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Auditory distance perception in front and rear space

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Highlights

- Auditory distance bisection is more precise for front than for rear space.
- Minimal audible distance discrimination is similar for front and rear space.
- Vision can calibrate auditory distance cues for front but not rear space.

Abstract

The distance of sound sources relative to the body can be estimated using acoustic level and direct-to-reverberant ratio cues. However, the ability to do this may differ for sounds that are in front compared to behind the listener. One reason for this is that vision, which plays an important role in calibrating auditory distance cues early in life, is unavailable for rear space. Furthermore, the filtering of sounds by the pinnae differs if they originate from the front compared to the back. We investigated auditory distance discrimination in front and rear space by comparing performance for auditory spatial bisection of distance and minimum audible distance discrimination (MADD) tasks. In the bisection task, participants heard three successive bursts of noise at three different distances and indicated whether the second sound (probe) was closer in space to the first or third sound (references). In the MADD task, participants reported which of two successive sounds was closer. An analysis of variance with factors task and region of space showed worse performance for rear than for front space, but no significant interaction between task and region of space. For the bisection task, the point of subjective equality (PSE) was slightly biased towards the body, but the absolute magnitude of the PSE did not differ between front and rear space. These results are consistent with the hypothesis that visual information is important in calibrating the auditory representation of front space in distance early in life.

Keywords: spatial hearing; distance; auditory; distance perception; sound localization

1. Introduction

Our sensory systems receive information about the location of events in the environment mainly via vision and hearing. The nature of the spatial information that hearing and vision provide is very different. The visual system can quickly and precisely process spatial information about multiple objects in parallel, while hearing provides less precise information when there are multiple sound sources (Best et al., 2004). However, whereas vision is limited by the size of the visual field and the current direction of gaze, hearing provides information about auditory events all around the body. These differences between the two sensory systems form the basis of sensory spatial calibration, a process whereby information from a more accurate modality (vision) is used to calibrate a less accurate modality (audition).

It has been reported that the absence of one sensory modality during the first few years of life influences the development of other sensory modalities. Cross-sensory calibration theory emerged from the observation that, before 8–10 years of age, the more accurate sense “teaches” (calibrates) the others, and that when a calibrating modality is missing, the other modalities are impaired as a result. Cross-sensory calibration theory is supported by evidence from studies of animals reared with altered vision and studies of congenitally blind individuals (Gori et al., 2014; King, 2009; Knudsen and Knudsen, 1985; Vercillo et al., 2016). Studies of barn owls reared with prism glasses that shift the visual input in a specific direction show that auditory localization shifts in the same direction (Knudsen and Knudsen, 1985). These results highlight the important role of vision in calibrating auditory spatial perception. In humans, congenital blindness (a lack of vision from birth) causes severe impairments in some aspects of the auditory perception of space. When congenitally blind individuals perform a bisection task, in which they hear three successive sounds and have to indicate whether the second is closer in space to the first or last sound, they perform significantly worse than sighted individuals (Gori et al., 2014). Vision is thought to be especially important for calibrating extrapersonal auditory space beyond reaching and grasping distance, for which tactile information is not available for calibration (Gori et al., 2014; Kolarik et al., 2016; Voss, 2016). However, vision cannot be used to calibrate auditory space in the rear hemifield.

Most studies supporting a role of vision in calibrating auditory spatial perception have focused on sources varying in azimuth, i.e. in horizontal space (Aggius-Vella et al., 2018;

Gori et al., 2014; Vercillo and Gori, 2015; Vercillo et al., 2016). Both spatial-bisection and minimum audible angle (MAA) tasks have been used (Aggius-Vella et al., 2020, 2018; Gori et al., 2014; Tonelli et al., 2015; Vercillo and Gori, 2015; Vercillo et al., 2016). Performance in a bisection task is thought to depend on an internal spatial representation of the three sound sources (Aggius-Vella et al., 2020; Voss, 2016). The task is assumed to be performed by comparing relative distances within that internal representation. Hence, performance is likely to depend on the availability of vision to accurately calibrate the internal representation of auditory space during development. An erroneously calibrated or uncalibrated internal representation of auditory space results in poor performance on this task (Gori et al., 2019; Knudsen and Knudsen, 1985).

In an MAA task, participants hear two sounds in succession and report whether the second (probe) sound was to the right or left of the first (reference) sound (Mills, 1958). The MAA task can be performed using cues such as interaural level or time differences, without relying on an auditory spatial representation. The observation that sighted and blind participants perform similarly on MAA tasks (Gori et al., 2014; Vercillo and Gori, 2015; Vercillo et al., 2016) is consistent with this notion. This finding also suggests that performance on MAA tasks is not dependent on the availability of vision to calibrate auditory space. Two studies showed that bisection performance was better for front than for rear space, while MAA thresholds were similar for front and rear space (Aggius-Vella et al., 2020, 2018). These results are consistent with the idea that vision plays a role in mapping acoustic cues to an internal representation of the azimuth of sound sources, which is important for the spatial-bisection task, but not crucial for the MAA task.

Although much is known about how vision influences auditory localization in horizontal space (for a review, see King, 2009) it is unclear what role vision plays in calibrating acoustic cues for distance (Alais and Carlile, 2005; Van der Stoep et al., 2015). Visual distance judgments are generally more accurate than auditory distance judgments (Anderson and Zahorik, 2014; Da Silva, 1985). Therefore, it seems plausible that vision plays a role in calibrating acoustic distance cues early in life (see Agganis et al., 2010; Calcagno et al., 2012). The distance of a sound source with a fixed level at the source can be estimated using the level at the listener's ears and the difference in level between the direct and reverberant sound in echoic environments (the direct-to-reverberant ratio, DRR; Bronkhorst and Houtgast, 1999; Kolarik et al., 2013). Studies of auditory distance perception have shown that both sighted and blind participants underestimate the distances of sounds located farther than 1 m away and, in addition, blind participants overestimate the distance of nearby sounds

(Kolarik et al., 2013; Kolarik et al., 2017b). These findings indicate that blindness results in compressed auditory spatial representations of distance compared to sighted controls. The finding that blindness alters auditory distance perception suggests a role for vision in calibrating auditory distance perception. Partial visual loss has also been shown to affect absolute auditory distance judgments; greater severity of visual loss is associated with poorer accuracy in judging closer sound distances and greater accuracy in judging farther sound distances (Kolarik et al., 2020) (Kolarik et al., 2020). However, previous studies that assessed absolute distance perception investigated performance for sounds presented either in front space only (Kolarik et al., 2013, 2017b, 2020; Zahorik and Wightman, 2001; Zahorik, 2002a), or at 90° azimuth relative to the participant (Zahorik, 2002a).

The present study compared auditory distance judgments for sounds in front space and in rear space using a spatial-bisection task and a minimum audible distance discrimination (MADD) task, using sighted participants. As mentioned above, findings in the literature strongly suggest that vision plays an important role in calibrating auditory spatial perception during the early years of life (Gori et al., 2014). Vision is available to calibrate auditory spatial perception during development for sounds originating in front but not in rear space (see Spence et al., 2020, for a discussion of auditory perception in front and rear space). Therefore, we tested blindfolded normally sighted participants using sounds in both front and rear space and compared their performance on the two auditory spatial tasks between these regions of space. We hypothesized that bisection thresholds would be lower for front space than for rear space. Based on the assumption that the MADD task can be performed using "raw" distance cues without relying on a calibrated auditory representation of space, we also hypothesized that there would be no difference in MADD thresholds between front and rear space.

2. Materials and methods

2.1 Participants

There were twenty participants (mean age 27 yrs, range 23-30 yrs), 10 of whom were female. All participants had normal or near-normal hearing, based on audiograms measured using the procedure described by the British Society of Audiology (2011). Pure-tone average (PTA) better-ear hearing thresholds over 0.5, 1, 2, 4, and 8 kHz were less than or equal to 25 dB HL. The experiments were carried out in accordance with the tenets of the Declaration of Helsinki. Following an explanation of the experimental procedure and possible consequences, informed consent was given by all participants. Ethical approval was provided by the ethics committee of the local health service (Comitato Etico, ASL3 Genovese, Italy).

2.2 Apparatus and stimuli

A schematic of the set up is shown in Figure 1. An array of 11 loudspeakers was positioned at the level of the participant's ears, by adjusting the position of a chin rest at the start of the experiment. During the experiment, a chin rest was used to position the participant's head at the correct distance relative to the array, and to ensure that the head position was kept constant throughout the task. The loudspeakers were produced in-house by the Istituto Italiano di Tecnologia, and the on-axis frequency responses of the individual loudspeakers were equalized (for more details, see Ahmad et al., 2019). The sounds were played through the loudspeakers, which were positioned in a straight line on a table with 7 cm between each loudspeaker, the closest loudspeaker being 20 cm from the center of the head (see Figure 1). The loudspeakers faced upwards. This ensured that the sounds reaching the participant's ears were very similar for sounds in front and rear space. The participant and loudspeaker array were positioned in the approximate center of a quiet room measuring 4 (width) × 8.7 (length) × 2.7 (height) m, which had painted walls, a tiled ceiling and floor, and equipment and tables against the walls.

Each participant performed a bisection task (Figure 1A) and a MADD task (Figure 1B) in two spatial regions: (1) directly in front of the participant (at 0° azimuth, Figure 1C), and (2) behind the participant (at 180° azimuth, Figure 1D).

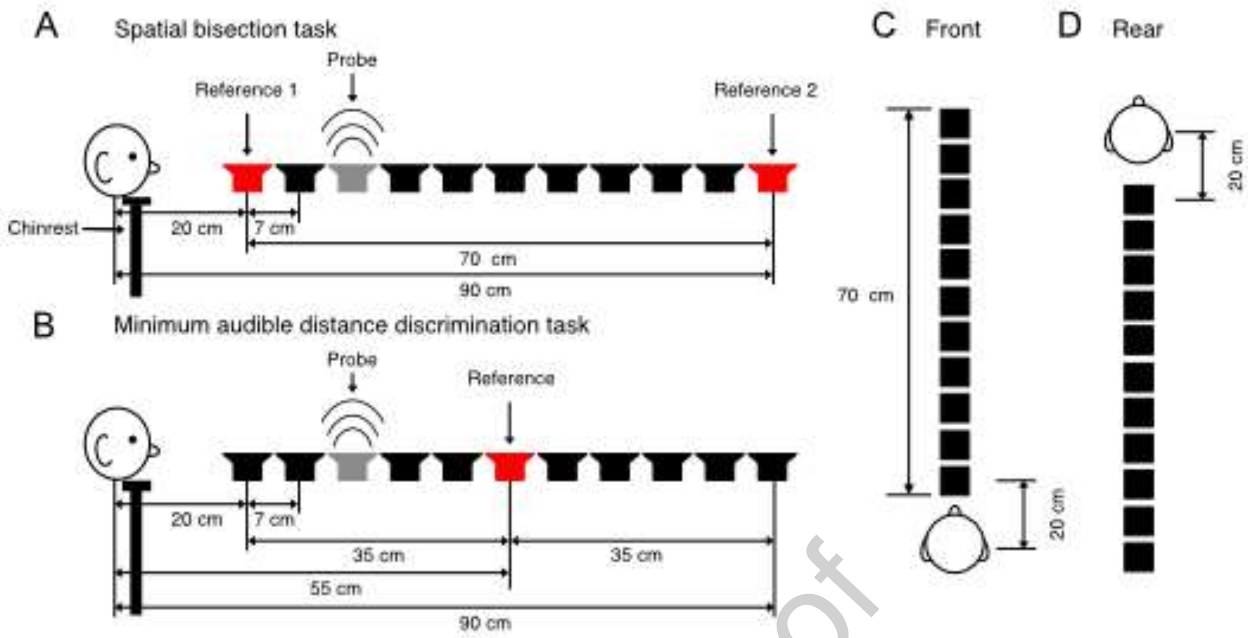

Figure 1. A schematic depiction of the positions of the sound sources and the participant's location in the spatial bisection task (A) and the minimum audible distance discrimination task (B). The locations of the reference sounds are indicated in red and an example location of a probe sound is indicated in grey. The figure shows the front condition (A, B, C) and the rear condition (D). In the rear condition, participants were seated at the same distance from the closest loudspeaker but with their back to the loudspeaker array.

A custom-written Matlab (Mathworks, Natick, MA) script was used to generate the stimuli on an Asus AA185 computer with a 64-bit Realtek High Definition sound card. Sounds were routed to the loudspeakers via a virtual serial port (RS485), allowing the selection of the appropriate loudspeaker through software (Ahmad et al., 2019). Stimuli were broadband white noise bursts sampled at 44.1 kHz with 16-bit resolution, a frequency range from 20 to 20000 Hz, and a duration of 100 ms, including 10-ms rise/fall times, as used in previous work (Aggius-Vella et al., 2020). Sound files were produced and saved prior to the experiment. For each stimulus presentation, a new noise sample was generated. The inter-stimulus interval was 500 ms. The sound level ranged from ~69 dBA for the nearest loudspeaker to 59 dBA for the farthest loudspeaker (see Figure 2A), as measured by placing a sound level meter near the location of participant's ear during the experiment, but without the participant being present.

2.3 Procedure

The participants were blindfolded before entering the testing room and throughout the experiment. Participants were instructed about the procedure and were informed that they would hear sounds originating from different distances.

In the bisection task, the two reference sounds were presented in a randomized order: the first sound was presented at a distance of 20 cm and the third sound at 90 cm, or vice versa. The second/probe sound was presented from one of the 9 other loudspeakers (the reference loudspeakers were excluded). Participants were required to verbally report if the second sound was closer to the first sound or the third sound. The probe distance in each trial was chosen by the QUEST adaptive algorithm (Watson and Pelli, 1983), which estimated the point of subjective equality (PSE, the location of the probe perceived to be an equal distance from the two references) following each response and positioned the probe near the PSE in the following trial. Sixty trials were run for each space. The bisection task took about 45 minutes.

In the MADD task, two sounds (the reference and the probe) were presented in a random order on each trial. The reference sound was played from the central loudspeaker (55 cm from the participant). The probe sound was played from one of the other 11 locations. The participants were instructed to report which of the two sounds was farther away. The probe position was determined by a QUEST procedure that tracked the location of the probe leading to a 50% probability of it being judged as closer than the reference sound. Sixty trials were run for each spatial region, which took about 45 minutes.

In both tasks, participants' responses were recorded by the experimenter. The order of space tested (front and rear) and the order of tasks (bisection and MADD) was random between participants. No feedback was given, and the response time was not constrained. Data were collected in a single session of approximately 1 hour and 45 minutes, with rest breaks.

2.4 Analysis

For the bisection data, the probability of the probe being judged as closer to the nearest reference was computed for each probe position. For the MADD data, the proportion of "farther" responses to the probe sound was calculated for each probe position. Bisection and MADD data were then fitted with cumulative Gaussian functions. An example for the bisection task is shown in Figure 2. The standard deviation (σ) of the fit (for which $1/\sigma$ is proportional to the slope of the psychometric function) was computed as the estimate of threshold (a measure of precision), for each participant and spatial region. For the bisection data, the midpoint of the fitted function was taken as the PSE. The bias was calculated as the distance of the PSE from the physical center point at 55 cm. For the MADD data, the function midpoint was not analyzed. Measures of goodness of fit were obtained by calculating R^2 values based on the differences between the obtained judgments and the fitted cumulative Gaussian functions. This method has been validated and applied in several studies (Alais and Burr, 2004; Gori et al., 2012; Morrone et al., 2005). To assess whether the R^2 values differed significantly from 0, we computed the associated t-value obtained by the transform $t = \mathrm{sqrt}(R^2/(1-R^2))/\mathrm{sqrt}(1/(N-2))$ and we compared it to Student's t-distribution with N−2 degrees of freedom, where N is the number of trials. The significance level (α) was set to 0.05.

For the bisection task, the bias (PSE shift from the true center) was compared between front and rear space and to zero using a t-test for each region of space, with $\alpha = 0.05$. The threshold values (σ) were subjected to a within-subjects analysis of variance (ANOVA) with factors task (spatial bisection versus MADD) and region of space (front versus rear).

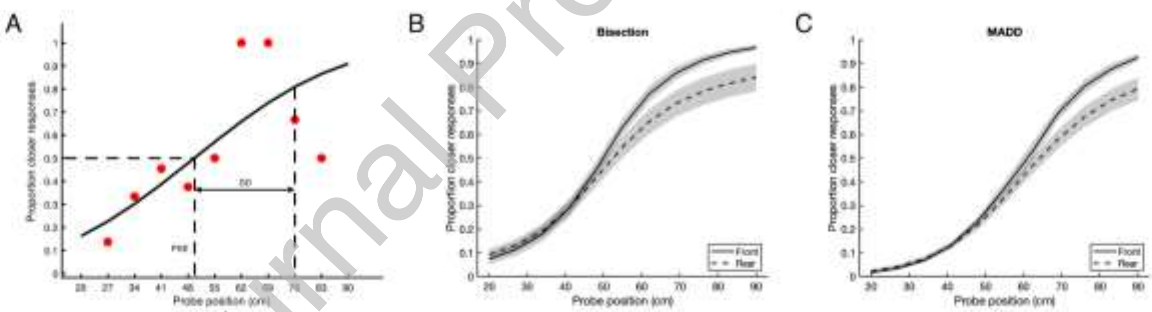

Figure 2. A) An example of a psychometric function for the bisection task. The x axis shows the position of the probe (0 corresponds to the position of the participant). The y axis shows the proportion of closer responses. The data (the dots) were fitted with a cumulative Gaussian function (continuous line). The midpoint of the function (corresponding to a proportion of closer responses equal to 0,5, see horizontal dashed line) was taken as the PSE (see the dashed v li id the distance of the PSE from the physical center point between the two references was taken as the bias. In this example, the PSE is to the left of the actual midpoint of 55 cm, indicating a bias towards the body. The standard deviation (σ) of the fit, which is the reciprocal of the slope of the psychometric function, was taken as the estimate of threshold/precision. B) The group average psychometric functions in the front (solid line) and rear space condition (dashed line) of the bisection task. C) The group average psychometric

functions in the front (solid line) and rear space condition (dashed line) of the MADD task. Shaded error bars in B and C indicate stand errors.

3. Results

3.1 Participant selection

The measures of goodness of fit were used to determine whether the data for any participants should be excluded. Exclusion criteria were non-significant fit values ($p > 0.05$) and/or R^2 values smaller than or equal to 0.1. Based on these criteria, the data for three participants were removed from further analysis. Data from 17 participants was further analyzed. There were no significant differences in R^2 between front and rear space for any of the tasks (all $0 < t < 1.85$, $p > 0.08$).

3.2 Points of subjective equality

The PSEs for the bisection task are shown in panel B of Figure 3. The PSEs for front space (*M* = 50.0 cm, standard error, *SE* = 1.6) and rear space (*M* = 51.5, *SE* = 1. 6) did not differ significantly ($t(16) = -0.782$, $p = 0.446$).

To compare the PSE values with the actual center point between the two references of 55 cm, two one-sample *t*-tests were performed (with α corrected for multiple comparisons, giving $\alpha = 0.025$). The PSEs were significantly closer to the head than the actual center for front space ($t(16) = -3.138$, $p = 0.006$, $d = -0.761$) but not for for rear space ($t(16) = -2.229$, $p = 0.041$). See Figure 2 for the group average psychometric fits for both tasks.

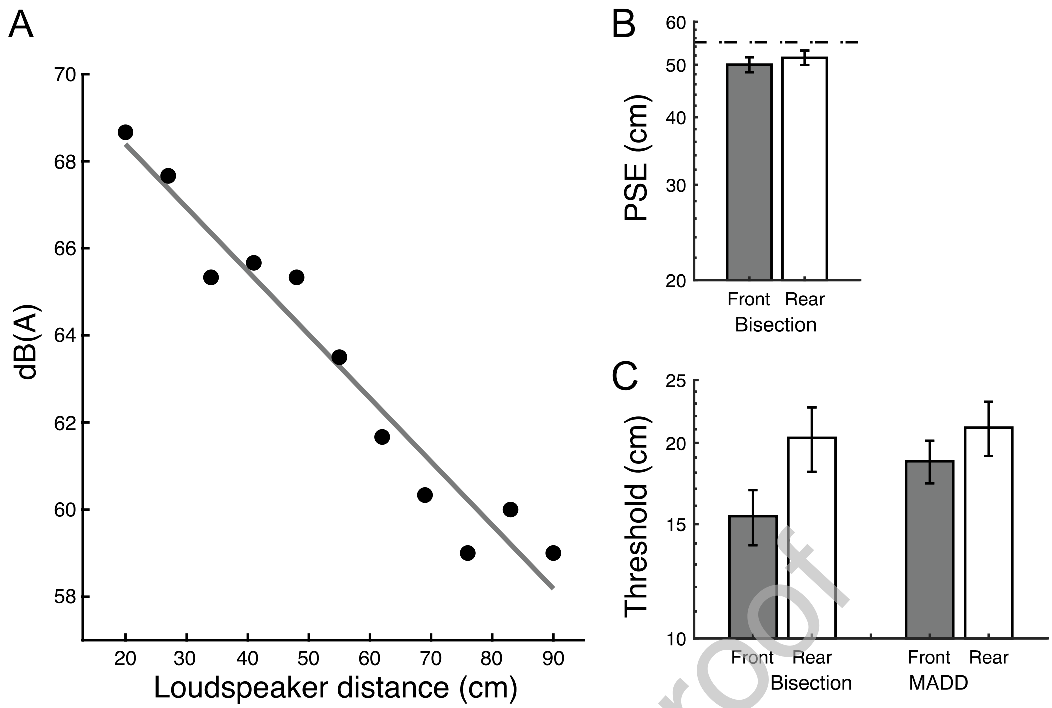

Figure 3. A: The sound level of the stimulus at the participant's ears for each loudspeaker distance. B: The average PSE values for front and rear space in the bisection task. The dashed line indicates the actual midpoint of 55 cm. C: The average thresholds for front and rear space for the bisection and MADD tasks. Error bars indicate ±1 standard error. The asterisk indicates a significant difference with $p < 0.05$.

3.3 Thresholds

The bisection thresholds are shown in panel C of Figure 3. See Figure 2 for the group average psychometric fits for both tasks. An ANOVA showed a significant main effect of region of space: $F(1, 16) = 6.2$, $p = 0.024$. Thresholds were lower (better) for front than for rear space. However, there was no significant interaction between task and region of space: $F(1, 16) = 0.61$, $p = 0.445$. Thus, the results do not support our hypothesis that thresholds would be lower for front than for back space for the spatial-bisection task but not for the MADD task.

The most reliable auditory distance cue available to the participants in the current study was probably sound level. This cue could be utilized either with or without relying on an internal auditory spatial representation. The sound level at the participant's ear is plotted as a function of sound source distance in panel A of Figure 3. The level decreases almost monotonically with increasing distance. The smallest detectable change in level for long-duration noises and highly trained listeners is approximately 1 dB (Irwin, 1989). For 100-ms noise bursts presented at a moderate level to untrained listeners, as in the current study, the smallest detectable change in level is probably about 2 dB. The change in distance required to produce a change in level of 2 dB was approximately 20 cm. This value is similar to the threshold estimates for the bisection task (15 cm for the front and 20 cm for the rear) and the MADD task (19 cm for the front and 21 cm for the rear), consistent with the idea that level was used as a cue.

4. Discussion

The thresholds for both tasks were lower for front space than for rear space, consistent with the idea that vision is used to calibrate acoustic distance cues during early life for front space only. The finding that the MADD thresholds were lower for front than for rear space could be explained in two (not mutually inconsistent) ways. Firstly, participants may perform the MADD task using an internal spatial representation, rather than relying solely on "raw" acoustic cues. This internal representation may be more poorly calibrated for rear than for front space. Secondly, the available cues may differ for front and rear space. Sounds coming from the rear are partially shielded by the pinnae at high frequencies, so the physical intensity of the high-frequency components of the noise reaching the ear canal of the participants would have been lower for sounds from the rear than for sounds from the front. Indeed some of the highest frequency components in sounds from the rear might have been inaudible. This would apply mainly to the direct sound from the loudspeaker. Discrimination of changes in level is better at higher levels than low levels, and better for broadband sounds than for narrowband sounds (Moore, 2012), and this could have led to the level cue being more effective for front space than for rear space.

The PSE for the spatial-bisection task was biased slightly towards the body, regardless of the region of space from which the sounds were presented. This may indicate that the internal spatial representation used in the bisection task is slightly distorted, consistent with previous work showing differences between actual distance and distance judged using auditory cues (Kolarik et al., 2013). However, the distortion might have occurred because the sound level at the participant's ears did not vary with distance as "expected" based on previous experience. The variation of sound level with distance from a sound source depends on a variety of factors, such as the directivity of the source, the orientation of the source relative to the listener, the positions of nearby reflecting objects, and the extent of reverberation in the room. Our particular set up, with upward-facing loudspeakers lying on a table, may not have led to a typical variation of sound level with distance.

Previous studies of blind participants showed that their performance in judging absolute auditory distance (Kolarik et al., 2013; Kolarik et al., 2017a) and azimuth (Gori et al., 2014; Vercillo et al., 2015) in front space was poorer than for normally sighted controls, presumably because their internal auditory spatial representations were poorly developed or deteriorated due to vision loss. These results are consistent with the current findings for normally sighted participants, for whom the significantly lower thresholds for both tasks for front space than for rear space are probably due to the tasks being performed more accurately when visual calibration information is available early in life. Taken together, the current and previous results provide support for the sensory calibration theory, which is that visual information is required to accurately calibrate internal representations of auditory space. It remains to be determined how an auditory representation of the space behind the listener, where vision is not available, is calibrated or formed. It has been proposed that rear auditory spatial representations may be calibrated using motor and/or tactile information. For example, blind participants could calibrate rear auditory space by making active head movements in response to ongoing sounds or by feeling sound sources in close proximity to the body. Alternatively, it may be the case that judgments of distance in rear space are always based on the use of “raw” acoustic cues, rather than on an internal spatial representation.

The nature of auditory spatial representations in front and rear space may depend on the frame of reference in which the information is encoded. Auditory information is initially encoded in a head-centered reference frame and later transformed into an eye-centered reference frame (Cohen and Andersen, 2002). However, the results from a study of the objective auditory egocenter suggests that the auditory information is not always encoded into an eye-centered frame of reference. Whereas auditory locations in front space are encoded in an eye-centered reference frame, auditory information from rear space seems to be encoded in a head-centered reference frame (Neelon et al., 2004). This makes intuitive sense as no eye-movements can be made to sounds that originate from the space behind the head and therefore does not require a transformation from a head-centered to an eye-centered reference frame. In contrast, humans can make eye-movements to sound sources that occur in the visual field in front space which requires a rapid transformation of auditory locations in a retinotopic/eye-centered frame of reference (Schut et al., 2018). These differences in spatial reference frames between sounds originating from front vs. rear space are in line with the idea that vision plays an important role in the spatial representation for front but not rear sounds. It could be that the different types of spatial reference frames have different spatial resolutions. As a result, rear auditory spatial representations may be less precise due to the lack of visual calibration of those spatial representations.

One avenue for future research would be to investigate what cues are actually used for spatial bisection of distance. As stated in the Introduction, the two primary cues to auditory distance are level (Gamble, 1909; Gardner, 1969; Kolarik et al., 2013) and DRR (Bronkhorst and Houtgast, 1999; Kolarik et al., 2020, 2017a, 2016; Zahorik, 2002a, 2002b; Zahorik et al., 2005). In the "normal" room tested in the current study, both level and DRR cues were available. However, environments can vary greatly in terms of their acoustic characteristics. For example, highly echoic environments such as churches contain substantial reverberant energy, making the DRR cue more salient. But if the distance of the source is too large, the direct sound might not be audible at all, making distance judgments difficult or impossible. Future studies could help to elucidate the role of level and DRR using virtual acoustics, allowing the two cues to be systematically manipulated.

Another area for future research would be to compare bisection and MADD performance for distance in peripersonal space, within approximately 1 m from the participant, and in extrapersonal space, farther than 1 m. In the absence of vision, touch might be used to calibrate peripersonal auditory space (Serino et al., 2011). Measurements of distance bisection and MADD thresholds could provide insight regarding whether auditory distance can be calibrated using tactile feedback in peripersonal space for blind participants.

5. Conclusions

Thresholds for both the spatial bisection task and the MADD task were lower for front than for rear space. This is consistent with the notion that auditory representations of space are better calibrated for front than for rear space, because of the availability of vision for the former. However, the differences between front and rear space might also partly be a result of differences in the available cues, especially the level cue.

6. Author Contributions

E.A.V., N.S, M.G., A.J.K, C.C. conceived the studies and designed the experiments. E.A.V. carried out the experiments. E.A.V., C.C., N.S. analyzed the data. A.J.K, E.A.V., N.S, M.G., C.C., B.C.J.M, S.P. wrote the manuscript. All authors reviewed the manuscript.

Declarations of Competing Interest

None.

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