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Research paper

Blind people are more sensitive than sighted people to binaural sound-location cues, particularly inter-aural level differences

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A B S T R A C T

Blind people use auditory information to locate sound sources and sound-reflecting objects (echolocation). Sound source localization benefits from the hearing system's ability to suppress distracting sound reflections, whereas echolocation would benefit from “unsuppressing” these reflections. To clarify how these potentially conflicting aspects of spatial hearing interact in blind versus sighted listeners, we measured discrimination thresholds for two binaural location cues: inter-aural level differences (ILDs) and inter-aural time differences (ITDs). The ILDs or ITDs were present in single clicks, in the leading component of click pairs, or in the lagging component of click pairs, exploiting processes related to both sound source localization and echolocation. We tested 23 blind (mean age = 54 y), 23 sighted-age-matched (mean age = 54 y), and 42 sighted-young (mean age = 26 y) listeners. The results suggested greater ILD sensitivity for blind than for sighted listeners. The blind group's superiority was particularly evident for ILD-lag-click discrimination, suggesting not only enhanced ILD sensitivity in general but also increased ability to unsuppress lagging clicks. This may be related to the blind person's experience of localizing reflected sounds, for which ILDs may be more efficient than ITDs. On the ITD-discrimination tasks, the blind listeners performed better than the sighted age-matched listeners, but not better than the sighted young listeners. ITD sensitivity declines with age, and the equal performance of the blind listeners compared to a group of substantially younger listeners is consistent with the notion that blind people's experience may offset age-related decline in ITD sensitivity.

1. Introduction

Many blind people develop impressive hearing skills that help them navigate in their environment (Thaler et al., 2011). Studies have found that some blind listeners outperform sighted listeners on sound localization tasks, such as determining the horizontal or vertical position of sound sources (Ashmead et al., 1998; Collignon et al., 2009; Muchnik et al., 1991; Voss et al., 2004), and tasks involving the detection or localization of sound reflections from nearby objects (Kolarik et al., 2014), i.e., echolocation (Stoffregen and Pittenger, 1995). Sound-source localization benefits from the hearing system's ability to suppress potentially misleading sound reflections (the precedence effect), whereas echolocation would benefit from “unsuppressing” the same reflections (Dufour et al., 2005; Wallmeier et al., 2013). We tested basic discrimination abilities relevant to both source localization and echolocation to clarify how these potentially conflicting aspects of spatial hearing interact in sighted and blind listeners.

Two main cues for sound source localization in the horizontal plane are inter-aural time differences (ITDs) and inter-aural level differences (ILDs). In most environments, the direct sound from the source is accompanied by reflections from nearby objects and surfaces. Such reflections have their own ITDs and ILDs, which may indicate another direction than the ITDs and ILDs of the direct sound. The auditory system's solution to this problem is to suppress reflected (or lagging) sounds in favor of the direct (or leading) sound. This results in a set of perceptual phenomena known as the “precedence effect,” including perceptual fusion of leading and lagging sounds, localization dominance of the leading sound, and discrimination suppression of inter-aural differences in lagging sounds (Brown et al., 2015; Litovsky et al., 1999).

Blind listeners have displayed impressive acuity in

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discriminating between closely spaced reflecting objects (Dufour et al., 2005; Teng et al., 2012), as have sighted listeners after extensive training (Rowan et al., 2013; Schörnich et al., 2012; Wallmeier et al., 2013). However, it is unclear to what extent the ability of blind and trained sighted listeners to localize sound-reflecting objects involves increased sensitivity to binaural differences in general, or increased ability to unsuppress lagging sounds, or both. Perceptual training studies suggest that both ILD and ITD discrimination improves with training (Sand and Nilsson, 2014), whereas it is less clear whether training leads to increased ability to unsuppress lagging sounds (Litovsky et al., 2000; Saberi and Perrott, 1990; Saberi and Antonio, 2003). Studies suggest that the ILDs of lagging sounds are particularly useful for echolocation (Rowan et al., 2013) and that echolocators tend to use high-frequency sounds (Schörnich et al., 2012), for which ILDs provide more efficient location cues than do fine-structure ITDs (e.g., Hartmann and Macaulay, 2014). However, the envelope ITDs of time-varying sounds may be useful for localizing high-frequency sounds (e.g., Bernstein and Trahiotis, 2002).

In most real-life situations, ITDs and ILDs are correlated. However, they can be manipulated independently using headphone presentation. In this setup, the sounds are usually localized inside the head of the listener, and the effect of changing the ILD or ITD is the lateralization from one ear to the other. To our knowledge, blind and sighted listeners' ITD and ILD sensitivities have not previously been compared in the same lateralization experiment. However, Simon et al. (2002) asked listeners to match an ILD to a given ITD, and found that blind listeners used larger ILDs to match ITDs, suggesting between-group differences in how one or both of the binaural cues affect perceived lateralization. Two studies measured detection of ITD changes and found support (Yabe and Kaga, 2005) as well as lack of support (Starlinger and Niemeyer, 1981) for higher ITD sensitivity in blind compared to sighted listeners, and one study reported no difference in ILD sensitivity between blind and sighted listeners (Collignon et al., 2006).

The precedence effect can also be demonstrated in lateralization experiments. A sound pair consisting of a short leading and a short lagging sound will be perceived as a single sound provided that the time separation between the component sounds is less than approximately 4 ms (Litovsky et al., 1999). Inter-aural discrimination thresholds are substantially higher if the ITD or ILD is present in the lagging components of the sound pair rather than the leading component (Tollin and Henning, 1998) or in a single click (Saberi and Antonio, 2003; Saberi et al., 2004).

We tested blind and sighted listeners' ability to discriminate inter-aural differences present in (a) single clicks, (b) in the leading component of click pairs, or (c) in the lagging component of click pairs (Fig. 1). Performance on the single-click task relates solely to the ability to discriminate ILDs or ITDs, whereas performance on the tasks involving lead- or lag-click discrimination also relates to the ability to suppress and unsuppress lagging clicks. We tested both ILD and ITD discrimination, because the two inter-aural cues are effective for different frequency ranges and are processed differently by the auditory system. Blind people may therefore have acquired a heightened sensitivity to one or both cues, which would lead to better performance on the single-click condition for one or both cues. If blind people have acquired an increased ability to overcome the precedence effect, we would expect them to outperform the sighted on the lag-discrimination task but not on the lead-discrimination task. In the latter task, they might instead be distracted by the unsuppressed click and perform worse, as suggested by one previous study (Dufour et al., 2005).

The temporal resolving capacity of the auditory system degrades with age (Frisina, 2010), reducing ITD sensitivity, whereas ILD sensitivity seems to be less affected by age (Babkoff et al., 2002; Strouse et al., 1998). To assess and control for potential age effects, we included two groups of sighted listeners: one group matched in age to the sample of blind listeners (mean age = 54 y) and one group of young listeners (mean age = 26 y).

2. Method

We used procedures and experimental sounds similar to those used by Saberi et al. (Saberi and Antonio, 2003; Saberi et al., 2004). Novel in our study was that we added a lead-click condition (cf., Tollin and Henning, 1998), tested both ILD and ITD discrimination in the same experiment, and included both sighted and blind listeners. The experimental protocol was approved by the regional ethics committee and informed consent was obtained from all listeners.

2.1. Stimuli

Experimental sounds were composed of 125-μs rectangular pulses (clicks) with an inter-aural time or an inter-aural level difference (Fig. 1). The inter-aural difference click (the signal) was presented alone ("single-click" condition), as the leading component of a click pair ("lead-click" condition), or as the lagging component of a click pair ("lag-click" condition). In the lead-click condition, the signal was always presented 2 ms before a lagging click with no inter-aural differences (the distracter). In the lag-click condition, the signal was always presented 2 ms after the leading distracter. To keep the overall loudness of the clicks approximately equal in the ILD conditions, ILDs were created by attenuating the stronger and amplifying the weaker signal by half the ILD. The peak sound pressure level of the distracter click was 94 dB.

2.2. Staircase procedure

We used a two-interval, two-alternative forced-choice task with an adaptive two-down, one-up rule that tracks the listener's 71% discrimination threshold (Levitt, 1971). On the first interval of each trial, the signal's ILD or ITD favored one randomly selected ear, whereas in the second interval, it favored the other ear by the same ILD or ITD. The listener's task was to decide whether the two intervals in each trial were heard in left-then-right or right-then-left sequence. Auditory feedback was provided after each trial.

The ITD runs started with an ITD of 650 μs and the ILD runs with an ILD of 20 dB. Two successive correct responses led to a reduction of the ITD or ILD by 37% (a step size of 0.2 log units) until the fourth reversal and by 11% (0.05 log units) thereafter. An incorrect response led to an ITD or ILD increase by the step size, or to the starting value if the rule implied an exceedance of this value. ITDs were rounded to the nearest 5.2 μs, the resolution determined by the sampling rate of 192 kHz.

The experiment was conducted in a sound-proof listening room with an ambient sound pressure level below 25 dB(A). Sounds were presented through earphones (Sennheiser HD 580 Precision) using an earphone amplifier (Lake People Phone-Amp G109) connected to a computer equipped with an external sound card (RME Fireface 400) that allowed a sampling frequency of 192 kHz (24-bit depth). A script written in MATLAB generated the sounds and collected the listener's responses, which were entered via a keyboard on which the relevant keys were indicated with small plastic tags to allow touch identification. Both sighted and blind listeners were tested blindfolded.

2.3. Threshold estimates

Two runs were conducted for each of the six stimulus conditions

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