



Encoding audio motion: spatial impairment in early blind individuals

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The consequence of blindness on auditory spatial localization has been an interesting issue of research in the last decade providing mixed results. Enhanced auditory spatial skills in individuals with visual impairment have been reported by multiple studies, while some aspects of spatial hearing seem to be impaired in the absence of vision. In this study, the ability to encode the trajectory of a 2-dimensional sound motion, reproducing the complete movement, and reaching the correct end-point sound position, is evaluated in 12 early blind (EB) individuals, 8 late blind (LB) individuals, and 20 age-matched sighted blindfolded controls. EB individuals correctly determine the direction of the sound motion on the horizontal axis, but show a clear deficit in encoding the sound motion in the lower side of the plane. On the contrary, LB individuals and blindfolded controls perform much better with no deficit in the lower side of the plane. In fact the mean localization error resulted 271 ± 10 mm for EB individuals, 65 ± 4 mm for LB individuals, and 68 ± 2 mm for sighted blindfolded controls. These results support the hypothesis that (i) it exists a trade-off between the development of enhanced perceptual abilities and role of vision in the sound localization abilities of EB individuals, and (ii) the visual information is fundamental in calibrating some aspects of the representation of auditory space in the brain.

Keywords: auditory perception, blindness, spatial cognition, movement, early blind

OPEN ACCESS

Edited by:

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Specialty section:

This article was submitted to
Cognition,
a section of the journal
Frontiers in Psychology

Received: 18 June 2015

Accepted: 24 August 2015

Published: 07 September 2015

Citation:

Finocchietti S, Cappagli G and Gori M
(2015) Encoding audio motion: spatial
impairment in early blind individuals.
Front. Psychol. 6:1357.
doi: 10.3389/fpsyg.2015.01357

Introduction

Together with the visual information, audition provides important cues for the perception of object localization and movement. Visual and auditory spatial cues are usually associated. It has been demonstrated that our brain can increase spatial localization precision by integrating these two cues (Stein and Stanford, 2008). However, which is the role of vision on the development of auditory spatial skills is still unclear. Auditory space representation in visually deprived individuals has been extensively studied. The loss of vision results in changes in auditory perceptual abilities and in the way sounds are processed within the brain. An enhancement of certain aspects of spatial hearing and an impairment of some others have been observed in visually impaired individuals (Thinus-Blanc and Gaunet, 1997). The enhanced performance seems to be related to the recruitment of occipital areas deprived of their normal visual inputs (Gougoux et al., 2005; Collignon et al., 2009). Early-blind subjects are properly able to form spatial topographical maps (Tinti et al., 2006; Fortin et al., 2008), express superior auditory pitch discrimination (Gougoux et al., 2004), and can map the auditory environment with superior accuracy (Lessard et al., 1998; Voss et al., 2004). However, neurophysiological studies support the hypothesis of auditory impairment in absence of vision, showing that vision drives the maturation of auditory spatial properties of superior colliculus neurons (King et al., 1988; King, 2009). The superior sound localization accuracy has usually been reported only for peripheral rather than for central regions of space (Röder et al., 1999;

Voss et al., 2004) and for monaural testing conditions (Lessard et al., 1998; Gougoux et al., 2005). Furthermore, the localization in the mid-sagittal plane (Zwiers et al., 2001; Lewald, 2002) and the performance of more complex tasks requiring a metric representation of the auditory space (Gori et al., 2010, 2013) tend to be worse in these subjects than in sighted controls.

Importantly, most of these studies investigated spatial skills of blind using static stimuli. In contrast, the dynamic localization of sounds – which requires a continuous encoding in time and space of a moving sound source – has been largely neglected in the literature, with only a few studies investigating it. Poirier et al. (2006) showed that blind individuals can determine both the nature of a sound stimulus (pure tone or complex sound) and the presence or absence of its movement. Lewald (2013) showed that visually deprived individuals were superior in judging the direction of a sound motion on the horizontal direction. These two studies investigate simple aspects of dynamic sound evaluation like its presence and its direction. Both these tasks do not require the presence of a metric representation of space. Since it has been shown that blind individuals results impaired in performing tasks that require a metric representation of the auditory space (Gori et al., 2013), one may expect to find an impairment when a more complex auditory dynamic task, like the capability of blind individuals to completely reproduce a continuous dynamic sound and to determine its end point, is evaluated. While the discrimination of sound direction can be evaluated by comparing the position of the two sounds in a relative way, the reproduction and definition of a sound end point requires the creation of a complex Euclidian map which considers the relationship between sounds positions in space and time [as well as it occurs in the space bisection task, see (Gori et al., 2013)].

For this reason, we studied the ability of early and late blind (EB and LB) individuals and of sighted blindfolded controls, to encode the trajectory of a 2-dimensional sound motion, reproducing the complete movement, and reaching the correct end-point sound position.

We advance the hypothesis that (i) EB, LB, and sighted blindfolded individuals are able to correctly determine the direction of sound motion on the horizontal direction (as previously shown by (Lewald, 2013), but not in the vertical direction; (ii) contrary to LB and sighted blindfolded individuals, EB individuals are impaired in encoding the complete trajectory and in correctly localizing the end-point sound position.

Materials and Methods

Subjects

Forty participants have been enrolled in the study: EB ($N = 12$, 7 females; average age 34 ± 11 years old), LB ($N = 8$, 3 females; average age: 33 ± 13 years old), and sighted blindfolded controls ($N = 20$, 11 females; average age: 32 ± 13 years old). All the participants had similar education (at least an Italian high school diploma, indicating 13 years of school). Clinical details regarding the blind participants are presented in **Table 1**. All the EB participants were blind at birth. All the

TABLE 1 | Clinical details of the early blind (EB) and late blind (LB) participants.

Participant	Age at test	Gender	Pathology	Age complete blindness
EB				
#EB1	21	Female	Congenital glaucoma and retinal detachment	Birth
#EB2	25	Female	Retinopathy of prematurity	Birth
#EB3	26	Female	Retinopathy of prematurity	Birth
#EB4	20	Female	Congenital Glaucoma	Birth
#EB5	36	Male	Retinopathy of prematurity	Birth
#EB6	37	Female	Retinopathy of prematurity	Birth
#EB7	49	Male	Retinopathy of prematurity	Birth
#EB8	32	Female	Congenital cataract	Birth
#EB9	26	Female	Retinopathy of prematurity	Birth
#EB10	56	Male	Retinopathy of prematurity	Birth
#EB11	56	Male	Congenital Glaucoma	Birth
#EB12	42	Male	Leber amaurosis	Birth
LB				
#LB1	27	Male	Corneal opacity	17
#LB2	45	Female	Leber amaurosis	40
#LB3	65	Male	Glaucoma	14
#LB4	25	Male	Retinal detachment	22
#LB5	22	Female	Bilateral uveitis	12
#LB6	27	Male	Damage to the optic nerve	10
#LB7	24	Male	Retinal detachment	13
#LB8	37	Female	Exudative retinopathy	14

The table shows the age at test, the gender, the pathology, and the age since they became completely blind.

participants had no history of hearing impairment and were right handed. The handedness was defined by the Edinburgh handedness inventory (Oldfield, 1971). The participants provided written informed consent in accordance with the Declaration of Helsinki. The study was approved by the ethics committee of the local health service (*Comitato Etico, ASL3 Genovese, Italy*).

Set-Up and Protocol

The experiment was performed in a dark room. The apparatus consisted of a graduated circular perimeter (radius = 45 cm) mounted on a wooden panel positioned in front of the participant on the frontal plane. Eight different positions were marked on the perimeter, starting at 22.5° and increasing of 45° (**Figure 1**). Sighted participants were blindfolded before entering the experimental room. Each participant was seated, the center of the circle corresponding to the tip of his nose, and was able to comfortably reach and explore with their hand the graduated circular perimeter. Two experimenters instructed the participant and performed all the experiments (SF, GC). The two experimenters were previously trained to perform the task as similar as possible, so that the movement's velocity was consistent across trials, positions, and groups. The experimenter was seated opposite to the participant, holding a sound source. The sound source was a digital metronome (single pulse at

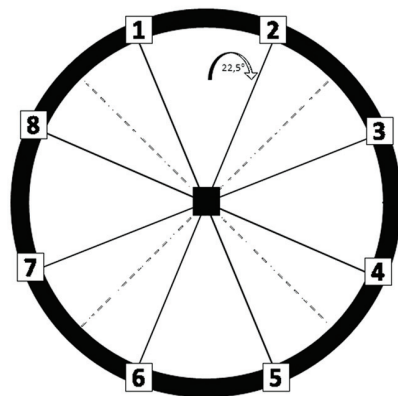


FIGURE 1 | Experimental set-up. The graduated circular perimeter (radius = 45 cm) is mounted on a wooden panel positioned in front of the participant on the frontal plane. The eight different positions are marked on the perimeter starting at 22.5° and increasing of 45°.

500 Hz, intermittent sound at 180 bpm) and was clearly audible by every participant. A spherical marker was mounted on the distal phalanges of the index finger on both the participant and experimenter for motion tracking (Vicon Motion Systems Ltd., UK). The experimenter moved the sound source from the center of the plane toward one of the possible positions highlighted on the circular perimeter in a randomized order. The participant was instructed to keep his index finger pointed to the center until the end of the audio motion. He then had to reproduce the complete trajectory, reach the estimated sound end-point position, and return to the original central position. The movement was performed at participant's own pace. All the eight positions were reached five times, for a total of 40 trials per participant.

Data Analysis

Kinematic data were post-processed and analyzed using Matlab (R2013a, The MathWorks, USA). The spatial accuracy, indicated by localization bias and localization error, was computed for each participant and for each spatial position. Each end-point position was computed as the average of the last 10 samples and normalized on the origin position (the center of the circumference), in order to avoid movement's errors. The localization bias represents the average position in the space of the end-point reached by the participant. The localization error was calculated as the Euclidean distance (in mm) between the end-point position reached by the participant and the one reached by the experimenter. This error was averaged on the number of trials per position and on the number of participants. In order to evaluate top-bottom and left-right judgments, the end-point positions of the experimenter and the participants were categorized as follows: 1 = top, related to position 1–2, and with ordinate value higher than 0; 2 = right, related to position 3–4, and with abscissae value higher than 0; 3 = bottom, related to position 5–6, and with ordinate value less than 0; 4 = left, related to position 7–8, and with abscissae value less than 0. The correct

direction of judgment was defined as the difference between the experimenter and participant categorization was used for further analysis.

Statistics

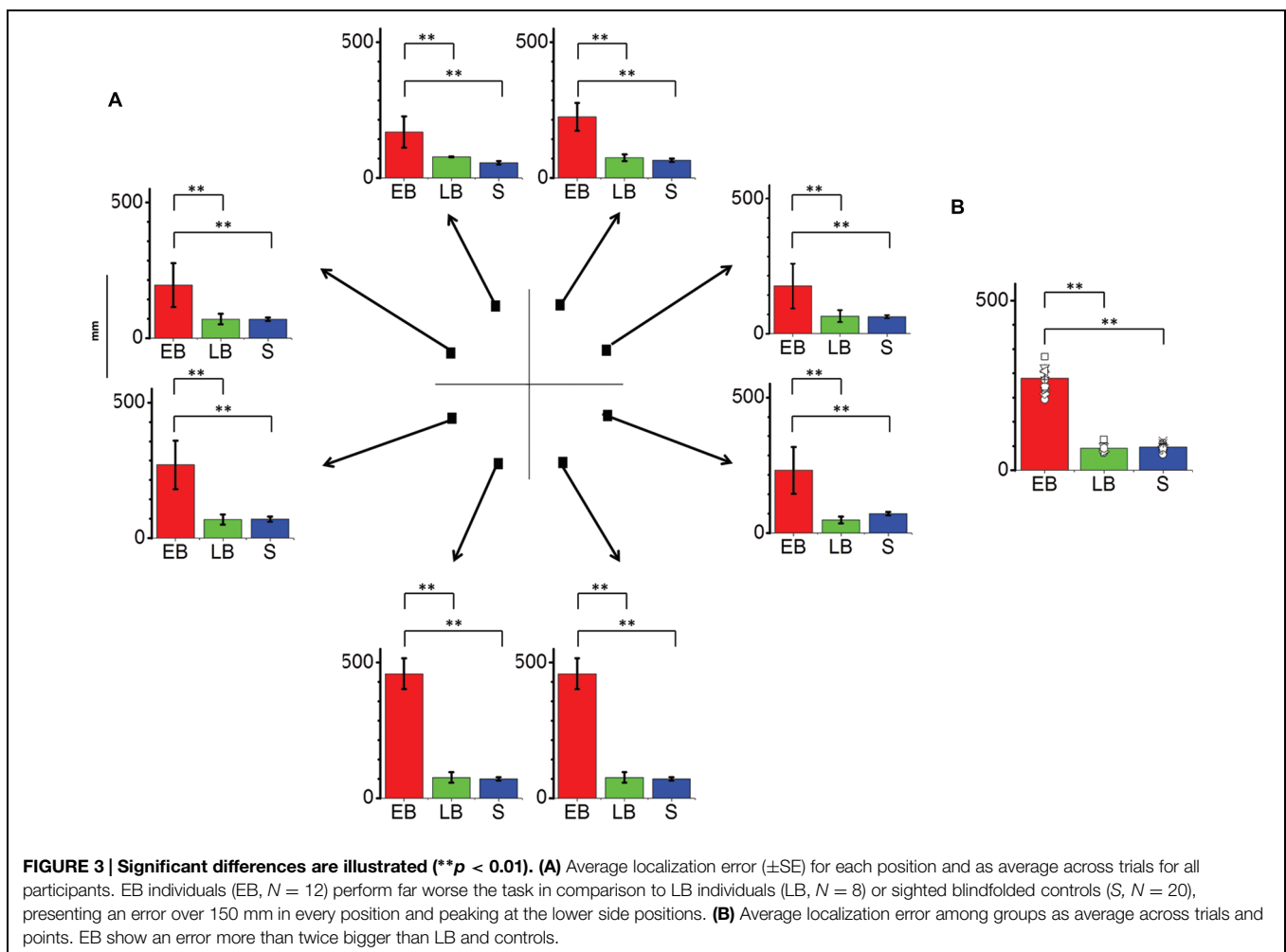
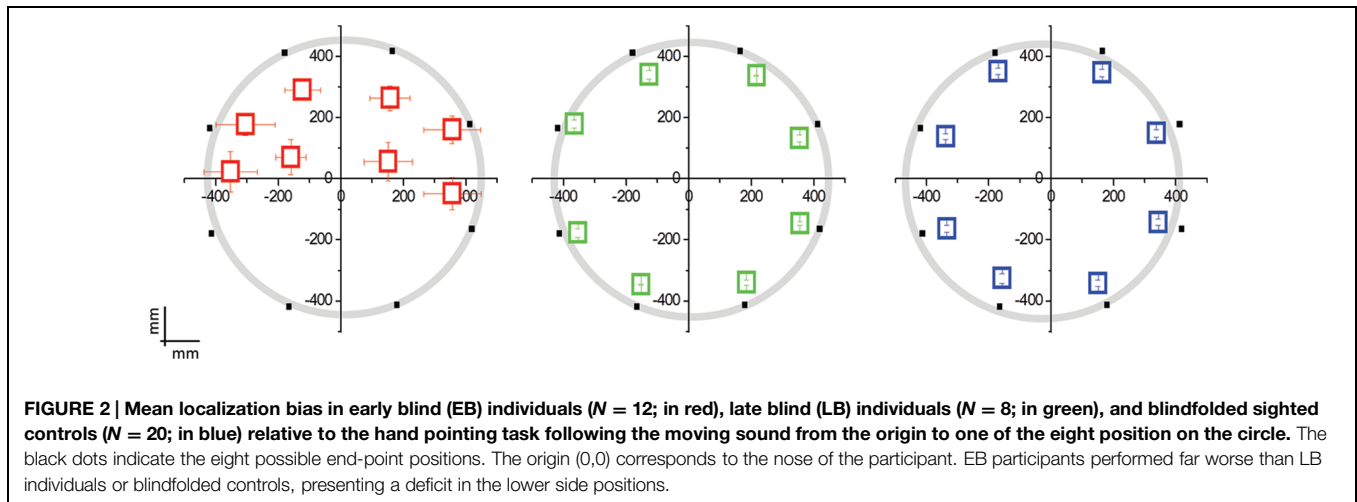
Data were normally distributed, confirmed by visual inspection of Q–Q plots. Data are presented as mean and SE. Localization bias was analyzed by two separate factorial ANOVA (one for the abscissae value, one for the ordinate) with factors participant group (EB, LB, controls), and trajectory (experimenter, participant). The Levene's test for homogeneity of variance was used to compare EB and LB. In order to evaluate the left–right and top–bottom judgments, a factorial ANOVA of the correct direction judgment, with factor participant group (EB, LB, controls), and panel area (top, left, right, bottom) was performed. The localization error was analyzed by a factorial ANOVAs, with between factors participant group (EB, LB, controls), and point (1–8). The mean velocity was analyzed by a one-way ANOVA, with between factor participant group (EB, LB, controls). The Bonferroni *post hoc* test was used in the case of significant factors. $P < 0.05$ was considered significant.

Results

As can be observed in **Figures 2 and 3**, the pattern of results for the EB is completely different with respect to the ones for the other two groups.

Localization Bias

The interaction Group \times Point resulted significant for both the abscissae ($F_{14,296} = 5.14$; $P = 0.001$) and the ordinate value ($F_{14,296} = 33.76$; $P = 0.001$). LB individuals and sighted individuals do not show any localization bias for both the abscissae and ordinate value (Levene's: $F_{1,222} = 0.005$; $P = 0.94$): their responses are superimposed with the physical



endpoint position ($P > 0.1$; back dots in **Figure 2**). On the contrary, EB individuals showed a strong localization bias and a general compression of the targets toward the upper part of the space (Point 5 and 6, ordinate value, $P < 0.003$).

The interaction Group \times Panel area of the correct motion judgment resulted significant ($F_{6,308} = 24.27$; $P = 0.001$). In agreement with previous results (Lewald, 2013), the left/right motion judgment did not show any statistical difference among the three groups ($P > 0.05$), EB individuals, LB individuals

and controls were able to correctly judge the stimulus direction in the horizontal axis. On the opposite, the top/bottom motion judgment show statistical difference among the three groups, as EB individuals were not able to correctly judge the stimulus direction in the vertical axis for the bottom positions ($P < 0.001$).

Localization Error

The interaction between group and point resulted significant ($F_{14,296} = 17.10$, $P = 0.01$). In fact the average localization error (Figure 3) on lower side positions was more than 400 mm compared to less than 100 mm for both LB individuals and blindfolded controls, respectively. On the opposite, LB individuals performed equal to blindfolded healthy participants, as no statistical difference was present in both localization bias and error ($P > 0.1$).

Velocity

Every participant was free to perform the movement at his own pace, but no difference in mean velocity between groups was observed ($F_{2,317} = 0.51$; $P > 0.1$).

Discussion

We present the first study whose aim is to evaluate the dynamic audio localization in visually impaired individuals with a task requiring a continuous encoding in time and space of a sound source in the sagittal plane. This is a complex task that requires the ability to distinguish the spatio-temporal change imposed on moving sounds in space by the dynamic filtering mechanism of the two external ears from the intrinsic spectral structure of the sound (Wightman and Kistler, 1989; Hofman et al., 1998).

Early blind individuals result impaired in performing this task, which results more complex than a static localization task, and they show a clear deficit in encoding the sound motion in the lower side of the plane. On the contrary, LB individuals and blindfolded controls perform much better with no deficit in the lower side of the plane. In agreement with previous results (Lewald, 2013), no deficit was observed in EB subjects for the identification of sound direction.

Some studies suggest that the absence of vision does not impact audio perception in visually impaired humans (Lessard et al., 1998; Röder et al., 1999; Lewald, 2013) and animals (Rauschecker et al., 1995; King and Parsons, 1999). These auditory spatial abilities are more remarkable in peripheral than in central regions of space and in the horizontal plane (King and Parsons, 1999; Röder et al., 1999; Voss et al., 2004). In contrast, localization in the mid-sagittal plane tends to be worse in blind individuals than in sighted controls (Zwiers et al., 2001; Lewald, 2002). A possible explanation about the different static localization ability in the horizontal vs. mid-sagittal plane is that the vertical localization is based primarily on spectral cues that are mainly guided by vision (Tollin et al., 2013). In addition visually impaired individuals, especially EB individuals, show impairments in performing more

complex tasks that require a metric representation of space (Gori et al., 2013).

In the first years of life, the brain continuously needs to calibrate the developing system (Gori et al., 2008, 2010; Nardini et al., 2008; Gori, 2015). In case of a sensory loss, such as vision in EB individuals, the important communication between sensory modalities cannot occur (Warren and Pick, 1970) and this can directly affect the development of the audio spatial maps in the superior colliculus (King et al., 1988). While the development of a complex Euclidian representation of space is compromised in absence of vision from birth (Gori et al., 2013), results obtained in LB individuals suggest that even a short early visual experience can guarantee this representation (Fine et al., 2003). Some EB individuals can partly build a representation of space in the case of simple audio spatial tasks, like monaural static sound localization (Röder et al., 1999; Voss et al., 2004), with changes within the auditory pathway and the recruitment of the visual cortex (Merabet and Pascual-Leone, 2009; Bavelier and Hirshorn, 2010). In our case, both early and LB individuals show, in agreement with previous studies (Poirier et al., 2006; Lewald, 2013), an equal auditory motion perception on the horizontal axis. Our task resulted more complex as it required the ability to relate sound positions in a two dimensional space and time; in this case other brain areas cannot intervene, and EB individuals clearly result impaired. What is the reason for this? When the visual calibration is not possible, audio spatial information may be self-calibrated by the auditory system. This audio self-calibration is limited by: (i) the physiology of the auditory system and associated processing of the audio signal; and (ii) the audio environmental statistics.

First, like in the case of the elevation-related spectral cues (Zwiers et al., 2001; Lewald, 2002), the auditory system is not equally good in perceiving sounds coming from the frontal or from the peripheral plane (King, 2009). This suggests a trade-off in the localization proficiency between the two auditory spatial planes that has recently proposed for a static auditory localization task (Voss et al., 2015). The ability to perform such a complex task may then require a full development of the audio spatial maps in superior colliculus, where signals from the different senses are combined and used to guide adaptive motor responses.

Second, in the peri-personal space, the most frequent dynamic sounds we face with are the ones related to individuals speaking around us, sounds that generally are at our height. Recent findings show that the natural auditory scene statistics shapes human spatial hearing, suggesting that both sound localization behavior and ear anatomy are fine-tuned to the statistics of natural auditory scenes (Parise et al., 2014). This statistical environmental cue may then affect the way blind individuals built their spatial representation.

Conclusion

The absence of spatial references from the visual inputs has widespread consequences on the brain; the important

communication between sensory modalities cannot be created, therefore auditory space perception can only rely on the physiological and statistical information heterogeneity. This information results insufficient in dynamic localization tasks, as the one presented here, producing direct impairments on auditory space cognition in blind individuals.

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Acknowledgments

This research was supported by the EU Project ABBI (FP7-ICT 611452). The authors have no conflict of interest to report. The authors would like to thank Prof. Giulio Sandini and Ing. Marco Jacono for their support during the development of the study, and Prof. Flavio Parmiggiani for proofreading the manuscript.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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