

LATERALIZATION OF SOUNDS USING BONE-CONDUCTION HEADSETS

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Participants reported the apparent lateralization of sounds as a function of interaural level differences, for stimuli delivered through bone-conduction headsets and standard headphones. The results showed that non-externalized spatial audio can be invoked with the bonephones, a device that provides the unique advantage of not covering the ears of the listener. Furthermore, the degree of lateralization with bonephones can be similar to that produced using headphones. These data provide a function relating the input into bonephones or headphones to the resulting percept of lateralization, in a manner that may be particularly useful for mobile and low-resource computing applications.

The apparent location of a sound source can be used to facilitate many auditory display tasks, including wayfinding (Walker & Lindsay, 2006) and segregation of simultaneous speech channels (Walker, Stanley, Iyer, Simpson, & Brungart, 2005). Delivering interaural time and level differences through headphones is a simple way to adjust the apparent location of a sound, requiring fewer computing resources than full head-related transfer functions used in three-dimensional audio. The resulting sound is generally “lateralized,” as compared to “spatialized.” Properties of lateralization have been studied extensively with conventional headphones (e.g., Yost & Hafter, 1987).

Although headphones provide the advantage of allowing private presentation of high-fidelity dichotic (stereo) sounds in a portable package, they have the unfortunate characteristic of covering the ears of the listener, which may deteriorate detection and localization of sounds in the environment. In addition to pressure waves transmitted through air, the auditory system is also sensitive to waves transmitted through bones in the skull. Presenting sounds to listeners through bone conduction by placing vibrators on the skull avoids covering the ears of the listener. In the past, bone-conduction headsets have typically been used for audiometry to assess locus of hearing damage. Recently, compact binaural bone-conduction headsets (“bonephones”) have become available that are more suitable for

auditory displays, because of their potential for stereo presentation of sounds, their small size, comfort, and standardized input jack.

Although there has been some research aimed at obtaining information useful for implementing bonephones in an auditory display (e.g., Walker & Stanley, 2005), there is little basic research on the perception of lateralization through bone-conduction. In the past, many have considered spatial audio with bone conduction to be difficult or even impossible because the interaural attenuation, and thus the maximum interaural level difference (ILD), was not considered sufficient (e.g., Goldstein & Newman, 1994). However, these conclusions are generally drawn from conservative estimates based on theory for the purposes of audiology, rather than direct empirical evaluation of interaural attenuation through bone conduction.

Recent evidence, on the other hand, has suggested that there may be a considerable amount of lateralization possible through bone-conduction headsets. In particular, Kaga, Setou, and Nakamura (2001) found that the subjective report of image lateralization systematically depended on interaural time and level differences delivered through binaural application of clinical bone-conduction vibrators. The researchers showed sensitivities to interaural differences in time and level that were not significantly different from interaural difference thresholds assessed through air-conduction. Recent research has also tested spatial audio capabilities

with bonephones, rather than traditional clinical headsets, and found strong evidence for lateralization. In particular, Walker, Stanley, Iyer, Simpson, and Brungart (2005) used the Coordinate Response Measure (CRM) task (Bolia, Nelson, Ericson, & Simpson, 2000) to see how interaural differences delivered to headphones and bonephones changed task performance. Performance changed in a systematic manner as a function of the interaural differences. The assumed mechanism underlying this effect is the same as for Cherry's "cocktail party effect," in which spatial cues lead to auditory stream segregation, and thereby improve speech intelligibility (Cherry, 1953). The fact that performance on the CRM task increased as interaural differences increased makes it clear that sound cues can, indeed, be lateralized by changing interaural cues delivered through bonephones. The measure of spatial separation, however, did not reach as high performance with the bonephones as it did with the regular headphones. Given these results and audiologists' concern with the interaural attenuation with bonephones, the degree of spatial separation with bonephones may not match that of air conduction.

The direct percept of lateralization with bonephones has not yet been tested. Furthermore, there are no specific recommendations available on how to process a sound for it to be lateralized through the bonephones. The purpose of the present experiment was to determine the relationship between ILDs to perceived lateralization, for bonephones relative to standard headphones. Lateralization was measured by the subjective impression of where in the head the sound source seemed to be located. Determining this psychophysical function will suggest the degree to which lateralization can occur with bonephones. It will also indicate exactly how to implement spatial audio through a computing system with low resources while using an apparatus that has distinct advantages over standard headphones.

METHOD

Participants

Three volunteer graduate students volunteered. All reported no hearing deficiencies.

Task & Stimuli

The stimuli and task were modeled after Yost and Hafter (1987). Pulse trains were delivered to the participant, each consisting of eight pulses. The first three pulses had no interaural difference and the remaining five had an ILD of 0, 4, 8, 12, 16, or 20 decibels. Each pulse lasted 100 msec, with an 8 msec rise time. There was a 50% duty cycle and a 700 msec delay between the train of 8 pulses. The task was to specify the location in the head of the last five pulses by adjusting the position of a slider overlaid on a simple diagram of a head (see Figure 1). Pure tones of three different frequencies were used: 500, 3000, and 8000 Hz. Although ILDs are most indicative of the spatial location of sounds with higher frequencies, the degree of lateralization possible at lower frequencies was also tested (in this case, at 500 Hz), since lower-frequency tones may need to be lateralized with ILDs in applied environments. The ILD was achieved by attenuating one of the ears by the values stated above. These attenuation values were applied to either the left or right ear, and thus both ears were tested for each participant. Attenuation values were specified at the input into the sound delivery apparatus. Loudness was approximately matched across frequencies and devices through pilot testing.

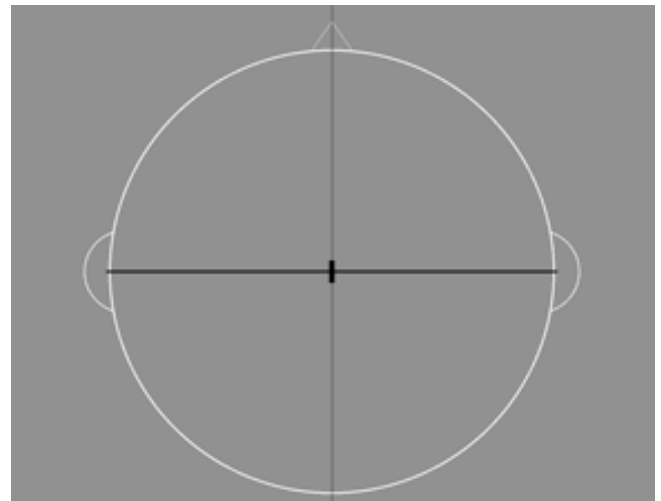


Figure 1. *The head model that participants used to indicate perceived lateralization. The slider indicator is the solid black rectangle in the middle. Participants adjusted the position of this slider indicator by pressing keys on the numeric pad.*

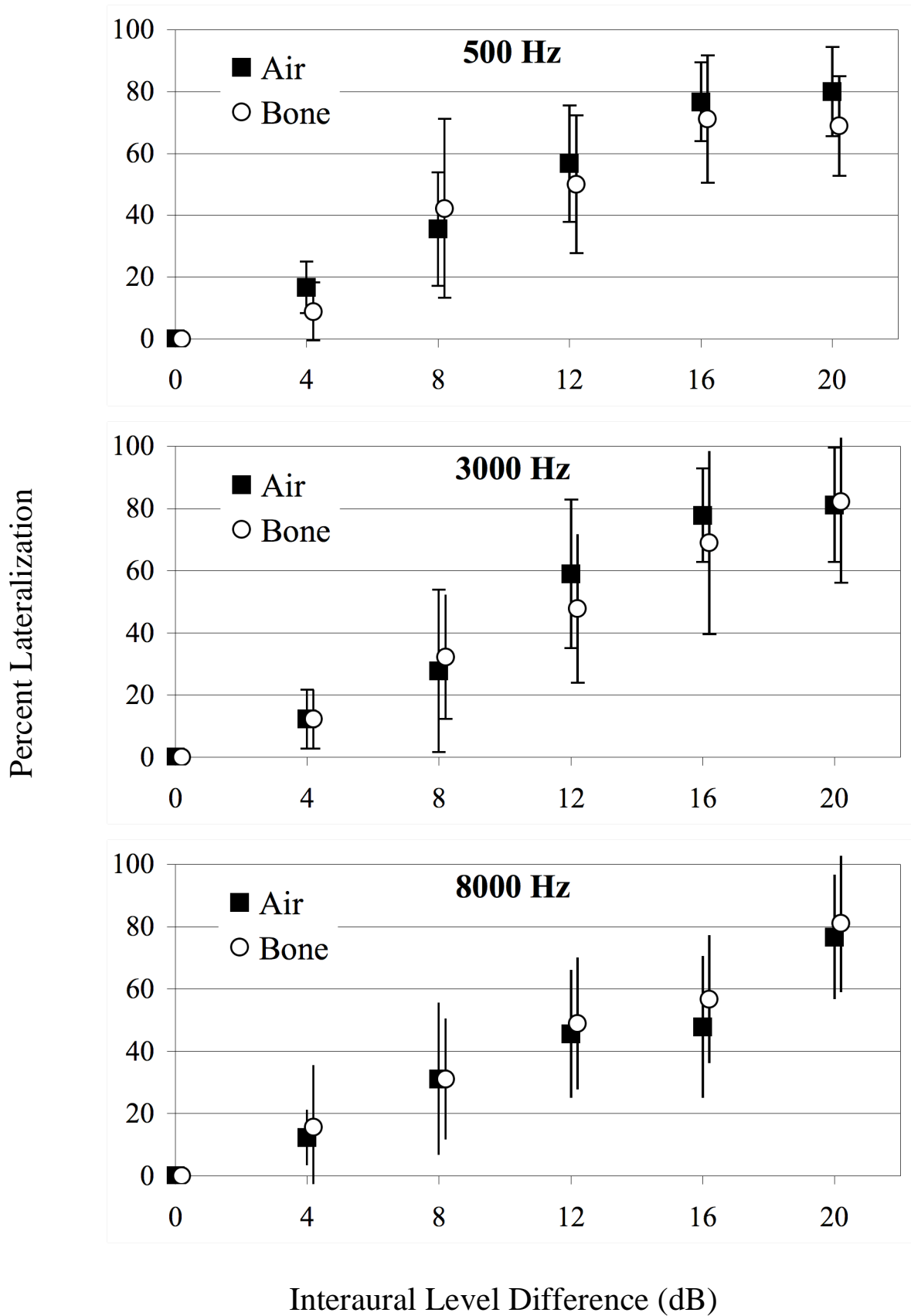


Figure 2. Percent lateralization as a function of interaural level difference delivered to the apparatus. Filled squares show data for sounds presented via normal air-conduction headphones; open circles represent data for bonephones contacting the mastoid. Error bars represent the total range of responses.

Apparatus

Participants listened through one of two sound delivery apparatus: a pair of Temco binaural bone-conduction headsets (“bonephones”) that contact the mastoid process behind the ear, or a pair of Sony MDR-7506 circumaural headphones. Participants adjusted the slider position using the numeric pad on a computer keyboard (“4” to adjust left and “6” to adjust right). Each keypress shifted the slider a set distance from its previous position, such that there were 15 possible positions to each side of the center of the head. The slider began in the middle of the head on every trial.

All sound and interface software was run within Matlab in conjunction with the Psychophysics Toolbox on a Macintosh G5 with OS X. From the computer, sound was sent out through the sound card optically to an M-Audio SuperDAC 2496 digital-to-analog converter, and then to a Behringer HA4600 headphone amplifier, before the head or bonephones.

Procedure

Each trial was triggered by a space bar press, after which the head diagram with the slider appeared and the sound started playing. The trial ended after the slider was adjusted and submitted (with a “2” keypress on the numeric pad). The sound subsequently stopped and the trigger screen appeared again.

There were three frequencies, two pathways (air and bone), two ears (left and right), six stimulus values, and five observations per stimulus value, for a total of 360 trials per subject. Data were collapsed across ears since previous research has shown that data to be symmetrical (Yost & Hafter, 1987), so there were 10 observations per ILD across ears. The study took approximately one hour for each participant to complete.

Participants completed a randomized order of frequency blocks. Within each frequency block, the air pathway at each ear and stimulus value was always completed before moving on to the bone pathway. This was done based on the assumption that bone conduction may not yield the same degree of spatial separation that air conduction can. By completing the air pathway first, we avoided

unwanted order effects associated with completing the bone pathway before the air pathway. Based on the assumption that bone conduction could lead to less lateralization, we reasoned that if the bone pathway trials occurred first, the participant might scale their responses to the maximum lateralization, and then might discover that the air pathway had even more lateralization. In this case, the participant would have no way to indicate the increased amount of lateralization (i.e., the scale only went to 100%). Thus, the air pathway was run first. However, within each pathway run, the ear and stimulus value was randomized and repeated until 5 observations were obtained for each combination of ear and stimulus value.

RESULTS

Data were graphed in terms of percent lateralization, with 100 percent being all the way to one side of the head and 0 percent being in the center of the head. Median perceived lateralization was averaged across participants. Range was used as the measure of variability. The relationship between interaural level differences and perceived lateralization can be seen in Figure 2.

Figure 2 shows that for each frequency tested, the perceived lateralization was similar for headphones and bonephones. It also shows that the pattern of results were similar across frequencies tested. Also note that even with an ILD of 20 dB, the perceived lateralization was not typically much higher than 75 percent.

DISCUSSION

The similarity in ILD-lateralization functions between headphones and bonephones suggests that indeed ILDs can be invoked with bonephones, and that just as much lateralization can occur with bonephones as with headphones. Although the present data support the finding by Walker et al. (2005) that lateralization is possible with bonephones, the present data in fact suggest greater lateralization is possible than previously expected. There are numerous possible causes for differences in these results, including the complex auditory stimuli in Walker et al. (2005). A difference

between air and bone could also be concealed by a lack of testing more extreme interaural differences.

Previous research on air conduction alone (Yost & Hafter, 1987) has also shown a relationship between interaural differences and lateralization that levels off much earlier, whereas the current data do not seem to reach asymptote. This is likely due to the specification of the stimulus at the level of input rather than output. If this is true, then the curve may flatten out if given even greater differences in levels between the ears. Sensitivity to ILDs at the lower frequencies being similar to sensitivity to ILDs at higher frequencies was an unexpected finding, since interaural time differences (ITDs) are thought to dominate the perception of lateralization at lower frequencies. The present findings may be due to harmonics that occur after a pure tone is delivered through any apparatus.

One possible explanation for the high degree of lateralization with bonephones is sound leakage from the bone-conduction transducer, which could lead to a response based on air conduction in addition to bone conduction. This is quite unlikely, though, since ILDs were created by lowering the overall sound levels. It is important to note that this study can only provide information about spatial audio through bonephones (which may include some air conduction), and not necessarily spatial audio exclusively through the bone-conduction pathway. However, plugging the ears in Walker et al. (2005) made little difference in the performance with that spatial audio task, suggesting air conduction plays at most a minor role. Furthermore, it has been shown that listeners with middle and outer ear disorders (which inhibit or prevent hearing through air conduction) can detect lateralization (Kaga et al., 2001) via bone conduction alone.

Regardless of the mechanism at work, these data suggest that lateralization can be perceived with bonephones. This could allow spatial audio to be displayed without attenuating environmental sounds, which facilitates a unique combination of awareness of surroundings and access to spatialized auditory information. Greater awareness of surroundings could be useful for tasks using spatial audio such as segregating radio communications channels (Walker et al., 2005), or navigating the

environment with an auditory navigation system for visually-impaired people (Walker & Lindsay, 2006). In addition to providing evidence suggesting true spatial audio is possible with bonephones, the present research provides specific functions regarding how to implement this spatial audio. Specifically, it relates bonephones (and headphones) input to the resulting percept of lateralization. Thus, scalars corresponding to the decibels attenuation seen in Figure 2 can be applied to the output of a channel, to produce varying degrees of lateralization. This sort of scaling is much less computationally demanding than the implementation of spatial audio filters, and thus would be suitable for applications such as less expensive and older pc platforms, pc platforms that are running several other resource-intensive software applications, and PDAs.

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