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Blind individuals represent the auditory space in an egocentric rather than allocentric reference frame

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Abstract

It is not clear to date how visual deprivation affects auditory spatial perception. Recent psychophysical evidences described a spatial auditory deficit in congenitally blind individuals while some others found a spatial auditory improvement. Particularly, Gori, Sandini, Martinoli, & Burr (2014) and Vercillo, Milne, Gori, & Goodale (2015) reported that people who were born blind were less efficient in localizing sound sources with respect to auditory landmarks than sighted individuals. On the other side, blind people performed similarly or even better than sighted participants during the localization of single sound sources. We investigated auditory spatial perception in early blind using different auditory spatial tasks and found that blind individuals did not succeed in localizing sound sources in an external frame of reference. The performance of early blind was severely impaired during the localization of brief auditory stimuli with respect to acoustic landmarks (allocentric frame of reference) but was comparable to that one of sighted participants when they had to localize sounds with respect to their own body (egocentric reference frame). Our results suggest that, after early visual deprivation, auditory spatial perception is centered on an egocentric reference system.

Introduction

Visual deprivation in early life alters the functional and structural organization of the brain, affecting the perceptual abilities of the remaining sensory modalities. For several years researchers agreed on the fact that, despite the lack of visual information, blind people can find other way to properly picture the world, using the auditory system. The idea of a sensory compensation has been supported by scientific reports describing a cortical reorganization of the occipital cortex that after visual deprivation starts to be activated by auditory stimuli [3]–[6] and by behavioral studies reporting enhanced auditory sensitivity in early blind individuals [7]–[10].

However, evidences from recent researches suggest that the auditory spatial abilities of people with no visual experience can be impaired under specific auditory settings [1], [2], [11], [12]. Blind individuals showed deficit in audio distance evaluation and in motion discrimination in the lower side of the plane [11], [12]. More interestingly, Gori et al. [1] recently reported that auditory spatial precision of early blind individuals was severely impaired in the spatial bisection task, where subjects had to localize the relative position of a sound with respect to other two. On the other side, their performance was similar to that one of sighted individuals in the minimum audible angle task, in which participants had to report which sound of a sequence of two was located more on the right side. These findings challenge the traditional idea of an auditory perceptual enhancement induced by early visual deprivation and support the hypothesis that vision might be important for the spatial calibration of the auditory space [13]. Interestingly, the fact that auditory spatial precision of early blind participants was poor only in the space bisection but not in the minimum audible task, suggests that the deficit could be task-dependent and that early visual deprivation might selectively interfere with the development of specific auditory spatial mechanisms.

Interestingly, congenitally blind individuals who use echolocation everyday as a navigational strategy do not show the same spatial auditory impairment reported for blind non-echolocators [2]. Their auditory discrimination thresholds for the space bisection task were lower than those thresholds reported for blind non-echolocators denoting higher precision, and similar or even lower than those of sighted participants. To build mental pictures of the external environment, echolocators produce high frequency sounds, for example making mouth clicks, and listen to the reflected sound waves. More important is that the technique of echolocation helps in representing multiple objects at the same time and in understanding their spatial relationship. During echolocation, blind individuals move their heads, to gain additional information and to locate multiple objects. This strategy results in a spatial representation very similar to the visual one, where objects are localized with respect to inter-objects relations, then in an allocentric frame of reference.

In sighted individuals, spatial information is structured under different systems of coordinates where objects 'position is represented. In an egocentric reference frame, locations are represented in body-centered coordinates. This system provides a framework for goal-directed actions such as avoiding obstacles while walking and reaching objects [14]. On the other side, in an allocentric frame of reference, the spatial information is independent from the observer's position. This system uses element of the environment as anchor points or landmarks [15] and such representation has an important role in recognizing objects and scenes in the external space. Sounds locations are primarily represented in head and ear-centered, egocentric frames of reference and successively, this spatial information must be remapped within an allocentric reference system to facilitate the spatial alignment between sensory modalities. Without a visual representation of the external space, audio-visual integration might not occur and the spatial remapping in allocentric coordinates could not be a necessary condition. Therefore, the spatial auditory impairment reported in blind individuals might be related to the frame of reference adopted by the auditory system for sound localization. Indeed, while in the space bisection task sounds must be localized with respect to external auditory landmarks (allocentric frame of reference), in the

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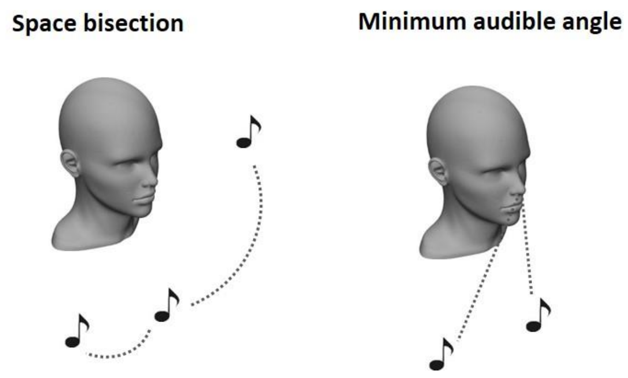

Figure 1. *Description of the space bisection (left panel) and the minimum audible angle (right panel) task. In the space bisection task a sequence of three sounds is played. The first sound is placed in a position on the left side of the subject and the third sound is placed on the right side of the subject. The middle sound has to be localized with respect to these two auditory landmarks. Subjects have to make a comparison between the two distances: the distance of the middle sound from the left anchor and the distance of the middle sound from the right anchor. Finally, they have to report whether the middle sound was closer to first or the third sound. This task might require and allocentric spatial representation. In the minimum audible angle, a sequence of two sounds is played and subject have to report which sound is more on the right side. In this task subject have to estimate the distance of each sound from the center of the head. This task could be performed within an egocentric frame of reference.*

minimum audible angle task the relative positions of sounds can be estimated with respect to the head of the participants (Figure 1).

In the current study, we investigated whether the spatial auditory impairment reported in early blind individuals for the space bisection task can be explained by the absence of a spatial remapping of sounds in allocentric coordinates. We have tested a group of early blind individuals in two perceptual auditory tasks in either allcentric or egocentric frame of reference and compared their performance with that one of a group of sighted control participants. Results confirmed that the lack of visual deprivation in the first period of life selectively compromises the ability to represent sounds in an allocentric reference frame.

Methods

Participants

The group of early blind was composed by eight congenitally blind individuals (three males and five females, mean age: 40.12 ± 6 years of age) while the control group was composed by ten age and gender matched sighted individuals (five males and five females, mean age: 34.7 ± 6 years of age). Blind participants lost their vision at birth and had no residual vision. All participants were right handed. Sighted participants had normal or corrected to normal vision and were blindfolded during the experiment. All participants signed a consent form before running the experiment (for the blind participants the form was read by the experimenter).

Apparatus and stimuli

The setup was composed by 18 speakers disposed in an arc and each speaker was located at 57 cm from the head of the participant (Figure 2, lower panel). The distance between speakers was 5 cm. We used 300 ms white noise burst as auditory stimuli at 70m dB of sound pressure level.

Procedure

Participants performed two perceptual tasks in both allocentric and egocentric coordinates. The order of the tasks was randomized across participants. In the allocentric task, we presented a sequence of three sounds. The first and the third sound were the two auditory landmarks while the second sound the probe stimulus. The position of the probe stimulus varied across trials between two possible locations: 10 or -5 cm. One of the two auditory landmarks was presented at ± 20 cm from the probe while the other one at a distance established by the constant stimulus algorithm ranging between ±5, ±10, ±15, ±20, ±25, ±30, ±35 cm where positive values represent a location on the right side and negative values a location on the left side of the participant. The three stimuli were presented with an inter-stimulus interval of 500 ms. After listening to the sequence of the three stimuli, participants had to report whether the probe stimulus was closer to the first or to the third. This task is very similar to the space bisection task performed by Gori et al.[1] and Vercillo et al.[2]. However, there is a particular difference extremely important for the aim of this study. In the space bisection task, the two auditory landmarks were fixed at the same spatial location: the extreme right and left of the participants. This procedure allowed participants to perform the task in egocentric coordinates simply reporting whether the second stimulus was more on the right or on the left side of the head (rather than comparing the distance of this stimulus with the two auditory landmarks). In our allocentric task, we solved this problem by switching the position of the probe stimulus between two locations and varying the positions of the two auditory landmarks across trials.

The egocentric task was very similar to the allocentric one, except that the probe stimulus was not played. At the beginning of each trail, the index finger of the participants was placed on a

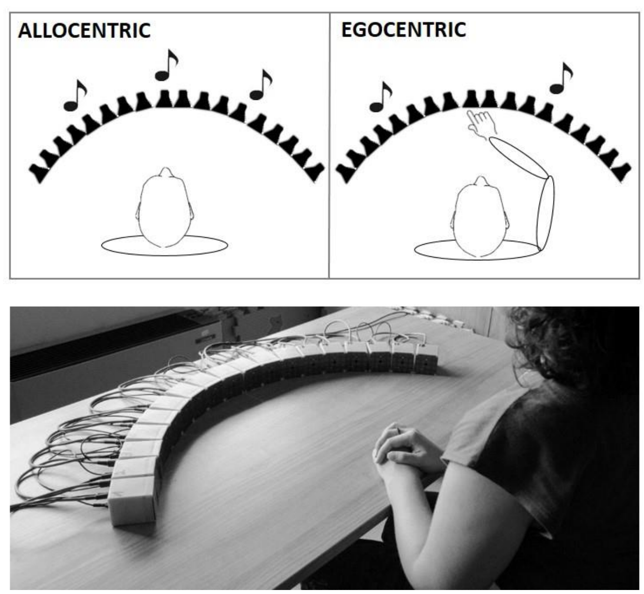

Figure 2. *Methods and setup. The lower panels describe the two perceptual tasks. The lower panel represent the setup that we used for the experiment.*

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speaker and the location of such speaker was varied between 10 or -5 cm (as for the probe stimulus).Then two sounds were played: one at ± 20 cm from the finger and the other one at ±10, ±15, ±20, ±25, ±30, ±35 cm. Participants had to report which sound was closer to their finger. See figure 2 for experimental procedures.
The experiment was performed according to the principles defined by the declaration of Helsinki. All testing procedures were approved by the ASL3 of Genoa (Italy).

Data Analysis

For each trial of the allocentric task, we calculated the spatial relation of the probe stimulus with respect to the two auditory landmarks and we expresses this relation as the difference between the distance of the probe from the first sound (D_f) and the distance of the probe from the second stimulus (D_s), so that $\Delta_{distance} = D_f - D_s$. Positive values of the $\Delta_{distance}$ designates a probe stimulus closer to the third sound, while negative values a probe stimulus closer to the first sound. For each value of the $\Delta_{distance}$ we calculated the proportion of responses where participants reported that the probe stimulus was closer to the third sound, and we fitted data with cumulative Gaussian functions. The mean of these psychometric functions represents the Point of subjective Equality (PSE) that is the $\Delta_{distance}$ for which participants were not able to discriminate whether the probe stimulus was closer to the first or to the third sound (they perceived the sound as in the middle of the two auditory landmarks). More important for the aim of this study, we calculated the standard deviations (thresholds) of these psychometric functions, which defines the variability of the response for each participant, i.e. the inverse of their precision.

Data analysis for the egocentric condition were similar to those adopted for the allocentric task. In this condition, the $\Delta_{distance}$ was calculated as the difference between the distance of the finger from the first sound and the distance of the finger from the second sound.

Results

Figure 3 shows individual thresholds of all participants for the two perceptual tasks. The thresholds for the allocentric task (on the y-axis) are plotted as a function of the thresholds in the egocentric task (on the x-axis). The dashed line describes an ideal performance were perceptual thresholds are the same across the two spatial tasks. The black symbols in the left panel describe the performance of

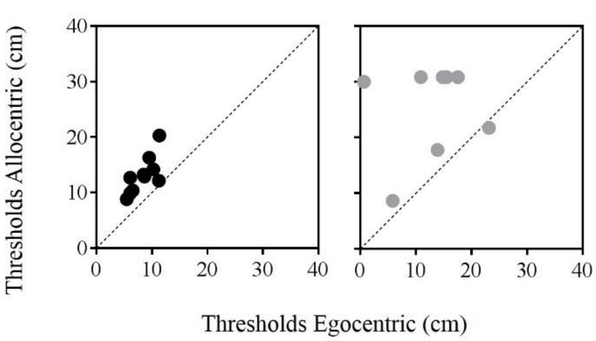

Figure 3. *Individual thresholds for the allocentric task plotted as a function of the individual thresholds for the egocentric task for the control group of sighted participants (black symbols, left panel) and for early blind participants (grey symbols, right panel).*

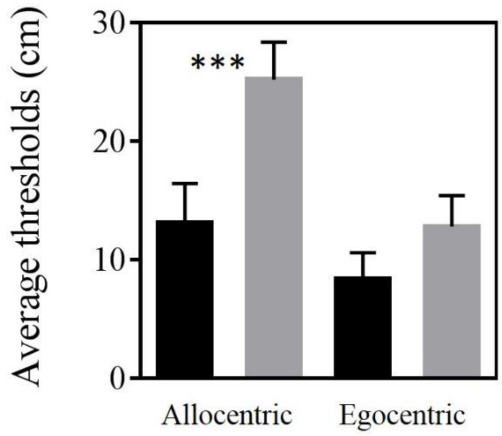

Figure 4. *Average thresholds for the control group of sighted participants (black bars) and for the group of early blind participants (grey bars) for both the allocentric and the egocentric conditions. Thresholds are statistically significantly different between the two groups only in the allocentric tasks.*

sighted participants from the control group. The grey symbols in the right panel describe the performance of early blind participants.

Sighted participants showed very low thresholds in both the tasks denoting high precision. Data are slightly scattered above the dashed line showing that thresholds were a bit lower, i.e. the performance was better, in the egocentric task as compared to the allocentric condition (two-tailed paired t-test $t_{(9)}$=6.70; p>0.001). In general, all the data of sighted participants are scattered in the lower left quadrant denoting very low thresholds in both the tasks, and showing a good performance. On the other side, individual thresholds for early blind participants are all scattered above the dashed line in the upper left quadrant, showing an extremely poor performance in the allocentric task as compared to the egocentric task (two-tailed paired t-test: $t_{(7)}$=3.46; p=0.005).

Figure 4 shows average thresholds in the allocentric and egocentric tasks for the two groups of participants. The color code is the same as in figure 1. In the allocentric condition, average thresholds for the group of blind participants were 25.2 ± 3 cm, almost twice as those of the control group of sighted participants that were 13.09 ± 1 cm (since participants were sitting at 57 cm from the speakers, for comparison with other studies cm are equal to degrees of visual angle). A two-tailed unpaired t-test confirmed that the thresholds of the congenitally blind individuals were significantly higher than those measured in sighted participants ($t_{(16)}$=-4.19; p>0.001). Surprisingly, early blind participants considerably improved their precision during the egocentric task, performing similar to sighted participants. Average thresholds were equal to 12.78 ± 2 cm, significantly lower than the thresholds in the allocentric task for the same group. The thresholds for the control group of sighted control were 8.37 ± 1 cm in this condition, so not statistically different from those of the group of early blinds (two-tailed unpaired t-test: $t_{(16)}$=-1.89; p=0.07).

We run a mixed design ANOVA and we found a significant interaction between the two factors group and task ($F_{(1,16)}$=5.5; p=0.03). Moreover, the Bonferroni correction confirmed that the

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impairment was significant only in the allocentric condition ($p<0.001$).

Discussion

In everyday life, vision drives our behavior and we use vision to represent the external environment and to interact with it. For this reason scientists usually refers to the visual modality as a "spatial sense"[16]. In this study, we showed that vision loss occurring during the critical period affects the creation of allocentric auditory spatial representations. Early blind participants successfully represented sounds locations with respect to their body but showed poor precision as compared to sighted participants during the localization of sounds with respect to external auditory landmarks. These results suggest that vision is crucial for an allocentric representation of the far space and point to the importance of visual information for the spatial calibration of the auditory system during the critical period.

Previous researches showed that in children younger than 8 years of age, multimodal stimuli are not integrated optimally, as in adults, but rather one sense dominates over the others, and sensory dominance seems to be task dependent [17], [18]. The reason of sensory dominance is cross-sensory calibration, a mechanism that makes use of redundant sensory signals to correct and calibrate perception. For example, during childhood vision dominates over touch for orientation discrimination and consequently visual loss affects tactile orientation discrimination in early blind [13], [17]. Similarly vision dominates over audition for spatial judgments in children [18] and consequently the auditory sense of space is impaired in early blind individuals [1], [2], [19]. However, the idea of a visual calibration of the auditory space appears to be a contradiction to previous researches showing enhanced auditory abilities in congenitally blind individuals [7]–[10]. In this study, we clarified that vision is fundamental for the spatial remapping of auditory stimuli into an allocentric frame of reference. Therefore, people without any visual experience show an auditory spatial impairment in tasks requiring an allocentric representation of space while their localization ability within egocentric coordinates is comparable to that one of sighted individuals [8], [9].

In support of our results, previous study reported that for navigation congenitally blind children can hardly remember locations and spatial maps, but rather routs and paths to reach locations from a starting point [20], suggesting that their spatial perception is not based on global representation. More important for the purpose of this study is that people born blind can't discriminate the orientation of tactile stimuli in allocentric frame of reference [21]. Another evidence for an egocentric representation of space for blind individuals is that they are not sensitive to the cross-hands illusion [22]. This phenomenon represents a drop in temporal precision that occurs when people have to perform a tactile temporal order judgment task with a crossed-hands position with tactile stimuli delivered to each hand. The poor precision is usually attributed to an internal conflict between allocentric and egocentric frames of reference generated by the crossed-hands position. Therefore, the absence of an allocentric spatial representation in early blinds might explain their resistance to the cross-hands illusion.

This study, together with previous researches on auditory spatial localization in early blind individuals [1], [2], suggests that after visual deprivation auditory spatial perception is centered on an egocentric frame of reference. We believe that visual information in the first period of life might offer sensory cues to generate external representations that are helpful to link sensory signals more efficiently. After vision loss, the auditory system might be anchored to spectral, temporal and intensity cues generating an inclination to the use of an egocentric rather than allocentric frame of reference.

Acknowledgments

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