SPATIAL AUDITORY REPRESENTATION IN THE CASE OF THE VISUALLY IMPAIRED PEOPLE

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ABSTRACT

Over the years, it has been widely believed that the blind individuals possess enhanced sound localization abilities that help them to navigate and orient in space in the lack of visual stimuli. In addition to this, it has been argued that the visually impaired people develop increased capacities of the remaining senses (auditory skills, in particular) that exceed those of the normally sighted individuals. The following paper aims to present and compare the most notable sound localization experiments that involved the participation of both blind and sighted control subjects. As the results of these studies provided different results, they have been classified in experiments that show a better localization performance for the blind participants and on the other hand, experiments that yielded equal or worst localization accuracy in the case of the visually impaired subjects. The underlying purpose of our research is to understand the modality and the degree at which the presence or absence of visual stimuli affect the spatial auditory resolution for each of the two target groups.

Keywords: Sound localization, blind people, psychoacoustics, virtual auditory display, compensatory strategy, plasticity, virtual reality.

INTRODUCTION

Auditory spatial processing is a subject of considerable relevance for the medical field, due to its increased significance for the development of rehabilitative and assistive techniques. Acoustic spatial perception plays a fundamental role for promoting orientation and mobility, for improving navigational skills and for adapting to real-world stimuli and environmental conditions. Sound is very important for the sighted people, but more vital for the visually impaired individuals, who are obliged to rely on their auditory perception in order to interact with the environment. Practically, the blind persons are dependent on the acoustic cues, since they allow them to identify the attributes of the surrounding items, to recognize familiar or unfamiliar objects and to manage the spatial information in order to deal with various situations. Over the years, it has been argued that the visually impaired people benefit from augmented hearing and acoustic spatial localization abilities, due to sensory compensation and cross-modal plasticity in the lack of sight [1]. Several studies have demonstrated higher sound localization skills in the case of early-blind individuals, others have concluded that there is no difference between the two groups, emphasizing that vision is not responsible for auditory spatial perception, while others proved that the visually impaired listeners are less proficient than the sighted individuals in what concerns the sound localization acuity. This paper aims to perform a comprehensive parallel study between the most relevant sound localization experiments that involved the participation of both sighted and visually-deprived subjects (either suffering from congenital blindness or late-onset visual impairments). The purpose of our research is to understand how the visual condition of a person influences his ability of performing spatial auditory localization tasks.

VISION AND SOUND LOCALIZATION

There are many experiments that have studied the relationship between the visual and the auditory senses in respect to sound localization [2]. They have argued that the visual cues improve sound localization performance, especially when the inputs from both senses are correlated [3], as when the subject listens to a target sound and concurrently visualizes its source. There have been several studies that demonstrated the effect of vision for training the sound localization abilities of sighted individuals [4]. The visual information played a fundamental role, as it helped them to dynamically process the perceived sounds and their sources by using a crossmodal sensory association. In consequence, vision calibrates the acoustic perception of spatial information, directs the attention towards the incoming stimuli and ensures the development of a solid map representation of the environment. However, there should be made a clear distinction between the way in which the visual and the auditory channels encode the information received from the environment. For instance, the hearing sense uses a craniocentric frame of reference that depends on the position, direction and the other anatomical features of the external part of the auditory system (the pinna, which is well-known for its acoustic filtering effects, the head, which causes attenuations and a head shadowing effect or the torso), while, on the other hand, the visual sense relies on the oculocentric frame of reference, which shifts the focus of sight with the head movements [2].

In the case of the visually impaired people, the spatial representation of the environment is supported by another sensorial and perceptive organization. In the lack of sight, they are forced to use an alternate sensory modality, for instance hearing, to compensate for their visual deficit. The blind individuals rely intensively on the auditory sense in order to spatially map the external world [5] and to perform simple navigation tasks that involve mobility, orientation, cardinality or echolocation [6]. Perception, as the inner process of unconsciously transforming the sound energy arriving at the eardrums into relevant information for the listener, is significantly influenced by the characteristics of the incoming sound stimuli, generally referred to as “the auditory dimensions”. The auditory dimensions of a sound (pitch, loudness, timbre, directionality, distance, externalization) convey important information concerning the shape, size and attributes of the surrounding environment. All these cues are dynamically synthesized in a single, unitary acoustic image of space that is called “spatial cognitive map” [7]. For the visually impaired people, it is very important to enhance their sound localization performance, as it improves not only the ability to detect the position of a sound source in the environment (for detecting targets or for avoiding obstacles), but also promotes spatial awareness, the development of orientation and mobility skills and the overall quality of life [8].

CROSSMODAL PLASTICITY IN THE LACK OF SIGHT

The information from the central and from the peripheral regions of space is processed differently by the auditory system of the visually impaired people. The human mechanism of spatial auditory processing is divided into the spatial "where" (manipulated in the posterior-dorsal region of the auditory cortex) and the spectro-temporal "what" (that is activated in the anterior-ventral pathway) streams, similar to the perception acquired by the visual system [5]. It has been demonstrated that the blind people are more proficient at detecting the origin and direction of a sound source (by activating the "where" pathway), than at recognizing the spectral and temporal features of the sound (in the "what" cortical area). For instance, in the sound localization experiment that involved the participation of both sighted and visually impaired subjects, the latter group outperformed their sighted counterparts, especially at sound localization tasks in the peripheral region [9]. Moreover, in the same experiment, the neuro-imaging analyses concluded that the posterior-dorsal auditory "where" pathway was more activated in the case of the blind participants. In the experiment presented in [5], congenitally blind and sighted (blindfolded) subjects were required to undergo spatial localization and non-spatial frequency discrimination tasks under free-field listening conditions in the peripheral acoustic region of space. Each trial consisted in the presentation of a sound cue over the left or the right speaker (a pure tone, 555 Hz frequency), followed by the onset of an additional sound at the same or at a different location, with an equal or unequal frequency level. The subjects were required to locate the target sound and to specify if there is any difference in the spectral content of the two consecutive acoustic cues. The results of the study concluded that the visually impaired subjects were able to detect and localize the peripheral sound targets more accurately than the normally sighted participants, although they were less efficient in what concerned the frequency discrimination task. These results provided supplementary evidence in favor of the previous findings regarding the improved functionality of the "where" pathway and a minimization of the activation degree of the "what" pathway. This behavior is highly ecologically dependent, since the location of the peripheral audio cues is more important than its identity. The improvement in the "where" pathway helps the visually impaired people to focus on the most important features of the environment (direction and distance of the target sounds) and to navigate more safely by avoiding dangerous situations [5].

In what concerns the modifications that take place at the brain level, it has been observed (in the case of early-blind cats) that the occipital visual area has adopted some of the sound processing functionalities from the auditory cortex and at the same time the acoustic spatial representation became more accurate [10] [11] [12]. The sound localization experiment performed by Gougoux et al [10] supported the hypothesis that the auditory processing expanded into the visual cortex in the case of the early-blind subjects. This crossmodal plasticity was observed to occur especially under monaural listening conditions. The authors argued that the enhanced abilities for discriminating monaural sound cues are due to the recruitment of the occipital cortex for processing the spectral cues. Another study emphasized that the early and late blind individuals recorded significantly better results than the sighted subjects after performing binaural sound localization tasks [13]. The level of plasticity of the auditory system varies among the blind listeners, depending preponderantly on the level of practice, training and adaptation to the sound localization tasks [10]. The fMRI studies performed by Collignon et al [14] demonstrated that the spatial-auditory processing mechanism of the congenitally blind people makes use of the regions of the dorsal occipital stream which are responsible for spatial visualization in the case of the sighted individuals. Thus, spatial auditory localization in the case of congenitally people takes place in the same cortical regions that process visual inputs for the normally sighted persons. Moreover, the authors argue that this cross-modal plasticity of the blind people is unselective and does not require experience or practice to ensure a high degree of sound localization specialization in the occipital cortex.

According to Chan et al [15], the parietal cortex plays an important role in creating sound-to-distance associations in the case of the blind people. Furthermore, the hippocampus is implicated in the spatial process of dynamically linking sounds and locations, demonstrating that the crossmodal plasticity involves other cortical regions of the brain, besides the occipital cortex. The study concluded by supporting the idea that auditory localization in the case of the blind individuals requires the participation of the visual cortex and of the hippocampus more actively than in the case of normally sighted subjects (who rely on the activity of the frontal and temporal lobe).

Besides cross-modal plasticity, intramodal plasticity also influences the sound localization acuity in the case of visually impaired people. There have been studies that showed a certain level of intramodal plasticity in the auditory cortex, particularly in the tonotopic area of the primary auditory cortex (A1). The tonotopic area, which is responsible for decoding frequency, proved to be significantly enlarged in the case of the blind persons, suggesting a higher degree of use of the spectral cues [16].

COMPARATIVE SOUND LOCALIZATION EXPERIMENTS WITH NORMALLY SIGHTED AND VISUALLY IMPAIRED SUBJECTS

The following chapter aims to present the most relevant comparative sound localization experiments that involved the participation of both normally sighted and blind subjects. As these studies provided different conclusions, we have classified them into experiments that present either better or worst localization accuracy in the case of blind individuals or equal performance between the two groups.

IMPROVED SOUND LOCALIZATION PERFORMANCE IN THE CASE OF BLIND INDIVIDUALS

The study of Lessard et al [5] suggested that in the case of the visually impaired people, compensation takes place through the remaining senses. For instance, hearing plays an important role in allowing them to build a solid 3D representation of the surrounding space. The results of the test sessions that were performed under both monaural and binaural conditions showed that the congenitally blind subjects can localize sounds with equal or better accuracy than the sighted individuals. Furthermore, the subjects with residual vision were less accurate than the normally sighted participants, demonstrating that cross-modal compensation develops in time, as it may be correlated with the patient’s medical condition and with the duration of sight deprivation.

This belief is also supported by the study of Doucet et al [17], who investigated the binaural and monaural localization accuracy of blind and sighted control subjects in the horizontal plane. By contrast with the sighted subjects, half of the blind participants showed enhanced auditory discrimination abilities under monaural listening conditions, having one ear blocked. Their performance was consequently tested by either obstructing the pinna and by using low-passed and high-passed signals with the ears unobstructed. The results of the tests demonstrated that the visually impaired individuals possess an enhanced capacity (considered by the authors as supra-normal) of discriminating and processing the spectral content of the sound.

The experiment presented by Ohuchi [18] involved the participation of four congenitally blind and four normal sighted subjects. They performed a series of sound localization experiments under free-field listening conditions. The incoming stimuli consisted of low-pass-filtered pink noise, 2 seconds in duration, delivered through 12 loudspeakers arranged at 30 degrees intervals around the subject in a soundproof room. During the experimental procedure, the listeners were required to indicate the perceived direction of the sound source, as well as the apparent distance. The pointing technique consisted of indicating the position of the sound image using the hour hand of a clock, so that 12 o'clock corresponded to 0 degrees to the front, 3 o'clock was assigned to 90 degrees to the right and so on. The experiment was conducted under two listening conditions: CHF (where the listener was required to keep his head fixed) and CHR (where the subject was allowed to freely rotate his head). The results demonstrate that the blind subjects outperformed the normally sighted participants under both CHF and CHR listening conditions and that the localization errors when the subjects were allowed to rotate their heads were slightly lower than in the head-fixed condition. Moreover, the blind listeners were able to accurately report the distance to the sound source (especially when they kept their heads fixed), in comparison with the sighted participants, who showed a clear tendency of underestimating it.

The study described in [9] presents an experiment in which eight congenitally blind and eight sighted subjects took part. The sound localization ability of both groups has been tested in the central and in the peripheral regions of the acoustic space. The sound stimuli consisted of broadband pink noise bursts, rendered from eight loudspeakers arranged around the listener at 0, 6, 12 and 18 degrees (in the center) and at 72, 78, 84 and 90 degrees (in the peripheral area). There have been two different experimental conditions. In the first one, the subjects were required to listen to the source located at 0 degrees to the front and to report the deviants (the sounds that were not emitted by the target source). A similar procedure was devised for the target source situated at 90 degrees in the peripheral acoustic space. The results indicate that the blind subjects were more proficient at performing sound localization tasks in the peripheral region than the normally sighted individuals. This particularity was observed in the areas where localization accuracy is most inaccurate in sighted people, as the lateral directions. In addition to this, the authors suggest that this enhanced ability of sound localization in the peripheral space is influenced by the selective attention process that occurs within the first 100 ms after the sound onset. On the other hand, in what concerns the "attend center" condition, both groups of subjects detected with equal accuracy the deviant source from the attended position.

A similar experiment that investigated the ability of congenitally blind and sighted individuals to perform spatial (detection and localization) and nonspatial tasks (recognition of spectro-temporal acoustic features) in the peripheral auditory region concluded that the blind subjects were able to localize the sound sources more accurately than their sighted counterparts by showing the same degree of selective attention.

Nonetheless, the congenitally blind participants were slower at discriminating the frequency components of the sound, demonstrating that the “what” detection mechanism of the auditory system is less specialized than the “where” localization process. As discussed earlier in this paper, this behavior is highly ecological, since it supports orientation and cardinality for the visually impaired people.

In the study of Wersenyi [19], the sound localization performance of 28 blind subjects and of another 40 sighted people was tested in a virtual auditory environment. In the first experiment, a 300 ms white noise (separated by 400 ms of silence) was statically presented in the front and in the back of the listener, in order to assess front-back confusions and in-the-head localizations. In the second experiment, the listeners were asked to indicate the direction of movement of a sound source that was rotating around the listener’s head either in the horizontal plane (from left to right or from right to left) or in the median pane (up-down or down-up). Moreover, in the Minimum-Audible-Angle discrimination task, the subjects were required to discriminate between two consecutive white noise bursts (300 ms in duration, separated by 300 ms of silence) emulated in either the horizontal or vertical plane, by indicating if there is or there is not any difference between them. Also, they had the option “I am not sure”, if the localization perception was uncertain. The first stimulus was considered the reference point or the origin, while the second one was displaced on the left, right, up or down. The last experiment was performed using a 2D virtual auditory display in the form of a 3x3 grid that contained 3 rows and 3 columns (totalizing 9 cells that were marked with letters and numbers, from A1, A2, A3 on the first row B1, B2, B3 on the second row and C1, C2 and C3 on the third row). The listeners, who were previously accustomed with this notation, were presented 3D sound stimuli that were convoluted with the HRTFs of the corresponding direction. Briefly, the results of the experiments showed that the blind subjects reported better results for sound localization in the 3x3 grid virtual display and for detecting the direction of the static source, especially in the front. In what concerns the dynamic sources, they were able to identify the direction of movement of the secondary target source more accurately in the horizontal plane. Furthermore, the blind listeners showed a higher spatial discrimination ability during the Minimum-Audible-Angle measurement, outperforming the sighted group of users by 1-2 degrees. To sum up, this experiment’s findings are in agreement with the previous research studies in respect with the enhanced sound localization skills of the visually impaired individuals in the horizontal plane and reduced auditory localization abilities in the vertical plane.

Similarly, in Voss’s study [13], two groups of blind subjects (congenitally and late-blind individuals) were compared with a control group of sighted, but blindfolded people in three types of minimum-audible-angle and minimum-audible-distance experiments. In the first task (a minimum-audible-angle frontal task, where the broadband noise stimuli – 90 ms in duration, separated by 1500 ms of silence were presented to the front of the listener and consequently to the left or to the right), the subjects were required to indicate if the sound was emulated from the same or from a different position. The results of this task showed a similar performance between the sighted and the blind group of listeners. Further, the second task was a peripheral minimum-audible-angle localization test, where the stimuli were presented in both the left and the right hemifields. The results demonstrate that the early-blind group outperformed the other two groups when the sound was emulated in the front of the interaural axis. When the sound was presented behind the interaural plane, the results of the early and late onset blind groups were indistinguishable, but significantly better than those of normally sighted control group. Thirdly, the results of the minimum-audible-distance task reported that the blind listeners were more proficient than the sighted subjects at differentiating the distance between consecutive audio stimuli under the free-field listening conditions. The previously presented findings suggest that the blind people are able to create a solid spatial representation of the environment and to perform with high accuracy in specific tasks that involve the discrimination of slight changes in the spectral characteristics of the sounds and in the level of externalization and distance perception. These supra-normal auditory localization abilities have been encountered even in the case of late-blind individuals, suggesting that there is a high degree of compensatory adaptation and auditory calibration that has been developed after the "critical period for large-scale reorganization" [5], due to the need of adjusting to real-world situations.

EQUAL LOCALIZATION PERFORMANCE BETWEEN THE SIGHTED AND THE VISUALLY IMPAIRED PEOPLE

Zwiers et al [20] performed a series of sound localization experiments that studied the sound localization accuracy in the 2D hemifield of two groups of both sighted and early-blind subjects. The experimental procedures used sounds of different durations (long-duration stimuli of 500 ms – that allowed the listener to move his head and short-duration stimuli of 150 ms) and spectral content (broadband noise and tone pips of either 750 Hz or 5000 Hz) and two different pointing techniques (left arm and nose pointing). The results of the experiment demonstrate that the azimuth localization accuracy of the blind subjects when they were exposed to long-duration, broadband Gaussian white noise stimuli is comparable with that of the sighted individuals. These findings promote the belief that the visual cues are not indispensable for calibrating the human auditory system for performing spatial sound localization and representation tasks. Besides, the elevation localization accuracy was also indistinguishable between the two groups of subjects, independent of the pointing method that has been employed.

In the experiment described in [21], the sound localization performance of 5 congenitally blind and of another 5 sighted subjects was compared and discussed. The listeners were required to turn their heads towards the perceived direction of the incoming stimulus. Consequently, the localization error between the target and the perceived angle was calculated. The results of the experiment demonstrated that the blind subjects were not as accurate as the sighted individuals, suggesting that auditory acuity depends on the perceptual association with the visual cues that build a solid mental representation of the surrounding space.

Another experiment that demonstrated a decreased spatial auditory resolution in the case of the blind people is presented in [22]. The sound localization procedure took place under virtual acoustic conditions and the subjects were required to listen to 3D sound stimuli (narrowband and wideband sounds and white noise) based on their own HRTFs. The results revealed higher localization errors in the case of the blind subjects, with an increased level of inaccuracy in the vertical plane, compared to azimuth localization. Sound localization acuity for the moving sources (that oscillated by 20 degrees horizontally, vertically and diagonally) was though higher than in the case of the static sources, demonstrating that the shifting in the values of the binaural and monaural cues conduct to an improved spatial discrimination performance.

Katz and Picinali [23] designed a large scale immersive virtual auditory environment that consisted of a room (presented both physically and virtually) where six sound sources were arranged around the listener. The stimuli were very well-known auditory cues, such as the sound of running water, telephone ringing, dripping faucet, washing machine, coffee machine and a ticking clock. The experiment involved the participation of 54 subjects, divided into 3 groups: congenitally blind, late blind and sighted (blindfolded) subjects. The pre-test training sessions consisted of two learning procedures: verbal description, where the subjects received spoken information about the location of the sound source they had previously listened to by using the clock position method and an active exploration procedure, where the participants were required to move towards the perceived location of the sound source. During the test phase, the participants were required to stand in the center of a virtual circle, while one sound source was randomly emulated and the listener was asked to identify its direction. The results report no significant difference between the blind and the normally sighted groups in what concerns the absolute distance error (the difference between the correct and the selected location of the sound source). In respect with the angular error (the difference, in degrees, between the correct position of the sound source and that selected by the listeners), the congenitally blind people recorded worst results than the late-blind and the sighted subjects.

DISCUSSION

The previously presented studies were separated into two categories, depending on the trend they promoted in what concerned the comparative analysis between the results obtained by both groups of subjects, either sighted or visually impaired. On one hand, it has been demonstrated that the blind individuals possess enhanced sound localization abilities in the horizontal plane (while the sighted subjects were more proficient for vertical sound discrimination) and for performing spatial localization tasks under monaural listening conditions. Moreover, the blind subjects were more accurate at differentiating the direction of the sound targets in the peripheral region of the acoustic space, as this behavior is vital for adaptation and navigation in real-world situations. It has been also demonstrated that the blind individuals respond more quickly at identifying the direction of the sound source than at recognizing its spectral features. This is a highly ecological consequence of the blind condition, as for the visually-deprived people it is far more important to react to the location of the stimuli (for instance, the sound of a car approaching) than to distinguish its spectral shape and characteristics (to know if the car is a bus or a truck). On the other hand, there have been several studies that reported equal or reduced localization performance in the case of the blind individuals. It has been argued by some researchers that the lack of visual stimuli does not influence the auditory spatial resolution. Besides, other authors supported the belief that the visual cues are a fundamental prerequisite of the human auditory system for properly mapping and recalibrating the representation of the extra-personal surrounding space.

CONCLUSIONS

This paper has presented a comparative study of the most relevant sound localization experiments that tested the acoustic spatial resolution of the blind individuals. Although there is enough evidence in favor of the development of cross-modal compensatory strategies in the case of the visually impaired people for performing spatial auditory localization tasks, there have been reported some results that demonstrate the contrary. Nonetheless, the arguments that support the theory of enhanced spatial auditory resolution in the case of the blind people are more solid and reliable. Accordingly, the blind individuals are able to discriminate the direction and distance to a sound source in the horizontal plane (particularly in the peripheral area of the acoustic space) and under monaural listening conditions more accurately than the normally sighted individuals.

Future plans concern the development of both training and test strategies that would investigate the sound localization performance of the visually impaired subjects in a virtual auditory display [24], using 3D audio stimuli based on non-individualized HRTFs.

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