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Research paper

Horizontal sound localization in cochlear implant users with a contralateral hearing aid

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ABSTRACT

Interaural differences in sound arrival time (ITD) and in level (ILD) enable us to localize sounds in the horizontal plane, and can support source segregation and speech understanding in noisy environments. It is uncertain whether these cues are also available to hearing-impaired listeners who are bimodally fitted, i.e. with a cochlear implant (CI) and a contralateral hearing aid (HA).

Here, we assessed sound localization behavior of fourteen bimodal listeners, all using the same Phonak HA and an Advanced Bionics CI processor, matched with respect to loudness growth. We aimed to determine the availability and contribution of binaural (ILDs, temporal fine structure and envelope ITDs) and monaural (loudness, spectral) cues to horizontal sound localization in bimodal listeners, by systematically varying the frequency band, level and envelope of the stimuli.

The sound bandwidth had a strong effect on the localization bias of bimodal listeners, although localization performance was typically poor for all conditions. Responses could be systematically changed by adjusting the frequency range of the stimulus, or by simply switching the HA and CI on and off. Localization responses were largely biased to one side, typically the CI side for broadband and high-pass filtered sounds, and occasionally to the HA side for low-pass filtered sounds. HA-aided thresholds better than 45 dB HL in the frequency range of the stimulus appeared to be a prerequisite, but not a guarantee, for the ability to indicate sound source direction.

We argue that bimodal sound localization is likely based on ILD cues, even at frequencies below 1500 Hz for which the natural ILDs are small. These cues are typically perturbed in bimodal listeners, leading to a biased localization percept of sounds. The high accuracy of some listeners could result from a combination of sufficient spectral overlap and loudness balance in bimodal hearing.

1. Introduction

In normal hearing, sound localization in the horizontal plane relies predominantly on interaural differences in arrival time and intensity of the sound reaching our ears. According to Rayleigh's duplex theory, interaural time differences (ITDs) dominate at low frequencies below 1.5 kHz, and interaural level differences (ILDs) are most effective at high frequencies above 3 kHz (Blauert, 1997; Rayleigh, 1907).

It is unclear whether binaural cues are available to hearing-impaired users of a cochlear implant (CI) in one ear, and a conventional hearing aid (HA) in the other ear ("bimodal" stimulation). Binaural cues can only arise in a frequency range that is audible through both hearing devices, which is typically the range from the low-frequency cut-off of the CI, at about 250 Hz, up to the frequency where hearing in the non-implanted ear becomes too poor for amplification (often between 750 and 4000 Hz). Numerous benefits, including improved speech understanding and sound-source localization, have been reported for the distinct, but complementary combination of acoustic HA amplification and electrical

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stimulation from the CI (Beijen et al., 2010; Ching et al., 2007; Mok et al., 2006; Morera et al., 2005; Veugen et al., 2016a). However, it is unclear whether these benefits result from true binaural integration at the brainstem level, or from alternative processes that depend on essentially monaural cues.

Binaural cues are highly distorted in bimodal stimulation for a number of reasons (Francart and McDermott, 2013). (i) The envelope-encoding algorithms used in CI processors eliminate access to temporal fine structure, thus abolishing the potential for low-frequency ITD processing. (ii) Devices typically operate independently, thereby distorting or even inverting ILDs when more gain is applied to the signal that is attenuated by the head shadow (Dorman et al., 2014). (iii) In the common case of low-frequency residual hearing, the CI and HA only overlap in the lower frequencies, where natural ILD cues are minimal. As such, bimodal listeners might have to rely on other localization cues that are typically less important for normal-hearing listeners (Macpherson and Middlebrooks, 2002). For example, ITDs based on the envelope of a sound, rather than on the fine structure from its carrier, could potentially convey location information (Henning, 1974). Monaural spectral pinna cues may also provide spatial information, which has been demonstrated for listeners without access to reliable binaural cues (Agterberg et al., 2012; Van Wanrooij and Van Opstal, 2004; Van Wanrooij and Van Opstal, 2007). However, these high-frequency cues (4–12 kHz) are probably not useful for bimodal listeners, as they fall often beyond their residual hearing, and are poorly, or not at all, preserved by hearing devices with behind-the-ear and in-the-concha microphones (Otte et al., 2013). Although bimodal listeners could in principle rely on subtle low-frequency monaural loudness cues that are caused by the acoustic head shadow, these cues are ambiguous, as they contain mixed information of both sound-source azimuth and intensity (Van Wanrooij and Van Opstal, 2004).

Even if ITDs and ILDs are highly distorted in bimodal hearing, the brain might be sufficiently plastic to use all available cues, provided that these are consistent and unique (Hofman et al., 1998; Van Wanrooij and Van Opstal, 2005). Bimodal users are sensitive to both ILDs and envelope ITDs when stimuli are presented directly on the electrode array, or acoustically via inserted earphones (Francart et al., 2008, 2009). It is unclear, however, to what extent these cues are preserved in commercially available devices. In sound-localization experiments that used speech or broadband stimuli, bimodal benefit over unilateral CI use has been observed in about 50% of the listeners (Ching et al., 2007), with bimodal behavior ranging from chance level to near-normal localization.

The present study aimed to determine the contribution of binaural cues (ILDs, fine structure and envelope ITDs) and monaural cues (loudness, spectral) to the horizontal sound localization behavior of bimodal listeners, by systematically varying the sound's frequency band, level and envelope. If there is no contribution of any localization cue, or if bimodal listeners would rely on cues that cannot be transmitted by the devices (such as fine structure ITDs, or spectral pinna cues), one expects that bimodal listeners simply cannot report a spatial percept. This would lead them to report only one fixed location (e.g. at straight ahead), or to completely random localization behavior, independent of the actual sound location. Alternatively, bimodal listeners could fully rely on the contribution of ILDs for sound localization, as this cue could potentially be preserved by the hearing devices. In particular, if bimodal listeners perceive a sound's location by ILDs alone, we predict that localization responses will be biased towards the dominant device in the sound's frequency range (Dunn et al., 2005). Fig. 1 schematically illustrates stimulus-response relationships for different stimulus conditions when the contribution of ILDs is dominant. Likewise, for monaural listening conditions we predict that stimuli will be perceived on the aided side, similar to the localization behavior of single-sided deaf and normal-hearing listeners with one ear plugged (Agterberg et al., 2011; Kumpik et al., 2010; Van Wanrooij and Van Opstal, 2004; Van Wanrooij and Van Opstal, 2007). Responses are then expected on the CI side in the monaural CI condition, but also in the bimodal condition for high-pass filtered sounds that fall outside the range of residual hearing through the HA (Fig. 1E). An opposite effect towards the HA side is expected for low frequencies that are well audible only through the HA (Fig. 1A). Accurate localization behavior with a clear stimulus-response relationship (Fig. 1C) is only expected when there is considerable bimodal spectral overlap in hearing (when the sound contains frequencies transmitted by both devices) that allows for access to veridical ILDs or to envelope ITDs. Furthermore, we predict that observed differences in aided hearing thresholds will largely explain individual differences in bimodal localization behavior.

2. Methods

2.1. Subjects

A group of fourteen postlingually deaf bimodal listeners participated in this study (nine male, mean age 63 ± 11 years, range 45–81 years). All used on a daily basis a Harmony or Naida Q70 CI processor (Advanced Bionics, Valencia, CA) in one ear, and a Naida S IX UP hearing aid (Phonak, Stäfa, Switzerland) in the other ear, that was adapted in compression characteristics for research purposes (see below). Fig. 2 shows the average aided and unaided hearing thresholds in the non-implanted ear, as determined by standard audiometry. For unaided thresholds, pure tones were presented through headphones; aided thresholds were measured for eleven subjects in a sound field with warble tones. To visualize the possible areas of binaural overlap, we also added CI-aided thresholds that were measured for nine subjects during their standard clinical examination. Subject and device characteristics are presented in Table 1. The study was approved by the local medical ethics committee (CMO) Arnhem-Nijmegen, the Netherlands (protocol number 40327.091.12).

At the time of the experiment, all subjects were bimodal users for at least one year. The CI and HA were matched in loudness and automatic gain control, according to a procedure described before (Veugen et al., 2016b), at least two months prior to this study, and used every day since then. Briefly, loudness matching was performed using steady-state speech-shaped noise, at two loudness levels (45 and 80 dB SPL) and in three frequency bands (250–548 Hz, 548–1000 Hz and 1000 Hz up to the frequency where hearing loss in the non-implanted ear exceeded 120 dB HL), therefore called ‘three-band balancing’. Compression knee-points were the same in both devices, as well as the attack and release times (Veugen et al., 2016a). Adaptive features including noise reduction and directional microphones were turned off in both devices (only the adaptive feedback reduction in the HA was activated).

2.2. Apparatus

The experimental setup was the same as described before (Bremen et al., 2010). Briefly, all experiments took place in a completely dark, sound-attenuated room. Sounds were presented via a motorized hoop with 58 speakers that rotated around the subject's chair. Head movements were recorded using the magnetic search coil induction technique (Agterberg et al., 2011; Robinson, 1963), for which subjects wore a custom-built lightweight spectacle frame with a small search coil attached to the nose bridge.