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The effect of spatial auditory landmarks on ambulation

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ABSTRACT

The maintenance of balance and posture is a result of the collaborative efforts of vestibular, proprioceptive, and visual sensory inputs, but a fourth neural input, audition, may also improve balance. Here, we tested the hypothesis that auditory inputs function as environmental spatial landmarks whose effectiveness depends on sound localization ability during ambulation. Eight blindfolded normal young subjects performed the Fukuda-Unterberger test in three auditory conditions: silence, white noise played through headphones (head-referenced condition), and white noise played through a loudspeaker placed directly in front at 135 centimeters away from the ear at ear height (earth-referenced condition). For the earth-referenced condition, an additional experiment was performed where the effect of moving the speaker azimuthal position to 45, 90, 135, and 180° was tested. Subjects performed significantly better in the earth-referenced condition than in the head-referenced or silent conditions. Performance progressively decreased over the range from 0° to 135° but all subjects then improved slightly at the 180° compared to the 135° condition. These results suggest that presence of sound dramatically improves the ability to ambulate when vision is limited, but that sound sources must be located in the external environment in order to improve balance. This supports the hypothesis that they act by providing spatial landmarks against which head and body movement and orientation may be compared and corrected. Balance improvement in the azimuthal plane mirrors sensitivity to sound movement at similar positions, indicating that similar auditory mechanisms may underlie both processes. These results may help optimize the use of auditory cues to improve balance in particular patient populations.

1. Introduction

Visual, vestibular, and proprioceptive input are considered the critical sensory inputs for maintaining balance. Visual cues act as external, earth-referenced landmarks allowing the position and motion of the head in space to be measured, vestibular inputs provide internal, head-referenced signals indicating similar information, and the proprioceptive system binds the orientation of the body parts relative to each other, to the head, and to the surrounding supportive substrate. These cues are merged and compared to provide feedback during body motion, allowing corrective actions to be taken to maintain balance.

The possibility of a fourth important contributor to balance, auditory input, has by comparison been relatively ignored. A small but increasing body of evidence, however, indicates that the presence of an external auditory source or sources may also contribute to maintaining balance. An early study tested this hypothesis by examining static postural stability in a group of congenitally blind and sighted subjects [1]. They mounted two speakers, each located 5 cm lateral to the subject's ears. Standing on a force plate in the dark, their subjects showed less motion of the center of pressure in the presence of the sound cues compared to silence.

Further experiments have generally confirmed this finding, although not unanimously. In one study, static postural stability, as measured by the motion of a subject's center of pressure on a force plate, was greater in a silent audio booth than in a clinic room, although the conclusions were limited by somewhat inconsistent results [2]. A similar result was found in a group of older adults who were found to be more stable when wearing their hearing aids than without amplification [3]. However, another recent article found no difference in sway between subjects listening to music through headphones versus hearing ambient noise in an untreated room [4].

Maintaining static postural stability while standing requires monitoring and adjusting to the position and orientation of the body to minimize its movement in space. Preserving dynamic balance during

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ambulation adds complexity, because one must anticipate and compensate for the body's planned direction and amount of motion through space rather than simply minimizing it. Along these lines, a common clinical observation among patients with vestibular loss is that they may complain most about difficulty with navigating in a straight line and less about postural stability while standing still.

Given the promising findings in a static situation, it seems reasonable to hypothesize that auditory stimuli could also be important in optimizing the ability to ambulate. Earlier work has asked normal subjects to march in place in the dark either in silence or in the presence of an auditory cue (a nearby loudspeaker or metronome) [5,6]. Audition was found to improve the error in subject heading during ambulation, as measured by the degree to which each subject turned during the task [5,6].

However, the amount of improvement under various relevant auditory conditions, and the reason for this variability, is not fully explored. Knowing this would elucidate the fundamental mechanism for the benefit of auditory inputs, and guide the development of auditory environments or augmentative devices that might improve balance using auditory cues. In this study, we tested two hypotheses: first, that auditory stimuli function as spatial landmarks, analogous to elements of a visual scene, to improve balance and orientation during ambulation; and second, that specific characteristics of the sound source, such as its location relative to the subject, influences its ability to provide meaningful spatial cues.

2. Methods

This study was completed with the approval of the appropriate Institutional Review Board. Subjects were required to have normal hearing (defined as pure-tone average (PTA) of no less than 25 dB at 0.5, 1, and 2 kHz) and PTA in the worse ear of no less than 10 dB below the better ear's level (Model 10D, Beltone, Chicago, Illinois), have normal or corrected-to-normal vision on a standard Snellen chart, and speak English. Exclusion criteria were inability to complete the experiment, history of degenerative neurologic disease, stroke, or spinal stenosis, or current use of balance-altering medication. Eight people participated; 6 male and 2 female subjects (mean age = 21; age range = 18–26). No subject had worse than a 12 dB pure-tone average in the poorer ear.

Dynamic balance was assessed using the Fukuda-Unterberger stepping test [7]. Subjects were required to walk 50 steps in place, arms outstretched and shoulder-width apart with the eyes closed. The 0° azimuth was defined as the initial direction faced by the subjects, with the positive direction measured clockwise. All subjects wore a blindfold and shoes. Error in heading direction at the end of the test was measured using a goniometer.

Auditory input was provided by a speaker with a frequency response of 0.1–22 kHz (model R1, YC Cable, Ontario, CA) providing a broadband white noise stimulus that was generated by MATLAB (bandlimited over 0–4 kHz). The speaker was positioned at ear level, 185 cm from the center of the subject's head. The sound intensity was measured to be 65 dB SPL re 20 uPa. All testing was performed in a quiet carpeted conference room without additional soundproofing.

Subjects performed testing under a total of seven different conditions. The "silent" condition used no speaker and prevented subjects from gaining ambient auditory input by using noise-canceling ear plugs, (−32 dB NRR, Hearos Ear Plugs, Aliso Viejo, CA) and, in addition, commercial circumaural ear muffs (−30 dB NRR). The "head-referenced" condition presented white noise (bandlimited at 0–4 kHz and derived from the same sound file as used for the external speaker) through in-the-ear speakers (Philips, SHS3200/37) to provide an auditory experience that did not provide any spatial information. In the "earth-referenced" condition, the auditory source was placed directly in front of the patient (defined as 0° in the azimuthal plane). Subjects were instructed to adjust the volume of the in-the-ear speakers to match the volume of the external sound source subjectively. In a separate experiment, for the "earth-referenced" condition, results at 0° were compared to performance in four additional locations at 45, 90, 135, and 180° along a semicircle in the azimuthal plane from directly forward, to over the right shoulder, to behind the head (subjects were tested only on one side to reduce the duration of the experiment) (Fig. 1).

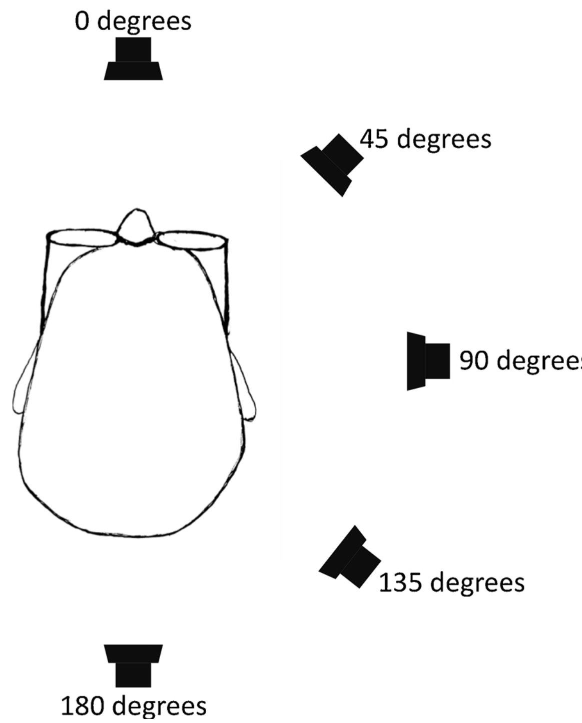

Fig. 1. Bird's eye view of the speaker locations.

Trial conditions were randomized. Each condition was repeated three times and the median value of the three trials was used in data analysis. After completion of each trial, subjects were guided away from their ending position in a large arc back to the starting point to prevent them from having any feedback on performance on the previous trial.

The independent variable for the first experiment was the auditory condition (silence, head-referenced, and earth-referenced) and for the second was the position of the sound source relative to the subject. The outcome was measured as the angular error, or absolute value of the difference in degrees between the starting orientation and the final orientation (the direction the subject was facing). Given the relatively small number of participants, a normal distribution could not be assumed and nonparametric statistics were required. These were performed using Friedman's test with Dunn's correction for multiple pairwise comparisons (GraphPad Prism 7.00).

3. Results

The comparison between the silent, head-referenced, and earth-referenced conditions was performed with the earth-referenced sound source at the 0° position. All subjects performed worse in the silent and head-referenced conditions than in the earth-referenced condition (Fig. 2). The mean angular deviation was 31.6° ± 11.5° in the silent condition, 28.7° ± 10.8° in the head-referenced condition, and 3.8° ± 3.1° in the 0° earth-referenced condition. The angular deviations in the silent and head-referenced conditions were not significantly different from each other ($p > 0.999$), but the angular deviations in both the silent and head-referenced conditions were significantly worse than the 0° earth-referenced condition ($p = 0.018$, and $p = 0.004$ respectively). These corresponded to a large effect size between the silent