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# Auditory perception of walls via spectral variations in the ambient sound field

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**Abstract** — Individuals with visual disabilities often use their hearing in order to maintain a line of travel parallel to walls, such as when walking down a hallway or along the side of a building. Previous studies established that this ability depends on the sense of hearing, but the specific acoustic information has not been investigated. The present paper describes a model of how sound pressure builds up within a meter or so in front of a wall, particularly in the low frequency end of the sound spectrum. This buildup of sound pressure is based on ambient or "background" sound, not self-produced sound such as footsteps. The model leads to a prediction that walls are detected by means of a spectral shift toward low frequencies. This prediction was tested in three experiments, in which sighted adults listened for such spectral shifts. In each experiment, a threshold value was obtained corresponding to the farthest simulated distance from a wall that could be detected. Threshold values were in good agreement with previous observations of the distance at which pedestrians can utilize acoustic information from walls. There was no evidence that simulated listener motion enhanced perception of walls. The model underlying these experiments implies that the term echolocation carries inappropriate connotations about the auditory processes that are involved in walking along walls. It is suggested that a more apt description is that pedestrians listen for spatial variations in the structure of the ambient sound field.

**Key words:** *auditory perception, blindness, orientation and mobility, profile analysis, psychoacoustics, space perception, spatial hearing, visual impairment.*

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## INTRODUCTION

Individuals who have visual impairments but intact audition utilize the sense of hearing in the course of many everyday activities. During the past few years, some investigators have reconsidered the role of hearing in orientation and mobility (O&M) tasks (1). Broadly speaking, auditory perception of spatial features of a person's surroundings can be considered in two categories. One involves the localization of sound-producing objects such as other people, automobiles, telephones, and the like. Ashmead et al. (2) reported that this kind of spatial hearing is not adversely affected by a developmental history of blindness; in fact, blindness was associated with a slight shift toward more acute spatial hearing. Thus, further O&M research on localization of sound-producing objects may be based on the assumption that persons with visual disabilities have good spatial hearing, but that more work is needed to explore the details of how audition plays a role in O&M tasks such as street crossing (3).

The second broad category of auditory space perception is the ability to detect and localize features of the surroundings that do not themselves produce sounds, such as walls, poles, street signs, and door openings. Carlson-Smith and Wiener (4) demonstrated that the human ability to perceive environmental features such as large obstacles and doorways is correlated with the auditory ability to detect fluctuations of amplitude and frequency in the low frequency range of hearing. In terms of theory, this is consistent with the idea that it is the buildup of sounds at low frequencies that we should examine with respect to many O&M tasks.

Within the O&M field, the ability to detect objects that do not make sounds is widely referred to by the term "echolocation." This terminology emphasizes the role of reflected sound in perception of objects and surfaces, and its popularity has been enhanced by demonstrations that some species of bats and marine mammals have sophisticated sonar-like abilities (5). Classic studies of "facial vision" or the "obstacle sense" in humans demonstrated conclusively that hearing is the necessary and sufficient sensory modality for perceiving walls and similar features (6). However, the nature of this auditory ability remains poorly understood.

Perhaps because of the association of the term echolocation with the process in which some species of bats and marine mammals engage to locate objects, it has been widely assumed that human echolocation involves high-frequency hearing. However, there is no evidence that humans can engage in such sonar-like processes, in terms of either the emission or temporal analysis of signals in the ultrahigh frequency range needed for effective echolocation. The echolocation abilities of bats (7) and dolphins (8) are astonishingly sophisticated, allowing bats to catch flying insects and dolphins to perceive the shapes of small objects at a distance. In comparison, the ability of humans to hear the features of silent objects is rather meager. We suggest that human echolocation is not a sonar-like process at all, but rather is based on perceiving variations in the ambient sound field as one moves about. In the present article, this claim is elaborated with respect to the task of using hearing to "shoreline" along the wall of a hallway or building.

Although the term echolocation is frequently associated with obstacle detection, the underlying auditory ability is also important for maintaining one's orientation with respect to stable architectural features such as walls. As a traveler walks down a hallway or along a building, it is possible to maintain a constant distance from the wall through the use of hearing. When shorelining in this manner, the wall is not so much an obstacle to be avoided as it is a useful feature for promoting safe, efficient travel. Strelow and Brabyn (9) reported that blind adults could walk a path parallel to a wall reasonably well, though not as accurately as sighted adults when the latter were allowed to use vision. Ashmead et al. (10) investigated the ability of children and teenagers with visual impairments to walk along hallways. By controlling the listening conditions and hallway widths, it was shown that good performance depended on the use of hearing and that the acoustic information was most useful approximately 1 m or less from the wall. One reason that participants in the latter study may have done somewhat better than those in the earlier study involves the difference between walking along a hallway versus a single wall. When walking along a single wall, a traveler may veer away from the wall and lose perceptual contact with it. Such strong veering is less likely in a hallway if the traveler begins to perceive one wall while veering away from the other. The findings from these studies are also consistent with a study by Guth[1], in which adults were asked to walk parallel to a wall, at several distances from it. Appropriate walking paths were maintained considerably longer when the path was closer to the wall (e.g., ~0.33 m as opposed to >1 m).

The usefulness of hearing for detecting large surfaces such as walls is based on different kinds of variations in the ambient sound field. For example, Bassett and Eastmond (11) described a pattern that arises when a broad-spectrum sound source is directed toward a wall (see also Bilsen and Ritsma, 12). The incident and reflected sound waves interact so as to produce a filtering effect that depends on distance from the wall. In such a situation, a listener moving toward the wall hears a low frequency, but rising pitch. This can be demonstrated easily by placing a radio, tuned to static, aimed toward a wall from about 3 m away, then walking toward the wall (note that the radio must remain in its original place). The acoustic conditions for this effect are probably rare in everyday travel situations, because the sound source must be aimed almost directly toward the wall and the listener must be moving along that direction. Nevertheless, the rising pitch as one moves toward a wall in this situation is a very compelling listening experience.

Another acoustical situation that allows perception of surfaces occurs when there are sound "shadows" or "bright spots" created within the overall sound field. A familiar example is the effect created by street signs and utility poles. As a pedestrian approaches such an object, if there is traffic noise coming from the far side of the object, then there is a sound shadow or hole in the ambient noise. If there is traffic noise from behind the pedestrian, then the object reflects sound, creating a bright spot. In these situations the acoustic information consists of rather strong variations in the amplitude and frequency of sound coming from a certain direction.

The acoustic scenario investigated here is based on another kind of variation in the ambient sound field, namely, the structure of the sound field in front of a wall when there is omnidirectional incident sound. The "omnidirectional" term simply means that there is general background sound but no particular, discrete source of sound. The particular model we are most concerned with was described by Kuttruff (13) as the acoustical structure in front of a wall when the sound incidence is from uniformly distributed directions. In an unbounded, omnidirectional sound field, the sound waves are free to move in all directions. A boundary constrains the motion of sound waves, creating a pattern of interactions that depends on two factors. These factors are the distance of the listener from the wall and the frequency of the sound wave. The sound pressure $p_x^2$ at a given distance $x$ from the wall is:

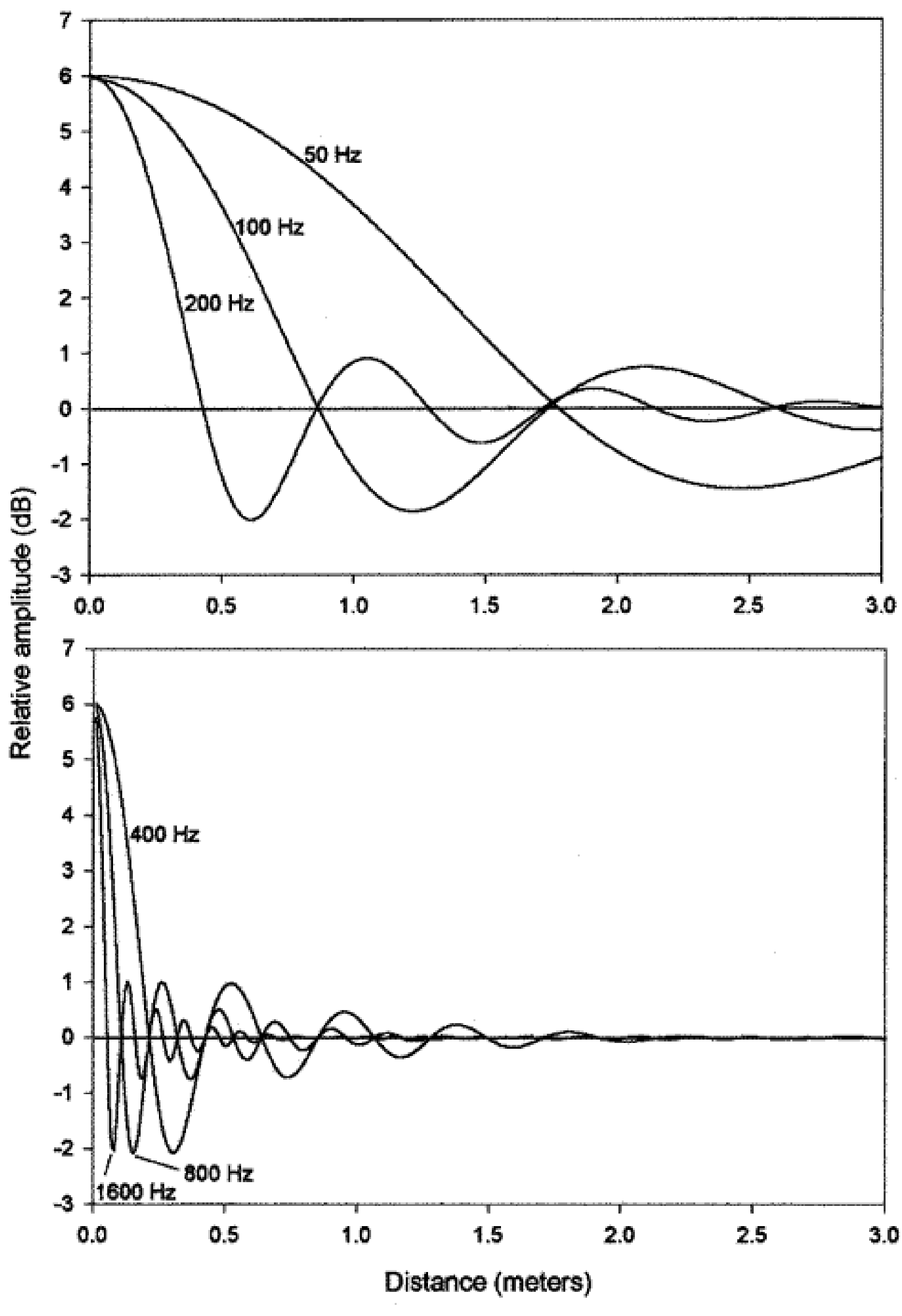
$$p_x^2 = 2p_{avg}^2 \left[1 + \frac{\sin(2kx)}{2kx}\right] \quad \textbf{[1]}$$

In this formula, $p_{avg}^2$ is the average sound pressure at a distance far away from the wall, and $k$ is two times pi divided by the wavelength of the sound ($k=\frac{2\pi}{\lambda}$). Wavelength is defined as $\lambda=\frac{c}{f}$ where $c$ is the speed of sound (e.g., 340 m/s) and $f$ is frequency in Hz. Therefore, another way of expressing $k$ is $k=\frac{2\pi f}{c}$. Using Formula 1, one can plot the sound pressure at a given frequency for different distances from the wall, relative to the average pressure at a location far away from the wall. As the distance $x$ from the wall increases ($x \rightarrow \infty$), the right side of the sound pressure equation approaches the average sound pressure level $2p_{avg}^2$. The ratio of sound pressures that is of interest is:

$$\frac{p_x^{2}}{p_{x\to+\infty}^{2}}=\frac{2p_{avg}^{2}\left[1+\frac{\sin(2kx)}{2kx}\right]}{2p_{avg}^{2}}=\left[1+\frac{\sin(2kx)}{2kx}\right]$$ **[1]**

This has an upper limit of 2, which occurs when the distance from the wall is very small (close to zero). At that point, the sound pressure is twice as high as the average pressure, which corresponds to a difference of approximately 6 dB in the decibel notation system typically used in studies of hearing ($20[\log_{10}(2)]=6.02$ dB).

The most important implications of this model are: 1) sound pressure at a given frequency is highest near the wall, decreasing with distance from the wall by a damped sine wave pattern; and 2) the rate of drop in sound pressure is frequency-dependent, so that from a practical perspective the buildup of sound near walls is more noticeable for low than for high frequencies. These implications are illustrated in **Figure 1.**



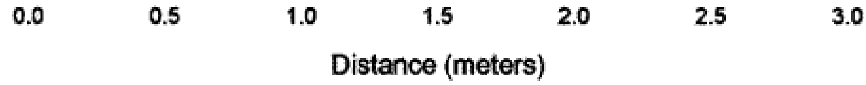



**Figure 1.** *Sound pressure variations as a function of distance from a wall, for critical frequency bands centered on, in the top panel: 50, 100, and 200 Hz; in the bottom panel: 400, 800, and 1600 Hz. Pressure was calculated from Equation 2 with summation across the critical band in 1-Hz steps. Critical bandwidths were estimated from a formula provided by Moore (14), with extrapolation for the 50 Hz center frequency, since there is little work on critical bands in the very low frequency range.*

Equations 1 and 2 are written with respect to a single frequency component, such as 100 Hz. However, the human auditory system groups sound frequencies in overlapping bins known as critical bands. Therefore, Equation 2 was modified for purposes of making **Figure 1,** by selecting a center frequency, such as 100 Hz, then aggregating across the critical band for that frequency (for 100 Hz, the critical band runs from about 82 to 118 Hz). The top panel shows how sound pressure changes across distance from the wall for three different center frequencies, 50, 100, and 200 Hz. For each frequency group, the pressure is at a maximum of about 6 dB closest to the wall, and pressure changes as a damped sine wave with increasing distance from the wall. Note that the final pressure buildup starts at about 1.75 m for the 50 Hz range, 0.9 m for the 100 Hz range, and 0.4 m for the 200 Hz range. Therefore, a traveler moving toward the wall would experience an increase in sound level that begins at low frequencies and spreads to higher frequencies. The bottom panel of **Figure 1** shows the scenario for three higher frequency ranges, centered on 400, 800, and 1600 Hz. For these frequencies, the pressure change occurs at such a close distance to the wall that the information is probably not very useful for guiding human locomotion or orientation.

A prediction from this model is that listeners detect a nearby wall because of an elevation of sound level in the low frequency range. In order to test this prediction, we presented listeners with sounds consisting of sinusoidal tonal components. The amplitude of each tonal component was set according to Equation 2, based on a certain simulated distance from the wall. On each trial, the listener heard two stimuli, one simulating a distance of 2 m from the wall and the other simulating a different (closer) distance from the wall. The order of the two stimuli was random, and the listener indicated which one was "closer" to the wall. **Figures 2a** and **b** illustrate the logic of the stimuli.

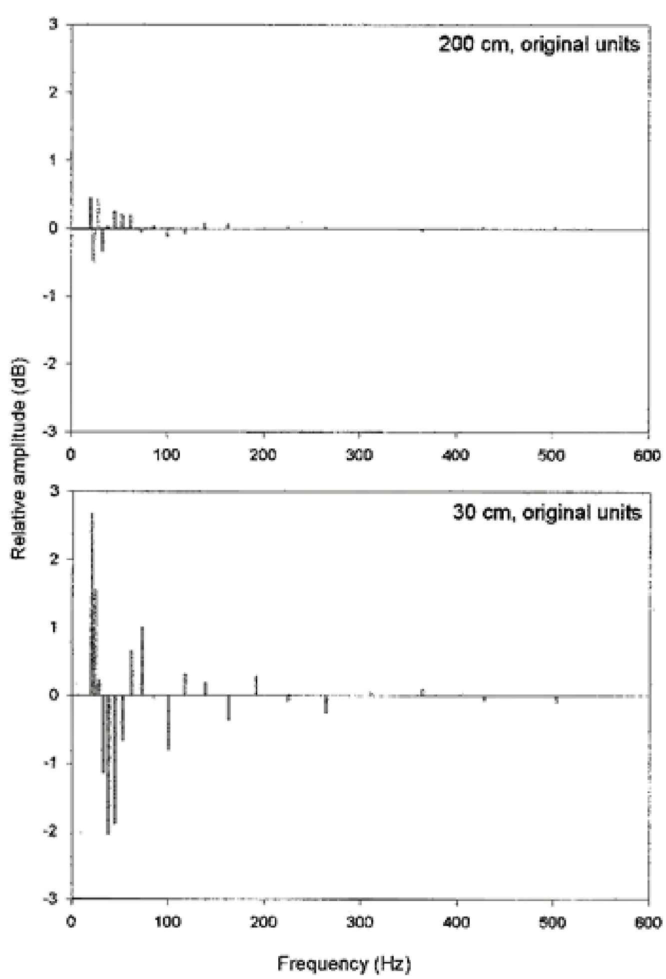



**Figure 2a.** *Examples of amplitude spectra relative to average amplitude level for the stimulus intervals representing "far" (200 cm) and "near" (in this case, 30 cm) positions. There are 21 frequency bins, in compounded multiples of 1.175 starting at 20 Hz and going to 503 Hz.*

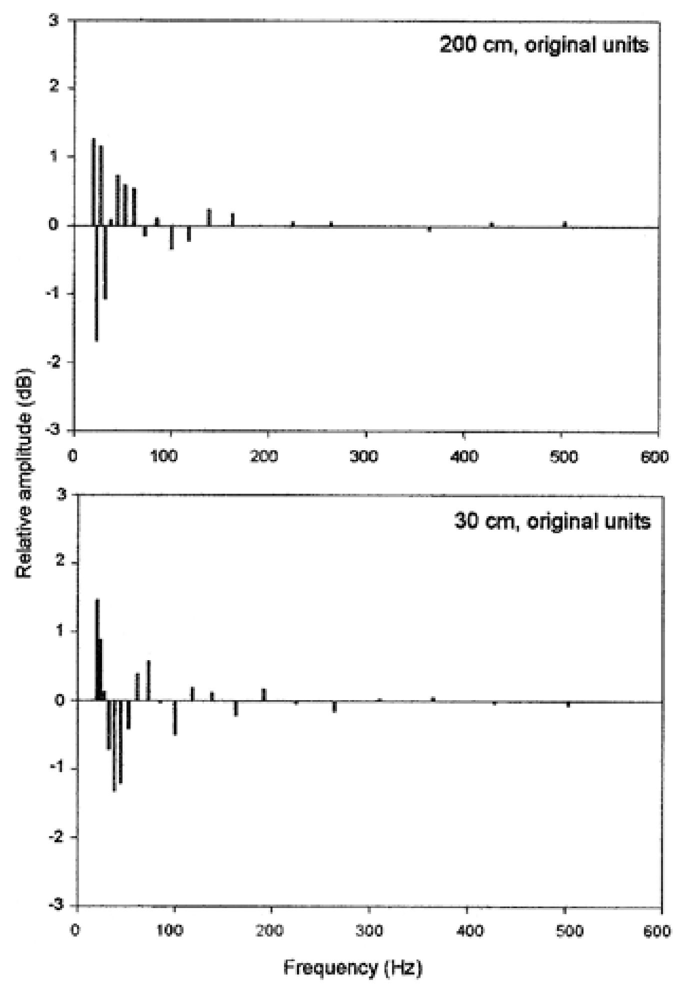



**Figure 2b.** *Examples of amplitude spectra normalized for equivalent overall amplitude for the same stimulus intervals presented in* ***Figure 2a.***

The top panel of **Figure 2a** describes the stimulus for the 200 cm distance, the bottom for a distance of 30 cm. In each case there were 21 tonal components, starting at 20 Hz and increasing by multiples of 1.175 up to 503 Hz. The amplitude for each tone was set according to Equation 2. In general, it was found that listeners could reliably discriminate between the 200 cm and 30 cm stimuli, so **Figure 2a** illustrates an amplitude difference that is "easy" to hear. It is obvious from the figure that a listener could distinguish between the two stimuli merely by listening at the lowest frequencies for which the stimulus seemed louder, or by listening for an overall level difference. However, we were interested primarily in whether listeners could distinguish between the stimuli on the basis of spectral differences. Therefore, the stimuli were normalized to the same average level prior to being presented, as shown in **Figure 2b.**

## METHODS

**Participants**

Three related experiments were conducted with sighted adults, aged 23 to 46 years, recruited from a university community. Each experiment had seven participants in a repeated measures design, with each experiment drawing from the same pool of nine participants. All participants had normal hearing on a pure-tone screening test.

**Apparatus and Procedure**

The sessions took place in a double-walled sound booth (Model 1202A, Industrial Acoustics Company, Bronx, NY) approximately 2 m on all three inside dimensions. Experimental control was by a Pentium 90 mHz computer interfaced with an audio system (Tucker-Davis Technologies, Gainesville, FL). For the first two experiments, sounds were presented through canal (insert) earphones (Model ER4, Etymotic Research, Elk Grove Village, IL); for the third experiment, circumaural earphones (Model TDH49P, Telephonics Corp., New York, NY) were employed. Participants pressed buttons on a response box to indicate their vote on each trial.

On each trial two stimuli were presented, one simulating the sound field at a distance of 2 m from a wall and the other simulating the sound field at a closer distance. Two m was chosen as the far distance because previous research (10) and casual observation indicated that at this distance a wall cannot generally be perceived. The order in which these intervals were presented was random from trial to trial. After both stimuli were presented, the participant pressed one of two buttons to indicate whether he or she thought the first or second interval contained the sound that was "closer to the wall." However, the listening experience was that of an intracranial sound image, not a nearby wall. Therefore, it was explained to participants that there is a change in tone color at very low frequencies as one approaches a wall. It was this difference in tone color for which participants were instructed to listen.

The stimuli were tonal complexes patterned after research on profile analysis, which is the study of sensitivity to changes in the shape of the frequency spectrum, or profile (15). The stimuli were created as digital signals and played at a sampling rate of 20 kHz with low-pass filtering (anti-aliasing) at 10 kHz. Each stimulus lasted 200 ms with cosine-squared rise/fall times of 10 ms, and there was a 1 s silent interval between the two stimuli presented during a trial. The tonal complex for each stimulus consisted of 21 superimposed sinusoidal frequency components, starting at 20 Hz and increasing by a compounded multiple of 1.175 to a top frequency of 503 Hz. For each stimulus presentation, every frequency component was assigned a random starting phase (therefore, even though the "far" stimulus was similar from trial to trial, it was not identical). The critical issue for the experiment was how the amplitudes of the frequency components were assigned. This was done according to the model of the way that sound pressure builds up near a wall, as described in Equations 1 and 2. Before being presented, the signals were normalized to the same average sound level, to prevent participants from listening for an overall level difference or an absolute level difference at a particular frequency.

The stimulus level was defined as the simulated distance from the wall, in cm units. This distance was initially set randomly in the range of 25 through 75 cm at multiples of 5 (25, 30, etc.). Across trials, the stimulus level varied according to a standard 2-down, 1-up adaptive staircase (16), with testing stopped after eight reversals. The step size was 10 cm through the first four reversals and 5 cm thereafter. Threshold was defined as the mean of the last six reversal points. Three thresholds were obtained for each experimental condition, and the data used for statistical analyses were each subject's mean of the three thresholds in each condition. In all experiments, each participant was tested using a different random order of experimental conditions.

## RESULTS

**Experiment 1**

This experiment was designed to obtain basic findings on threshold values, and to assess whether simulated motion toward a wall affects thresholds. Motion was simulated by calculating the sound as though the listener were moving a distance of 20 cm toward the wall during the 200 ms stimulus period, starting from the nominal distance. For example, if the nominal distance was 50 cm, then the distance that was simulated began at 50 cm and moved to 30 cm from the wall. Since the final distance to the wall was smaller than the nominal distance, there was a confound between motion and closest point of approach, a confound addressed in Experiment 2. Given the total motion of 20 cm during a 0.2 s time period, the rate of motion corresponded to a moderate pace of 1.0 m/s toward the wall. Thus, one independent variable in Experiment 1 was whether there was simulated motion or not.

Two additional independent variables were introduced for control purposes. Recall that stimuli were normalized in amplitude in order to prevent participants from solving the task by listening for overall level differences. To take this control a step further, the overall amplitude could be "roved" or not. Roving was accomplished by scaling the signal down from its normal level by a random z-score times 8 dB. For threshold runs when the rove was in effect, the two sound intervals were roved independently. The other independent variable introduced for control purposes was spectral "jitter." This was defined as variability in the amplitudes of the individual tonal components. **Figure 2a** shows the theoretical amplitude profiles for two distances from the wall. If jitter was in effect, the amplitude of each individual tonal component was modified by a random factor (2 dB times a random z-score). The comparison of thresholds obtained with and without jitter indicates whether listeners could tolerate a modest amount of random fluctuation in the spectral profiles. In summary, Experiment 1 had three independent variables: motion (stationary vs. moving), amplitude rove (on or off), and spectral jitter (on or off). These were fully crossed in a repeated measures design, resulting in eight experimental conditions. Each subject was tested on three thresholds in each condition.

**Figure 3** summarizes the results of Experiment 1. The grand mean across all conditions was 48 cm, indicating that the spectral information corresponding to fluctuation of sound pressure near a wall could be picked up at a distance of approximately one-half meter from the wall. In an analysis of variance there were significant main effects of rove ($F(1,6)=6.634$) and jitter ($F(1,6)=18.591$). These effects were expected, but were not of strong interest since these independent variables were introduced as control factors. On average, thresholds were better when sounds were not roved in overall amplitude ($M$=50.9 cm) than when they were roved ($M$=45.1 cm). Also, thresholds were better when the spectral components were not jittered ($M$=54.6 cm) than when they were jittered ($M$=41.4 cm). Despite the fact that thresholds for the moving conditions were consistently higher (i.e., "better") than for the corresponding stationary conditions, the main effect of motion was not significant ($F(1,6)=2.937$, $p<0.137$). There were no significant interactions among the variables. In summary, the principal finding from Experiment 1 was that listeners could use spectral information corresponding to the presence of a wall at a distance of about one-half meter.

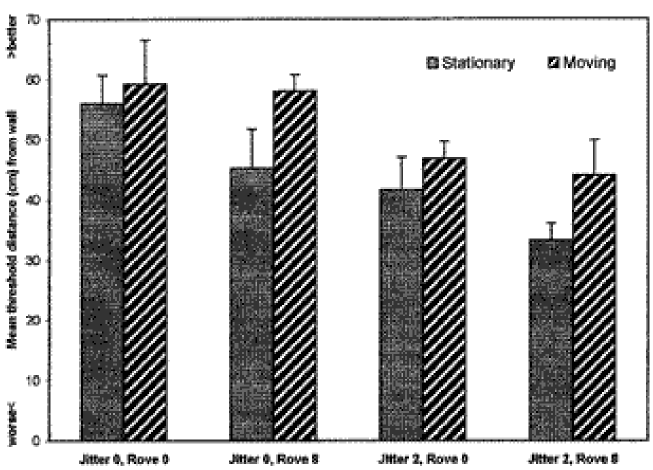



**Figure 3.** *Thresholds from Experiment 1, for simulated distance from a wall at which a sound could be identified as closer to the wall than a comparison sound at a distance of 2 m. Higher thresholds are "better" in the sense that the wall could be perceived from a greater distance away. The numbers for jitter and rove are standard deviations (in decibels) that were used to apply variability to the sounds, as described in the text. Error bars show +1 standard error.*

**Experiment 2**

Experiment 2 was performed to follow up on the role of motion in perceiving the spectral variations that specify a nearby wall. Since the motion effect was not statistically significant in Experiment 1 but was of considerable interest, Experiment 2 provided a chance to test the effect again. Also, recall that Experiment 1 contained a confound in the comparison of moving versus stationary conditions. In that experiment, the moving condition had the simulated listening distance start at the nominal distance and move toward the wall. Thus, any advantage shown in the moving condition could be attributed to the fact that the final listening distance was actually closer to the wall than the nominal (starting) distance. To control for this, Experiment 2 had two versions of the moving condition, a "moving/close" in which the distance began at the nominal distance and moved 20 cm closer to the wall (as in Experiment 1), and a "moving/far" condition in which the distance began 20 cm farther from the wall than the nominal distance and moved up to the nominal distance. Experiment 2 also contained a stationary condition. In Experiment 2, all sessions were run with an amplitude rove having an 8 dB standard deviation, but with no spectral jitter. Each participant was tested on three threshold runs for each of the three conditions (moving/close, moving/far, stationary).

The findings from Experiment 2 are illustrated in **Figure 4.** The overall mean threshold was 59 cm, which is consistent with the finding from Experiment 1 that the spectral information for a wall is detectable about one-half meter from the wall. In an analysis of variance there was not a significant effect of movement condition ($F(2,12)=2.452$, $p<0.128$). Planned comparisons showed a significant difference between the two movement conditions($F(1,6)=6.212$) but not between the stationary condition and either of the movement conditions. These findings suggest that the motion-related changes in spectral information are not helpful. Instead, thresholds seem to be affected most by how close the simulated distance is to the wall.

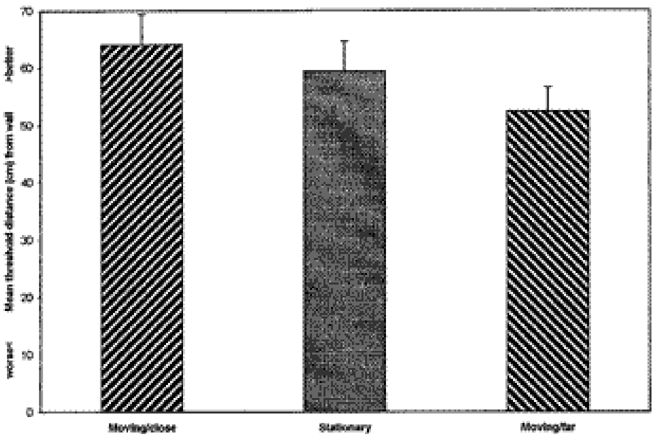



**Figure 4.** *Thresholds from Experiment 2, for simulated distance from a wall at which a sound could be identified as closer to the wall than a comparison sound at a distance of 2 m. The bar shading patterns for the Moving/close and Stationary conditions correspond to the Moving and Stationary conditions, respectively, for Experiment 1 as shown in* ***Figure 3.*** *Error bars show +1 standard error.*

**Experiment 3**

In a study of the way in which children with visual impairments used their hearing to navigate along hallways, Ashmead et al. reported that comparison of the information arriving at the two ears seemed to enhance performance (10). Children walked straighter, more efficient routes when able to listen with both ears than when one ear was occluded. Also, a sudden widening of the hallway on one side led to veering toward the widened side, presumably reflecting a tendency to equalize the ambient noise levels in the two ears. These findings suggested that binaural analysis may contribute to locomotor guidance along walls. This would make sense theoretically, because the binaural system is exquisitely sensitive to small between-ear variations in acoustic signals. The focus of Experiment 3 was to determine whether perception of the spectral information about a wall was affected by whether the signals to the two ears were different (dichotic) or the same (diotic). In the dichotic condition, for the sound interval simulating a close distance to the wall, one ear received a signal consistent with that close distance while the other ear received a signal corresponding to the far (2 m) distance. In the diotic condition both ears received an identical signal corresponding to the close distance. In addition to the dichotic versus diotic comparison, Experiment 3 included the moving versus stationary comparison (using the moving/close version of the moving stimuli). An amplitude rove was included with a standard deviation of 8 dB. As in Experiment 2, the amplitude spectrum was not jittered.

The findings from Experiment 3 are summarized in **Figure 5.** The mean threshold across all four conditions was 34 cm. In an analysis of variance neither main effect was significant, but the interaction between stimulus mode (diotic versus dichotic) and motion (moving versus stationary) was significant ($F(1,6)=8.596$). Simple effects analyses indicated that the difference between stationary and moving conditions was significant in the dichotic mode ($F(1,6)=16.069$) but not in the diotic mode. In the dichotic mode, thresholds were actually better for the stationary condition than for the moving condition. This pattern of findings suggests that patterns of spectral change across time due to self-motion are not useful and may be disruptive. As for the comparison of dichotic vs. diotic listening, the most straightforward test is the simple effect within the stationary condition. As **Figure 5** shows, mean thresholds were higher (better) for the dichotic condition, where each ear received a different signal, than for the diotic condition. However, this difference did not quite meet the 0.05 significance criterion ($F(1,6)=4.615$, $p<0.075$). Although the direction and size of the difference between dichotic and diotic listening warrants further attention, there is not strong support from the present findings for the idea that binaural comparison is important for auditory perception of nearby walls.

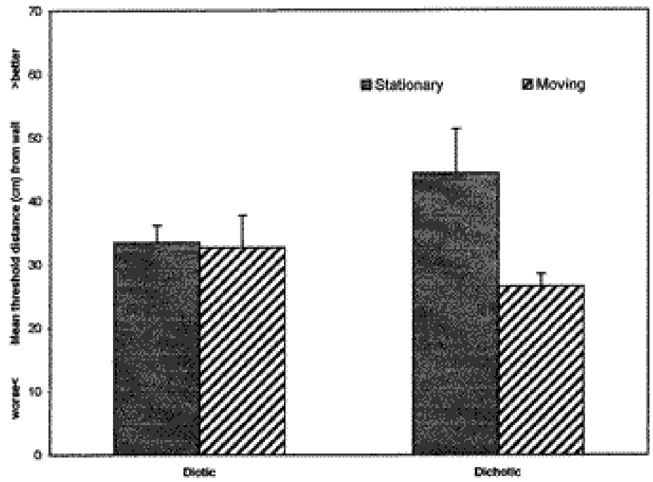



**Figure 5.** *Thresholds from Experiment 3, for simulated distance from a wall at which a sound could be identified as closer to the wall than a comparison sound at a distance of 2 m. As described in the text, diotic listening has the same input to both ears, whereas dichotic listening has different input to the two ears. Error bars show +1 standard error.*

## DISCUSSION

In this study of the simulated distance at which listeners can detect the spectral information specifying a wall, the mean thresholds were 48, 59, and 34 cm for Experiments 1, 2, and 3 respectively. Averaging across experiments the threshold was about 47 cm. Thus, spectral information appears to be useful in a range of one-half meter or less from the wall. This finding is consistent with observations from other studies in which locomotor performance was measured as travelers walked along walls. Ashmead et al. asked blind children to walk along artificial hallways varying in width between 1.5, 2, and 3 m (10). Walking paths were straighter and more parallel to the walls in the two narrower hallways than in the 3-m hallway. When the hallway was 1.5 or 2 m, even a slight veer brought the closer ear to within a half-meter or so of a wall, and the children usually made smooth, uninterrupted corrections to the direction of travel. In contrast, the 3-m hallway allowed considerably more veering before a wall was close enough to be perceived. Another study by Guth[1] is also consistent with the finding that useful information about a wall occurs within a half-meter distance. In that study, blind adults attempted to walk paths parallel to a wall, when positioned at various starting distances from the wall. At a close distance of about one-third meter, performance was very good, but when the distance was more than one meter from the wall there was much more veering. The only other relevant study we are aware of is that of Strelow and Brabyn (9), who had blind and sighted adults walk along a fiberboard wall. However, the published report did not provide an indication of how performance might have varied depending on distance from the wall.

The effective acoustic information for perceiving a nearby wall appears to be a change in the sound spectrum, generally a shift toward more emphasis in the low frequency range. This is to be contrasted with a simpler overall change in sound level within one or more frequency bands. The findings are consistent with the literature on profile analysis (15) in that listeners can respond to changes in the *relative* amplitudes of different frequency components. In the present study, the focus was placed on relative amplitude by the following procedural controls: a) signals corresponding to the closer and farther distances on each trial were scaled to the same average amplitude after their spectra were set; b) overall signal amplitude was then roved on a random basis for each stimulus; and c) in Experiment 1, adding a random jitter to the frequency spectra had a strong deleterious effect on thresholds. The practical implication of this emphasis on spectral change is that perceiving the presence of a nearby wall is based on a spectral shift toward the low frequency region, and not necessarily on an overall increase in sound level.

Considerable effort was made in these experiments to test whether simulation of motion toward a wall would enhance the ability to detect the wall. This effort was made because research on other topics such as auditory distance perception indicates a beneficial effect of dynamic, motion-related information (17,18). In the present study, we thought that listeners might use changes in spectral patterns to discern whether the distance to the wall was close or far. Although the pattern of comparisons between moving and stationary conditions varied across experiments, there was clearly no advantage due to motion. This finding must be reconciled with the fact that as blind travelers walk along walls, they are able to make smooth adjustments based on hearing so as to keep on a parallel course. Perhaps there is a fairly narrow boundary between the distance at which a wall can be perceived readily and the distance beyond which it cannot be perceived at all. If this boundary were less than 30 cm (one foot) or so, then an effective strategy might be to stay on a travel path that keeps crossing back and forth across the distance at which the wall is just perceptible.

The finding that there was no advantage due to motion is consistent with a study by Green and Nguyen (19). Using a profile analysis task, they reported that dynamic amplitude changes in the targeted frequencies of a spectral change did not enhance the salience of the spectral change. In fact, thresholds were somewhat worse for the dynamic condition than for a non-dynamic change. Thus, it appears that the lack of a benefit of simulated listener motion found in the present study is attributable to a general inability of the auditory system to utilize dynamic spectral changes.

In Experiment 3 the usefulness of diotic versus dichotic listening was compared. We were interested in this because locomotion along walls typically means that one ear is closer to a wall than the other. A simple demonstration suggests that there is an advantage of being able to make a binaural comparison. The demonstration consists of approaching a wall while facing in different directions. In informal tests, many people report that they can "pick up" the wall from farther away if they turn their heads sideways to the wall than if they face directly toward or away from the wall. With the head turned sideways, the two ears presumably get much different signals from one another, compared to when the head is faced toward or away from the wall. Experiment 3 provided some suggestive evidence that it helps for the ears to have different signals, but further work on this topic is needed.

A comment on the term echolocation is in order. This term has been widely adopted in the O&M field to refer to a variety of ways in which hearing is used for space perception and mobility. There are doubtless some situations in which self-produced, reflected sounds are used (e.g., "sizing up" a room by snapping one's fingers). Nevertheless, we think that most of the ways in which spatial hearing is used for O&M tasks depend on auditory processing that is not well described by the term echolocation. The specific scenario on which we have focused is the way that walls cause changes in the ambient sound field. This does not require sound-making on the part of the traveler; in fact, such sounds might interfere with listening for the subtle variations in the sound field. We suggest that the term echolocation be reserved for those situations in which it is clear that discrete, reflected sounds are being utilized. For other listening situations it will probably do more to advance theory and research if we use more generic terms such as spatial hearing or sound localization.

In summary, the principal conclusion from this set of studies is that auditory perception of nearby walls is mediated by variations in the spectral composition of the ambient sound field. An acoustical model was described to show how the sound spectrum shifts toward low frequencies in the vicinity of a wall. Threshold measures indicate that listeners can detect these spectral changes at a distance of about one-half meter, which is consistent with observations of blind children and adults as they walk along walls. A practical implication is that O&M instructors may encourage clients to expect the acoustic information to occur very near the wall, in the background sound, and at low frequencies.

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