Spatial and nonspatial peripheral auditory processing in congenitally blind people

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Congenitally blind adults' performance in spatial and nonspatial peripheral auditory attention tasks was compared with that of sighted adults in a paradigm manipulating location-based and frequency-based inhibition of return concurrently. Blind study participants responded faster in spatial attention tasks (detection/localization) and slower in the nonspatial frequency discrimination task than sighted participants. Both groups, however, showed the same patterns of interaction between location-based and frequency-based inhibition of return. These results suggest that early vision deprivation enhances the function of the posterior-dorsal auditory 'where' pathway but impairs the function of the anterior-ventral 'what' pathway during peripheral auditory attention. The altered processing speed in the blind, however, is not accompanied by alteration in attentional orienting mechanisms that may be localized to higher cortices. *NeuroReport* 17:1449–1452 © 2006 Lippincott Williams & Wilkins.

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Introduction

Blind people rely extensively on information in the auditory modality to create and update representations of the external world. Auditory information from the central and the peripheral auditory space may have different ecological consequences for the life of blind people. When an auditory sound appears in the periphery, blind people usually move their heads towards the orientation of the sound. Once the peripheral stimulus enters the central auditory space, 'what' and 'where' information might be processed equally efficiently. Empirical evidence from laboratory experiments confirmed that, compared with sighted individuals, blind people developed superior abilities to process the spatial and nonspatial properties of central auditory stimuli, including location [1,2], pitch/intensity and temporal order [3,4]. For the peripheral auditory stimuli, evidence shows that visual deprivation may enhance blind people's ability in processing 'where' information. For example, compared with sighted individuals, congenitally blind adults displayed enhanced localization abilities when they attended to sounds in peripheral, but not in central, auditory space [5]. Electrophysiological recordings obtained concurrently revealed sharper tuning of early spatial attention mechanisms in blind people. It is not clear, however, whether congenitally blind adults also possess enhanced abilities in processing nonspatial (i.e. 'what') information, such as frequency of auditory input from the periphery.

A related issue is whether the altered auditory processing skills of blind people are accompanied by alterations in their attentional orienting mechanisms. Most previous studies on blind people's auditory attention used the oddball paradigm, focusing on the attentional impact upon early perceptual processing [4,5]. Only one study addressed the more dynamic attentional orienting process. Using a spatial cueing paradigm, Després *et al.* [6] examined the effect of auditory attentional orienting on sound localization. Blind and sighted individuals showed similar attentional cueing effects despite the fact that the former exhibited shorter reaction times (RTs) than the latter when sound sources were placed at far-lateral locations. These results suggest that the improved auditory spatial abilities in blind people are independent of attentional orienting mechanisms. It is not clear, however, whether this conclusion is applicable when attention to nonspatial properties of peripheral sound is concerned.

The purpose of this study is therefore (i) to examine to what extent the processing of spatial and nonspatial properties of auditory stimuli in the periphery is altered in blind adults as compared with sighted adults; (ii) to investigate whether the attentional orienting mechanisms, specifically the mechanisms involving inhibitory processes, are altered by blind adults' general skills in processing spatial and nonspatial properties of the peripheral sound. We used the spatial and frequency cueing paradigms [7] and manipulated the location-based and frequency-based auditory inhibition of return (IOR) concurrently. Congenitally blind and normally sighted but blindfolded study participants were asked to perform spatial (detection and localization) or nonspatial (frequency discrimination) tasks on the same peripheral auditory targets. Both the general

response speed and the pattern of IOR effects were then compared between the two groups.

IOR refers to the phenomenon that response to a target after an uninformative peripheral cue is delayed when the target appears at the cued than at an uncued location, if the stimuli onset asynchrony between the cue and the target is longer than 300 ms [8]. IOR is observed not only in the visual domain but also in the auditory domain, and for different properties of auditory stimuli, including location and frequency [7]. In a recent study, we investigated the interaction between location-based and frequency-based IOR effects (Q. Chen, M. Zhang, X. Zhou, in preparation). The cue and the target varied in terms of location and frequency and participants were asked to perform a target detection, localization or frequency discrimination task. Results showed that the patterns of interaction between spatial and nonspatial (frequency) IOR effects varied depending on the task demand. The present study applied these manipulations to both blind and sighted participants and examined whether early visual deprivation alters the spatial and nonspatial processing speed to peripheral auditory stimuli on the one hand and whether the altered perceptual processing speed in blind people changes their higher attentional orienting mechanisms on the other hand.

Method
Participants
A total of 57 normally sighted participants and 44 congenitally blind participants were tested, 16 sighted (eight women, age: 22 ± 2.3 years) and 14 blind (seven women, 21 ± 2.5 years) for experiment 1, 18 sighted (nine women, age: 21 ± 1.8 years) and 15 blind (seven women, age: 22 ± 2 years) for experiment 2, and 17 sighted (nine women, 22 ± 2.5 years) and 15 blind (seven women, 23 ± 1.2 years) for experiment 3. The two groups of participants were all right-handed without hearing deficits and were matched on educational level (all second or third-year undergraduate students). Informed consent was obtained from each participant and this study was approved by the Academic Committee of the Department of Psychology, Northeast Normal University, China.

Design and procedures
The three experiments used essentially the same design and stimuli. The cue–target correspondence in location (same vs. different) was crossed with the cue–target correspondence in frequency (same vs. different), forming a 2×2 factorial design. Each condition had 40 trials. Experiment 1 also included 20 catch trials in which no target was presented.

The cue and the target were two pure tones (555 and 869 Hz), which served as the cue or the target in the four experimental conditions with equal probability. They were synthesized at a sampling rate of 16 000 Hz. Both tones were 100 ms in duration, beginning and ending with 5-ms linear onset/offset amplitude ramps to eliminate clicks. The experiments were conducted in a darkened, sound-attenuating chamber ($300 \times 100 \times 200$ cm) with a background sound level being lower than 35 dB sound pressure level. The cue and the target tones were presented over Laus LA-6000 speakers (Shenzhen Sannuo Ltd, Shenzhen, China) located $45°$ to the left or right of the mid-sagittal plane of the listener, with a distance of approximately 50 cm from the

midline. Sound stimuli were presented to the listener at a comfortable intensity of approximately 65 dB.

On each trial, a cue sound was presented over either the left or right speaker, followed by a target sound presented at either the same or a different location with either the same or a different frequency. No predictive relationships between the cue and the target along either the location or the frequency dimension were found. The presentation of the cue and the target on the ipsilateral or contralateral sides and the combination of the same or different frequencies were completely balanced. The target was presented 750 ms after the onset of the cue. Participants were asked to detect the presence of the target (experiment 1), localize the target (experiment 2), or discriminate the high or low of the target frequency (experiment 3). In experiment 1, participants responded by pressing one button on a joystick with the index finger. In experiments 2 and 3, participants used the middle and the index fingers to respond. The button-to-speaker and the button-to-frequency assignments were counterbalanced over participants.

Results
For each participant, the median RT and the mean error rate were calculated for each experimental condition. A 2 (participant group) $\times$ 2 (location correspondence) $\times$ 2 (frequency correspondence) analysis of variance was first performed on RT data in each of the three experiments. No meaningful results were obtained from the error rate analysis as they were all below 2% in conditions.

For experiment 1, the main effect of the cue–target location correspondence and the main effect of frequency correspondence were significant [$F(1,28)=27.72$, $P<0.001$; $F(1,28)=12.11$, $P<0.005$], suggesting that both the location-based (27 ms) and the frequency-based (12 ms) IOR effects appeared in the detection task. The main effect of the participant group was significant [$F(1,28)=5.04$, $P<0.05$], indicating that RTs to the peripheral targets were significantly faster for blind (315 ms) than for sighted (384 ms) participants. The interaction between location and frequency correspondences was significant [$F(1,28)=5.26$, $P<0.05$], suggesting that, for both groups of participants, the location-based IOR effect when the cue and the target had the same frequency (35 ms) was larger than the effect when they had different frequencies (20 ms). This interaction also suggested that the frequency-based IOR effect when the cue and the target appeared at the same location (20 ms) was larger than the effect when they appeared at different spatial locations (5 ms). The three-way interaction was not significant (F<1), indicating that the two groups of participants showed the same pattern of auditory attentional cueing effects (see Fig. 1a).

For experiment 2, the main effect of location correspondence was significant [$F(1,31)=6.10$, $P<0.05$], with localization responses being slower when the target was at the same location as the cue (550 ms) than when they were at different locations (534 ms). The effect of frequency correspondence was significant [$F(1,31)=3.22$, $0.05<P<0.1$], with responses being slightly slower when the target was of the same frequency as the cue (547 ms) than when they were of different frequencies (538 ms). The effect of the participant group was also significant [$F(1,31)=4.75$, $P<0.05$], indicating that the localization of peripheral sounds was much faster for blind participants
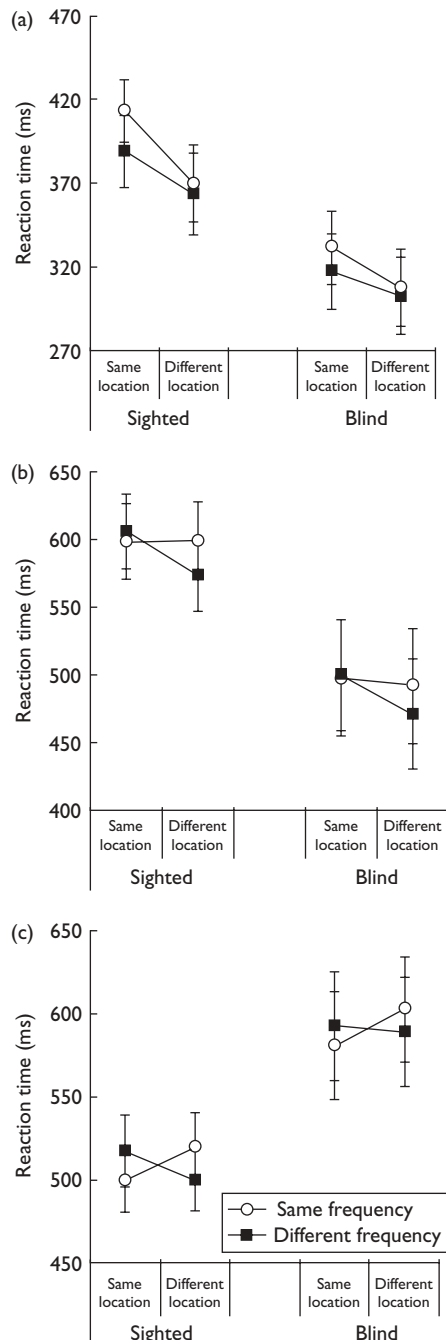
Fig. 1 Mean reaction times (with standard errors) as a function of participant group and cue–target location and frequency correspondences in each experiment. (a) Experiment 1, the detection task; (b) experiment 2, the localization task; (c) experiment 3, the frequency discrimination task.

there was no three-way interaction (F<1), indicating that the above two-way interaction was manifested in the same way in the two groups of participants (see Fig. 1b).

For experiment 3, the main effects of location correspondence and frequency correspondence were not significant [F(30)=1.33, $P>0.1$; F<1]. The main effect of the participant group, however, reached significance [F(1,30)=5.23, $P<0.05$], indicating that the frequency discrimination of the peripheral sound was much slower in blind participants (591 ms) than in sighted participants (509 ms). The interaction between location and frequency correspondences was significant [F(1,30)=11.58, $P<0.005$] (see Fig. 1c). When the cue and the target were at the same location, responses were faster (15 ms) when they had the same frequency than when they had different frequencies. When the cue and the target were at different locations, responses were slower (17 ms) when they had the same frequency than when they had different frequencies. Alternatively, when the cue and the target had the same frequency, responses were faster (21 ms) when they appeared at the same location than when they were at different locations. When the cue and the target had different frequencies, responses were slower (11 ms) when they appeared at the same location than when they were at different locations. The three-way interaction was not significant (F<1), indicating that the above patterns of interaction were the same for the two groups of participants (see Fig. 1c).

Discussion

This study showed that blind participants were much faster than sighted participants at detecting and localizing the peripheral target after the cue while they were much slower at discriminating the frequency of the target. The altered global response speed to spatial and nonspatial information in blind participants, however, was not accompanied by changes in the mechanisms underlying location-based and frequency-based auditory IOR and their interactions. Blind and sighted participants showed exactly the same patterns of auditory attentional cueing effects. The pattern of interaction between location-based and frequency-based IOR in the spatial and nonspatial tasks replicated our previous study with normal individuals (Q. Chen, M. Zhang, X. Zhou, in preparation).

Human auditory information processing can be parceled into spatial ('where') and nonspatial ('what') streams [9–12], resembling the segregation in the visual system [13]. The anterior-ventral stream identifies auditory objects by recognizing spectral and temporal characteristics of auditory input, while the posterior-dorsal stream is responsible for sound-source localization. Early vision deprivation may enhance blind people's auditory processing along the 'where' pathway. For example, Röder et al. [5] demonstrated that blind individuals performed better than sighted individuals at localizing peripheral sound, and this superiority was accompanied by the significantly steeper N1 component in electrophysiological recordings. Importantly, the scalp topography of the enhanced N1 in the blind was shifted posteriorly while it was largest over the anterior in the sighted, implying that the 'where' pathway was more activated in blind than in sighted individuals. The present finding of superior performance of blind participants in peripheral detection and localization tasks provides further evidence supporting the enhanced functioning of the 'where' auditory pathway in blind people.

(490 ms) than for sighted participants (594 ms). The interaction between location correspondence and frequency correspondence was significant [F(1,31)=15.34, $P<0.001$], suggesting that the location-based IOR effect when the cue and the target had the same frequency (3 ms) was smaller than the effect when they had different frequencies (31 ms). This interaction also suggested that the frequency-based IOR effect when the cue and the target were presented at the same location (−5 ms) was smaller than the effect when the cue and the target were at different locations (24 ms). Again,

A novel finding in this study is that blind participants were slower than sighted participants in discriminating frequency of the peripheral sound, a finding that differs from earlier studies showing that blind people could perform better in processing 'what' information when the input is from the central space [3]. This discrepancy might be caused by different roles that nonspatial information plays in central and peripheral auditory processing. When the sound is from the periphery, knowing 'where' it comes from is more important for blind people to update the representation of the environment and to avoid danger than knowing 'what' it is. For example, while crossing the road, the most important information for the blind is whether there is a vehicle coming and the direction from which it comes. Knowing what specific type of vehicle is coming is not so crucial. Indeed, anecdotal evidence shows that when blind people do need to know the identity of a stimulus, they usually turn their heads and render the stimulus in the central auditory space. Such ecological practice may have developed to minimize the activation of the 'what' pathway when the sound comes from the periphery. More stringent studies, however, should be carried out to test this suggestion.

Obviously, the alternation of processing speed in the blind is not accompanied by changes in attentional orienting mechanisms, as blind and sighted participants showed exactly the same patterns of attentional cueing effects. This argument is consistent with that of Després *et al.* [6] who also observed the dissociation between general response speed and the pattern of attentional cueing effects in blind people. This argument is also consistent with results of brain imaging studies on auditory processing in blind people [14,15]. These studies found that brain regions responsible for early sensory processing are reorganized to compensate for vision deprivation, such that occipital and temporal cortices are more sensitive to auditory input in blind than in sighted people. For example, a recent positron emission tomography study showed that blind individuals used occipital regions to carry out auditory localization under monaural conditions [16]. No evidence, however, suggests that such reorganizations in cerebral structures and functions involve attentional orienting mechanisms in the parietal cortex and frontal oculomotor regions. In other words, structural and functional reorganizations in the brain, due to vision deprivation, affect perceptual processing in blind people but have no impact upon higher level attentional orienting mechanisms, which can be localized to higher cortices.

Conclusion

Early vision deprivation in blind people enhances the spatial processing but impairs the nonspatial processing of peripheral auditory information. The altered processing speed in the blind, however, is not accompanied by alteration in attentional orienting mechanisms.

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