and corroborated by Kolarik, Pardhan, Cirstea, and Moore (2013), whose results showed that room-size perception through reverberation cues influenced auditory distance perception. Blind and sighted participants reported room-size and distance ratings for a sound source located in an either anechoic or reverberant virtual environment. Interestingly, the ability to auditorily perceive the room size depended on the participant's previous experience because only sighted participants associated reverberation levels with room size. The authors suggest that blind participants could not associate both variables because the lack of vision prevented them from translating reverberation into room size effectively. This result suggests that reverberation cues can be associated to room size after having observed and heard many different rooms.

Considering this, it is worth asking whether all of the participants in the Etchemendy et al. (2017) study had the same ability to aurally perceive the size of the room. A possible approach to answer this question is to take into account the participant's musical expertise. Musical training has been shown to enhance the perception of auditory information related to music, speech, language, and emotion (Kraus & Chandrasekaran, 2010). Although, to the best of our knowledge, it is unbeknownst whether musical expertise could influence spatial auditory perception, it is reasonable to assume that professional players and composers have a higher degree of auditory awareness, compared to individuals lacking musical training, and hence, are more prone to sense the auditory context and extract information from it.

In Etchemendy et al. (2017), most volunteers were music students from the Quilmes National University and some of them worked as professional musicians. Fortunately, we made participants answer a questionnaire to assess musical expertise. Added to the large sample size, this allowed us to separate musicians from nonmusicians and then reanalyze the data a posteriori, in order to explore whether musical expertise could influence auditory room-size perception and, therefore, whether it could modulate VDP. Our main hypothesis is that musicians will be better able, compared to nonmusicians, to associate the acoustical characteristics of the rooms with their size, influencing their perception of the room dimensions. Our secondary hypothesis is that differences in perceived room size will be transferred to the perception of distance to visual objects, affecting distance ratings differently in the reverberant room compared to the anechoic chamber.

## Methods

### Experimental Procedure

Here, we describe the essential aspects of the experimental procedure (which is thoroughly described in Etchemendy et al., 2017). Subjects were received and carried blindfolded to one of two randomly assigned rooms with different reverberation times: an anechoic chamber (A, $T \sim 0.12$ s) or a reverberant room (R, $T \sim 4$ s). The anechoic chamber had a size equal to $7.00 \times 6.90 \times 5.90$ m (length × width × height, size = 285 $m^3$) and a free working space equal to $5.40 \times 5.30 \times 4.30$ m (size = 123 $m^3$). The reverberant room was a seven-surface irregular polyhedron, approximately equivalent to a rectangular box of dimensions $7 \times 8 \times 4$ m, with a size equal to 189 $m^3$. Both rooms were located in the same hallway with their doors facing each other. Two identical experimental setups were mounted, one in each room, located in the same relative position with respect to the door. Thus, the proprioceptive information that subjects could have acquired between rooms was also identical and, therefore, the main perceptible difference between both rooms were their acoustical qualities. During the experiment, the room remained in total darkness so that the participants could see only the experimental targets.

After entering the room, the participant removed the blindfold and listened to a recording (reproduced through a speaker) describing the task. Then, the subject commenced the VDP task. Targets were $5 \times 5$ cm luminous squares, positioned at 2, 3, 4, 5, and 6 m from the seat. Only one target remained lit during each trial, and the subject reported distance estimates verbally using a scale of meters with one decimal. Each target was presented 5 times. Upon conclusion of the VDP task, the participant provided room-size estimates (width, length, and height) in the same scale. These steps comprised Experiment 1. Experiment 2 consisted of the same steps carried out in the other room, immediately after completion of Experiment 1. This resulted in two groups of participants, each one having visited the rooms in one of two possible orders: A→R (Group 1) and R→A (Group 2). The extreme differences in reverberation across rooms implied that during Experiment 2 subjects experienced a high contrast of acoustical information. Room acoustical information was provided in three ways: (a) by the loudspeaker placed inside the room reproducing the task instructions; (b) the participant's verbal reports; and (c) white noise employed to mask the target's servomechanism noise. Musical expertise was evaluated through a short questionnaire regarding formal music education and professional practice. Subjects were classified as musicians when they reported music as their main profession. Hobbyist musicians were classified as nonmusicians.

### Subjects

A total of 75 volunteers (19 women and 56 men) participated in the study. None had prior knowledge of the experimental rooms or the setup, nor were informed of any characteristic of the rooms. All subjects were naïve to the purposes of the study, had normal or corrected-to-normal vision (50 and 25 subjects, respectively), and reported to have no hearing problems, although no audiometric tests were undertaken to confirm this. Ages ranged between 19 and 50 years (average = 25.0 years; standard deviation = 5.9 years). The experiments were undertaken with the understanding and written consent of each subject. Thirty-seven subjects were assigned to Group 1 (24 musicians), and 38 subjects were assigned to Group 2 (27 musicians). The sample size was determined based on a preliminary study which indicated that ~70 subjects was an appropriate sample size for a desired statistical power of 80%.

## *Statistical Analysis*

Room-size estimates were fitted with a linear mixed-effect model (LMEM) on the log-response, with fixed effects Group (i.e., the order of presentation of the rooms, two levels), Room (i.e., the acoustical environment, two levels), IsMusician (i.e., the musical expertise, two levels), and all interactions between the three main effects up to the third order. The choice for a log-transformation of the response was based on the observation that between-subjects variance showed a dependence with the mean. Note that, for this reason, mean values and 95% confidence intervals (CIs) reported in the text were obtained in log-scale and then transformed back to $m^3$. The random effects of the model consisted of a random intercept for each subject. After analyzing the significance of effects, we tested differences across rooms by means of one-tailed $t$ tests, the null hypothesis being that the reverberant room was perceived smaller than, or equal to, the anechoic room. We performed three comparisons for each subgroup (musicians/nonmusicians): one for Experiment 1 (two-sample), one for Group 1 (paired-sample), and the last for Group 2 (paired-sample), giving six comparisons in total. The full set of comparisons was corrected using the Holm–Bonferroni procedure for six comparisons. In the text, we indicate next to the $p$ value the corrected $\alpha$-value for all relevant cases.

We modeled the VDP data by fitting the log-response (as with room size, the response variance showed a dependence with the mean, and this transformation ensured its homogeneity across conditions) with an LMEM with the same fixed effects as the room-size model but adding LogDistance (i.e., the target distance in log-scale, five levels). All interactions up to the fourth order were considered in the model. The choice of the log-scale for both the response and the target distance was based on the observation that model residuals presented a more normal distribution after transforming both. In this case, the random effects of the model consisted of correlated random intercepts and slopes with Room and LogDistance. This random-effect structure allows for individual variations of both the mean response (with the random intercepts) and the response range (with the random slopes for target distance) differently for each room. The choice of correlated intercepts and slopes was motivated by the analysis of linear fits to the individual responses (in log-log scale), which showed a strong correlation between both parameters.

Finally, in order to analyze the relationship between room size and VDP, we also analyzed the correlation between the maximum perceived distance (MPD) and room-size estimates (Kolarik et al., 2013) for all experimental condition tested (2 rooms × 2 experiments × 2 musical expertise conditions). We adjusted the type-1 error employing the Holm–Bonferroni correction for eight comparisons.

LMEM analyses were performed using the lme function from the nlme library (Pinheiro, Bates, DebRoy, Sarkar, & R Core Team, 2017) in R v. 3.0.2 (2013-09-25) "Frisbee Sailing" (R Core Team, 2013). See Supplemental Text 1 for the models syntax.

# Results

## Room-Size Responses

Room-size estimates are displayed in Figure 1(a) for musicians (upper row) and nonmusicians (lower row). Statistical analysis of the data (see Supplemental Table 1 for details) indicates significant effects for Room, $F(1, 71) = 46.2$, $p < .0001$, for IsMusician, $F(1, 73) = 5.12$, $p = .027$, for Group × Room, $F(1, 71) = 6.72$, $p = .012$, and for Room × IsMusician, $F(1, 71) = 4.24$, $p = .043$. The effect of Room is consistent with systematic differences in the perceived room size across both rooms (anechoic room, $M$: 66.2 $m^3$, 95% CI: [50.2, 87.3]; reverberant room, $M$: 146.8 $m^3$, 95% CI: [104.4, 206.5]), and the effect of IsMusician shows a tendency of musicians to report larger room estimates (musicians, $M$: 121.6 $m^3$, 95% CI: [91.1, 162.2]; nonmusicians, $M$: 63.12 $m^3$, 95% CI: [45.3, 87.9]).

The significant effect of Room × IsMusician indicates that the differences due to Room depend on the participant's musical expertise. Musicians show greater differences across rooms compared to nonmusicians (119.6 $m^3$ for musicians and 30.25 $m^3$ for nonmusicians). A good example of this effect are nonmusicians responses in Experiment 1, for which ratings were very similar for both rooms. The other interaction term (Group × Room) indicates that the difference of perceived size across rooms depends on the presentation order. Subjects from Group 1 (A→R) perceived larger differences (130.6 $m^3$) across rooms than subjects from Group 2 (R→A, 43.5 $m^3$).

We next analyzed the data by means of paired comparisons. We found that musicians significantly perceived the reverberant room as being larger than the anechoic chamber in the three conditions tested, Experiment 1: $t(49) = 2.44$, $p = .0092 < .0125$; Group 1: $t(23) = 5.33$, $p = 1.0e{-}05 < .01$; and Group 2: $t(26) = 4.46$, $p = 7.0e{-}05 < .0083$. This pattern, however, did not hold for the nonmusicians data, Experiment 1: $t(22) = -0.62$, $p = .73$; Group 1: $t(12) = 2.12$, $p = .028 > .0167$; and Group 2: $t(10) = 0.78$, $p = .22$.

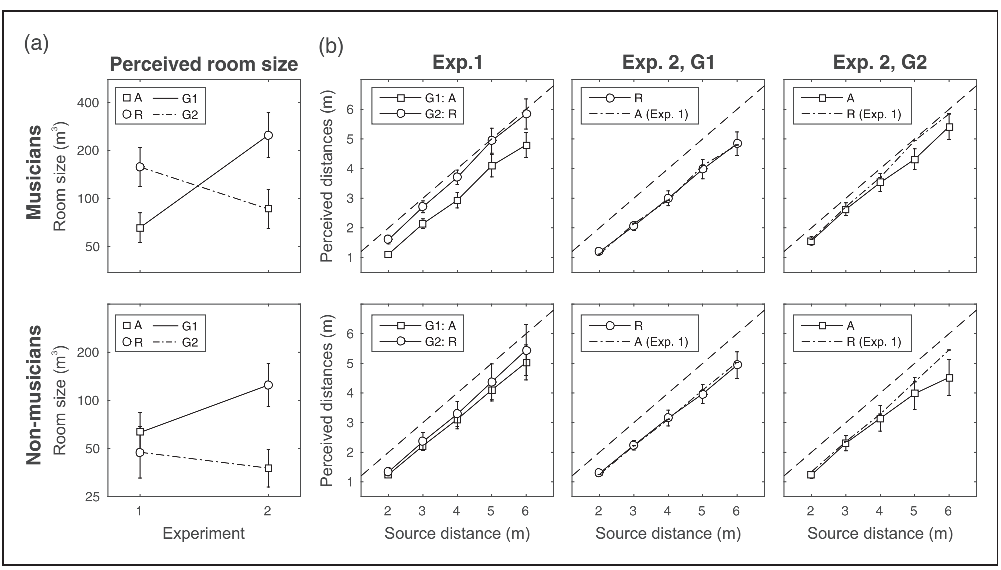


**Figure 1.** (a) Room-size and (b) VDP mean estimates (± SEM) for both experiments.

### Visual Distance Responses

VDP curves are displayed in Figure 1(b) for musicians (upper row) and nonmusicians (lower row). In Experiment 1, musicians display systematic differences in distance ratings across rooms. Targets in the reverberant room were perceived farther than in the anechoic room. On the contrary, nonmusicians responded almost in the same way in both rooms. Interestingly, subjects from Group 1 (A→R) kept their mean judgments almost unchanged when changing rooms (Experiment 2) while subjects from Group 2 (R→A) kept their mean responses unchanged for closer distances (<5 m), showing a shift toward closer judgments for farther ones. Statistical analysis (see Supplemental Table 2 for details) indicates statistical significant effects for LogDistance, $F(1, 663) = 179$, $p < .0001$, and for Group, $F(1, 71) = 6.97$, $p = .010$. The effect of Group is consistent with the observation that subjects showed differences across rooms in the VDP response in Experiment 1 and maintained the response in the other room in Experiment 2.

### Relationship Between Perceived Room Size and VDP

In order to better understand the influence of room-size perception in the VDP, we also analyzed the correlation between MPD and room-size estimates (Kolarik et al., 2013) for all experimental conditions tested. Musicians data showed a positive correlation in both rooms in Experiment 1 (A: $r = .53$, $p = .0071 < .01$; R: $r = .66$, $p = .00018 < .0063$) and in Experiment 2 in the anechoic room ($r = .63$, $p = .00042 < .0071$). Nonmusicians showed a positive correlation only in Experiment 2 in the anechoic room ($r = .81$, $p = .0024 < .0083$).

## Discussion and Conclusions

The goal of this work was to study whether the findings of Etchemendy et al. (2017) were modulated by the musical expertise of the participants. To this end, we reanalyzed the results taking (for the first time for this dataset) participants' musical expertise as an explanatory factor for their responses.

Our main hypothesis is that musicians are better able, compared to nonmusicians, to associate the acoustical characteristics of the rooms with their size, influencing their perception of the room dimensions. The analysis of room-size estimates showed that only musicians related reverberation cues with auditorily perceived room size. Interestingly, nonmusicians did not link both variables even though the acoustical differences between rooms were extreme. In this way, our analyses suggest that auditory room-size perception is modulated by learning and familiarity. In the same line, Kolarik et al. (2013) showed that only participants with normal vision associated levels of reverberation with the size of the room. The authors suggest that blind participants did not associate the two variables because the lack of visual cues prevented blind participants from interpreting reverberation cues effectively in large rooms. This result indicates that, in order to establish a relationship between two perceptual variables, the ability to accurately perceive them is required. In the context of our study, it is reasonable to assume that professional players and composers have a higher degree of auditory awareness, and hence are more prone to sense the auditory context and extract information from it, compared to nonmusicians.

Our secondary hypothesis is that differences in perceived room size are transferred to the perception of distance to visual objects. Here, only musicians associated the differences in reverberation with the perceived room size. Therefore, if our hypothesis were true, only this subgroup would show differences in VDP ratings across rooms. In this line, the analysis of

VDP responses yielded contradictory results. First, in Experiment 1, the correlation between MPD and room size was positive and significant only for the musicians. The fact that the musicians showed differences in perceived size across rooms, combined with the positive correlations between MPD and room size, is consistent with the aforementioned hypothesis. In this line, Gajewski, Philbeck, Wirtz, and Chichka (2014a) and Gajewski, Wallin, and Philbeck (2014b) proposed that the representation of the environment could contribute to the scale of perceived distance within the environment, constraining or expanding the response, especially for objects located near the perceived boundaries of the environment. Accordingly, Kolarik et al. (2013) reported a positive correlation between auditory room-size perception and auditory perception of distance to a sound source. However, the global analysis of VDP responses did not reveal any significant effect associated to musical expertise.

We believe that the effect of musical expertise on VDP ratings could have been masked by factors related to the experimental design, given that the original study was not designed to study the effect of musical expertise (the separation between musicians and nonmusicians was performed a posteriori). One consequence of this is the unbalance in the number of musicians and nonmusicians who participated in the study, which could have affected negatively the power of the statistical analyses, mostly for the VDP curves, whose responses were less robust than room-size estimates. In the same line, the total number of subjects was estimated in order to study the effect of the two rooms on VDP, disregarding any other influential factors.

In summary, our results show that the translation of the acoustical characteristics of the environment to a reliable representation of space is modulated by musical expertise, while its effect on the VDP estimates remains unclear, presenting itself as an interesting question for future research.

## Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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## Supplementary Material

Supplementary material for this article is available online.

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