

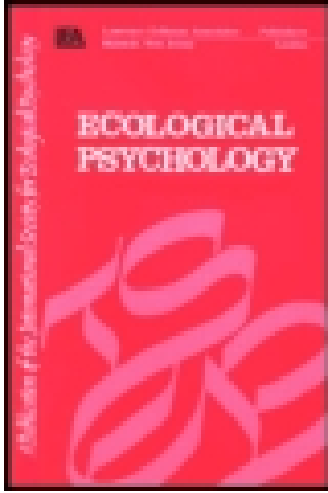
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Human Echolocation as a Basic Form of Perception and Action

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In this article we discuss known and possible uses of echolocation by humans. We argue that echolocation may be a basic perception-action ability of humans. We review studies which suggest that both blind and sighted humans are capable of substantial precision in the perception of properties of distal objects, such as distance, size, shape, substance, and relative motion. We analyze relations between acoustic pulse and echo that may provide information to support these percepts and others. Our analysis predicts echolocation-based sensitivity in humans and other animals to a number of properties of the animal-environment interaction. We also discuss echolocation-based acoustic specification of time-to-contact. We develop a new variable that provides this information and discuss "acoustic τ s" recently developed by Shaw, McGowan, and Turvey (1991) and by Lee, van der Weel, Hitchcock, Matejowsky, and Pettigrew (1992). Our analysis suggests that there may be important insights to be gained from an ecological study of echolocation in humans and other species. We end with suggestions for research derived from our analysis.

Through most of its history, the study of audition has been carried out within the context of inferential theories of perception (for recent examples, see Blauert, 1983; Handel, 1989; cf. Heine & Guski, 1991). More recently, ecological analyses of audition have begun to appear (Gaver, 1993a, 1993b; Gibson, 1966; Guski, 1992; Jenkins, 1985; Lee, 1990; Rosenblum, Carello, & Pastore, 1987; Shaw, McGowan, & Turvey, 1991; Warren & Verbrugge, 1984). Both traditional and ecological treatments have concentrated on sounds reaching the ears directly from their source and on vibratory events not under control of the

observer (Gibson, 1966, included a detailed discussion of the perception of self-generated sound, but dealt almost exclusively with speech). For instance, Gaver (1993a, 1993b) confined his analysis to the perception of "sound producing events," as did Guski (1992). Yet it is clear that in their everyday lives, people frequently produce sounds to make available information that supports perception and action. For example, carpenters knock on sheet rock to locate studs, physicians use percussion of the abdomen to assess the state of various organs, gardeners test clay pots for cracks by tapping on them, and so forth.¹ Although it is easy to think of such examples, little systematic research has been conducted. In most studies on audition, participants are not permitted to generate sounds, or the sounds they generate are held to be irrelevant to the percept under study (Guski, 1990; Mershon, Ballenger, Little, McMurtry, & Buchanan, 1989; Rosenblum, et al., 1987; Warren & Verbrugge, 1984). This is true also in studies of haptic perception, in which many participants generate sound (e.g., Barac-Cikoja & Turvey, 1991; Burton, 1992; Chan & Turvey, 1991). Thus, we have little knowledge of how often perceiver-generated sounds are used, how accurately they support perception and guide action (for examples, see Cabe & Pittenger, 1990; Okura, 1995; Pittenger, Guski, & Heine, 1994; and Seidel, Ball, Dains, & Benedict, 1991), or of just what patterns carry the relevant information.

In this article, we discuss what we take to be an especially common and important example of perception using sounds produced by the perceiver. This is the obtaining of information about the animal-environment system from relations between a *pulse*, a perceiver-generated wavefront coming directly to the perceiver's ear from its source, and its *echo*, that same sound arriving at the ear after reflection from the object or surface. Echolocation is most widely known as an ability of bats (*Chiroptera*). The focus on bats has tended to obscure the fact that echolocation is found in a wide variety of species across phyla. In addition to bats, echolocation has been demonstrated in dolphins (*Tursiops*) and in some other marine mammals, in species of birds that roost and nest in caves such as oilbirds (*Steatornis caripensis*) and the Himalayan cave swiftlet (*Collocalia brevirostris*), and in shrews (*Sorex*, *Blarina*) and terrestrial tenrecs (*Tenrecidae*) (McFarland, 1987). It has also been demonstrated in humans, in which it may be far more common than generally is supposed.

As with the eyes and stereopsis, certain informative relations are fundamentally unavailable to a single ear. Research with binaural sound localization has revealed that the two ears must be considered as parts of a single perceptual system: Instead of independent sound waves separately stimulating each ear, there is "one relational stimulus for one system" (Heine & Guski, 1991, p. 264).

¹The percussive events in these examples produce mechanical as well as acoustic stimulation (and may structure the optic array, as well). We do not assume that the purpose of such actions is solely to make information available in the acoustic array: The resulting percepts may be multimodal or intermodal.

Thus, the study of audition has been freed in space. However, it has not yet been freed in time. It is our contention that outgoing (self-generated) and returning sound waves should also be considered as a single relational stimulus. For perceptual systems, the speed of light is effectively infinite but the speed of sound is finite. It can take a detectable amount of time for an acoustic wave form to reach the ears. For sounds originating outside the self and traveling only directly to the ears, this time element is irrelevant: The acoustic array provides no information about when the sound began its journey, and so it provides no information about how long it took to reach the perceiver (this is independent of time-of-arrival differences for the two ears, which are used in localizing sound sources but provide no information about distance to a sound source).² But if there is any reflection and (especially) if the sound is generated by activity of the observer, the time element can provide rich information. The natural availability of this information and its potential utility for behavior suggest that the perceptual systems should have evolved to exploit it. Yet the theoretical literature on human echolocation is scanty. Jenkins (1985, pp. 126–129) discussed echolocation but touched only briefly on the possible use of this technique by humans: In his final summary (pp. 134–135) echolocation is not mentioned. Similarly, Lee (1990) discussed the echolocatory abilities of bats but made no direct assertion that echolocation might be of use to humans.

One reason for the lack of attention to echoes is that most of us are rarely aware of them in our daily lives. This may be because echoes have much less intensity than do outgoing sounds. It may also stem from the fact that in most circumstances, the delay between outgoing and returning sound waves is very brief—on the order of milliseconds. Typically, echoes enter consciousness only when they are relatively loud and when the delay between outgoing and returning waves is very large as it is at the Grand Canyon or in a cathedral. Our lack of awareness of reflected sound seems to have lead some researchers to conclude that people have little sensitivity to echoes and whatever information they contain (Schenkman & Jansson, 1986). However, conscious awareness is not a prerequisite for the pick-up of some kinds of information that are critical to the success of ordinary behavior such as the maintenance of postural stability relative to the visible surround (Stoffregen, 1986). Crucially, this means that we may engage in echolocation on a regular basis without having any conscious awareness that we are doing so. It also means that the extent to which humans are sensitive to information in echoes may depend on tests of perception and action rather than on tests of perception and conscious report (cf. Guski, 1990). There has been no sustained program of perception–action research on human perception via echolocation.

²This is true only if we consider acoustic structure independent of structure in other forms of energy. Relations between patterns in acoustic and other forms of energy are discussed in a later section.

In this article, we discuss existing research on echolocation. Although our focus is on humans, we frequently refer to echolocation in bats and marine mammals. The literature on these nonhumans is voluminous and sophisticated. Accordingly, it is not our purpose to review all that is known about information made available in echolocation (for a recent review of the literature on bats, see Simmons, 1989). Similarly, we do not attempt to review the complex physics of sounds, echoes, and so forth (for reviews, see Busnel & Fish, 1980; Camhi, 1984). Our goals are to discuss sources of information that may underlie known human echolocatory sensitivity, to present some higher order variables, unknown in the traditional echolocation literature that may make information available to humans and to other species, and to focus the attention of experimenters on the study of echolocation in humans.

RESEARCH ON ECHOLOCATION IN HUMANS

Research on the use of self-generated sounds by humans has concentrated on the blind. Many of these studies are descriptive rather than experimental (e.g., Passini, Dupre, & Langlois, 1986). Experimental studies have sometimes shown mixed results. For example, Schenkman and Jansson (1986) tested the ability of blind participants to perceive and negotiate path obstacles through acoustic stimulation generated by the tapping of handheld canes. Performance was mediocre, with many collisions. However, the obstacles were squares of flat cardboard, which may be unusually difficult to detect via reflected sound. In addition, participants were required to use only sounds generated by the cane. One participant was eliminated because she generated additional sound beyond the cane tapping (the nature of the additional sounds was not reported). The elimination was proper given that the topic of the study was echolocation with canes. However, it is noteworthy that the performance of the eliminated participant was much better than those who limited their sound generation to cane tapping. This suggests that human echolocation may be more refined than the data of Schenkman and Jansson imply. In fact, most other studies of human echolocation have found significant and robust performance.

The earliest studies of human echolocation were carried out by Dallenbach (Ammons, Worchel, & Dallenbach, 1953; Supa, Cotzin, & Dallenbach, 1944). These studies would be considered informal by contemporary standards, but remain valuable for the breadth of conditions they encompass. Participants were instructed to walk toward a target (a masonite board 122 × 147 cm, which was absent on some trials) and to stop when they first perceived its presence (and again when they felt that they were as close to it as they could come without a collision). In these studies, participants were prohibited from vocalizing or making sound manually. Instead, they were permitted to make as much noise as

they wished in walking, scuffing heels on the ground, shuffling, and so on. The experiments of Supa et al. (1944) were conducted indoors; both sighted and blind participants took part. In some conditions, participants wore shoes (presumably, in 1944 they were hard soled) and walked on a hardwood floor; in others, they walked in stocking feet on soft carpet. In the former condition, the target could be detected at distances of up to 5 m; in the latter, the maximum distance was about 3 m. Performance was better for blind participants.

The experiments of Ammons et al. (1953) were conducted outdoors in a large, open quadrangle, using only sighted participants. Participants were blindfolded, wore shoes, and walked on concrete. Some of the experiments of Supa et al. (1944) were replicated. In the outdoor setting, there was considerable uncontrolled ambient noise (commonly 60 to 70 dB), including the sound of pneumatic hammers at a nearby construction site. Under this condition, performance was reduced; the maximum distance from which the object was detectable was about 2 m. On trials in which participants wore earplugs (producing a hearing loss of 30–50 dB), performance dropped dramatically—many more false positives and collisions with the object occurred. The earplugs did not eliminate hearing completely: Participants were still sometimes able to hear their own footfalls, for instance (Ammons et al., p. 523). This may account for the accuracy that was observed in this condition.

Kellogg (1962) studied both sighted and blind participants in a laboratory setting. Participants were instructed to make “any sounds they wanted” (p. 401). They used both vocal (e.g., tongue-clicking or speaking) and manual (finger-snapping) techniques. Kellogg also reported that each of the blind participants engaged in exploratory head movements (rotation around the vertical axis) while listening. Sighted participants rarely made exploratory head movements that were visible to the experimenters. Kellogg suggested that the head movements varied the intensity and phase differences of the echoes reaching the ears. Performance of sighted participants was poor, but blind participants were able to discriminate objects of different distances, sizes, and substances.

The most extensive program of research on human echolocation was conducted by Rice (1967, 1969; Rice & Feinstein, 1965; Rice, Feinstein, & Schusterman, 1965), who tested both blind and sighted participants. Participants were instructed to make any oral sound they wished and were given an opportunity to try out different sounds before selecting a preferred sound for use in experimental conditions. Most participants chose either a long hissing sound or a punctate tongue click. Targets were present in half of the trials; participants indicated when they believed the target to be present. Accuracy varied with distance but was remarkably good. At a distance of 2.75 m, targets about 20 cm in diameter were discriminated more than 60% of the time. When targets were 0.6 m distant, this level of accuracy was reached for targets that were only 5 cm in diameter. This is close to the theoretical limit for the production of robust

echoes using frequencies within the range of human hearing (Rice, 1967).³ Participants also manifested accurate spatial localization (in azimuths) of silent objects and discrimination of objects having the same surface area but different shapes. Rice (1965) also noted the use of lateral head movements.

These studies suggest that blind and sighted humans have considerable sensitivity to information made available via echolocation. This ability seems to persist to some extent whether the self-generated sound is produced by the vocal tract (Kellogg, 1962; Rice, 1967) or by the extremities (Ammons, et al., 1953; Kellogg, 1962; Supa, et al., 1944). The reported phenomena might seem to provide strong motivation for perception-action research within the context of the ecological approach. To date this has not occurred. The existing research, often inappropriate for assessment of perception-action coupling, has received only modest empirical follow up (e.g., Boehm, 1986; Hausfeld, Power, Gorta, & Harris, 1982; Strelow & Brabyn, 1982) and none from an ecological perspective. There has been no direct replication and no extension. Equally important, there has been no detailed analysis of the information that supports observed perceptual sensitivity (e.g., Strelow & Brabyn, 1982) and no study of the use of exploratory head movements in human echolocation. Given our extensive knowledge of the information underlying echolocation in nonhumans (e.g., Simmons, 1989), this lack is puzzling and unnecessary and should be remedied.

Most of the studies employed passive psychophysical methods. We are not aware of any modern research on human echolocation in the context of perception-action tasks other than the very general studies of locomotion just cited. Measured perceptual accuracy often is dramatically greater when perception is employed in the service of action: Compare estimates of time-to-contact (e.g., Schiff & Oldak, 1990) with the control of interceptive action (e.g., Bootsma & van Wieringen, 1990). The extraordinary echolocation skills of bats and dolphins (some of which will be discussed shortly) generally have been demonstrated in the context of perception-action couplings. This suggests that human echolocation sensitivity may be considerably greater than has been suggested by previous research.

SELF-GENERATED INFORMATION IN ACOUSTIC ARRAYS

Animals generate sound. Except for occasions of stealth, the motion of animals is rarely silent. In addition to vocalizations, many bodily movements produce

³Waves (whether mechanical or electromagnetic) reflect poorly off surfaces that are smaller than the length of the waves (Camhi, 1984). For echolocation, this means that the higher the frequency, the smaller the object that can be detected. Humans generally are not sensitive to frequencies above 20 kHz, for which the theoretical limit of detectable object size would be about 2.0 cm. The limit for most bats would be about 3 mm.

sound. The most relevant example is footfalls, which produce a regular series of sound pulses (Supa et al., 1944). The sound that we generate travels to our ears. Usually, it arrives at the ears twice. It travels to the ears directly from the source (the vocal tract, the feet, etc.) and it arrives again after reflecting off surfaces in the environment. Aspects of the relation between the pulses (sound going directly to the ears) and echo (sound reflected to the ears) are related to various physical facts about the perceiver's relation to the environment. This information is known to be used with great precision in echolocation by bats (Griffin, 1958). The nature of this information, that is, the particular relations between pulse and echo that are uniquely related to properties of the animal-environment interaction, is often quite complex, involving interactions between temporal, magnitude, and frequency components of pulse and echo (see Busnel & Fish, 1980; Simmons, 1989).

Information for Distance in Pulse-to-Echo Delay

Echolocating bats get much of their information from the pulse-to-echo delay. The pulse reaches the ears after traveling directly from the bat's vocal tract—a very brief trip. The echo reaches the ears after traveling to and reflecting from distal surfaces. The speed of sound through the air is relatively constant (334 m per second at 0°C; Camhi, 1984). This means that the time delay between pulse and echo is a function of the instantaneous distance between the reflecting surface and the ear.

We now consider three situations of increasing complexity involving sound reflected from a wall. In each case we show that functions of the pulse-to-echo delay specify the distance to the wall.

Case 1: Sound source at the ear. First, suppose that the source is located at the ear; for example, a person holds a hand at one ear and snaps his or her fingers. If d_w is the distance to the wall and c is the speed of sound, then t_e , the time it takes the echo to go out to the wall and return to the ear, is equal to $t_e = 2d_w/c$. Thus, d_w is specified by the echo time up to the constant c :

$$d_w = ct_e/2 \quad (1)$$

Case 2: Sound source between the ear and the reflecting wall. For animals, the sound source usually is not at the ears but is at some other location—the vocal tract, the fingers, the feet, and so forth. This requires a modified equation. Consider a situation in which a person facing a wall snaps his or her fingers with the arm extended at distance d_p in front of his or her face (Figure 1); that is, the source is on the path along which the sound can be considered to travel. Because the distance the pulse travels from the source to the ear is d_p , the pulse time (the time that it takes the pulse to reach the ear), t_p , is equal to d_p/c . The echo travels

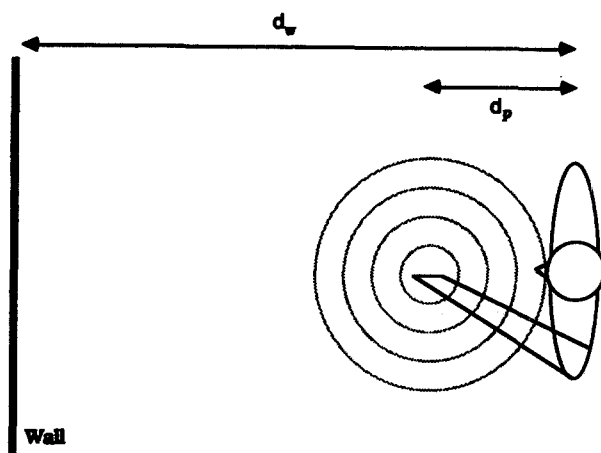


FIGURE 1 Details of pulse-to-echo delay: d_w = distance between the wall and the ears and d_p = distance between the ears and the sound source (snapping the fingers).

distance $d_w - d_p$ to the wall and d_w back to the ear. Thus, $t_e = (2d_w - d_p)/c$. The delay between the arrival of the pulse and the arrival of the echo is $t_e - t_p = 2(d_w - d_p)/c$. Therefore,

$$d_w = [c(t_e - t_p)/2] + d_p \quad (2)$$

Thus, the distance to the wall is specified up to the constant c and the parameter d_p .

Equations 1 and 2 can provide information for distance only if the perceiver has information about the speed of sound, c , and about the distance of the sound source from the ears, d_p . These are available in intermodal relations. We can see and feel the moment at which the fingers snap and the distance between the fingers and the ear. The delay between seeing and feeling the snap and hearing it specifies the speed of sound.

Case 3: Sound source in arbitrary location. Now suppose that the hand is not directly on the line between the ear and the wall (e.g., held out to the side). This case is more complex because the point on the wall from which the sound must be considered to be reflected varies with the position of the source. The analysis is presented in the Appendix, in which it is shown that d_w is again specified, although now as a function of the difference in the squares of the pulse and echo times. As before, the speed of sound and the distance of the source from the body are constants in the equation specifying the distance to the wall.

Consider an example of Case 2: If the wall were 3 m away and the fingers 0.5

m in front of the face, then the pulse-to-echo delay ($t_e - t_p$) would be about 0.015 s, and t_p would be about 0.0015 s. We do not have conscious access to durations of these magnitudes. Because pulse-to-echo delays are quite small, a question arises as to whether humans are able to detect them. Schenkman and Jansson (1986) suggested that humans are not sensitive to distance information over short distances (less than 2 m), arguing that the pulse-to-echo delay is then so short that "the two sounds are not perceived separately, but merge into one" (p. 608). However, the data on which this statement is based come from subjective reports of pitch (e.g., Yost, Hill, & Perez-Falcon, 1978), not from action-related sensitivity to distance. Kellogg (1962) reported that over a range of 30 to 120 cm, blind participants were able to resolve distance with an accuracy of about 10 cm, which suggests that they were sensitive to pulse-to-echo delays of about 0.0003 s. Similarly, Rice (1967; Rice, et al., 1965) reported that participants were able to detect the presence or absence of small targets that were only 0.6 m from their ears. Rice did not assess sensitivity to distance per se, but his data suggest that participants were sensitive to some aspect of pulse-to-echo relations when the delay was approximately 0.001 s. Some species of bats can discriminate distances on the basis of variations in pulse-to-echo delay of 10 to 12 ns (Simmons, 1989; cf. Pack & Herman, 1995), corresponding to differences in physical distance of about 2 μm ! Such intervals are orders of magnitude more brief than the duration of an action potential, prompting neuroethologists to admit that "the neural mechanisms responsible for this are entirely obscure" (Camhi, 1984, p. 180).

Information in pulse-to-echo delay for distance should also permit perception of the size of enclosed spaces and of one's location within them. Rooms of different sizes will have different pulse-to-echo delays. Anecdotally, people can hear the difference between large and small rooms (Jenkins, 1985): It is easy to distinguish a classroom from a closet. Controlled experimentation should be conducted to verify this ability and to determine its stimulus basis. Within a given room there will be differences in pulse-to-echo delay depending on the animal's distance from individual walls. This suggests that people may be sensitive not only to the size of a room but also to their location within it. We are not aware of any empirical evaluations of this possibility.⁴

Distance from Pulse and Echo Frequency Relations

Echolocating bats also obtain rich information from frequency relations between pulse and echo. When a broadband sound (one composed of a wide range

⁴Sensitivity to one's location as specified in pulse-to-echo relations may play a role in the experience of "presence" in simulated (virtual) environments (L. Hettinger, personal communication, December, 1994). A related possibility is that such sensitivity might be exploited in the design of acoustic and multimodal "displays" for virtual reality, aviation, process control, and so on (e.g., Vicente, Christoffersen, & Perekhita, 1995).

of frequencies) is reflected by a surface, constructive interference produces a class of variables that are related to the distance to that surface. In this section, we discuss two sources of information in this class. Our analysis is derived from Wood (1940, pp. 196–203) and Wilson (1966). The information sources that we discuss in this section are available to both echolocating and nonecholocating observers. We introduce them at this point because the relevant information will be more generally available when the observer uses echolocation (this is discussed in later sections).

A broadband sound that is reflected by a surface will return a broadband echo to the ear. The intensity of the sound reaching the ear is maximally reinforced when the sound wave travelling directly to the ear and the echo wave are in phase. The distance from the surface at which maximum reinforcement occurs varies with the frequency of the components of the sound wave. For a given frequency, f , reinforcement occurs at a distance d such that $f = c/2d$, where c is the speed of sound. In addition, components whose frequencies are integer multiples of f are also enhanced at distance d ; that is, at each distance from the reflecting surface a different constituent frequency of the reflected sound is amplified. The perceiver could, therefore, potentially hear a tone of a particular pitch in the background noise, a tone whose pitch changes as the perceiver's distance from the reflecting surface changes. It is this relation that leads to information for distance. Solving the above equation for d gives

$$d = c/2f \quad (3)^5$$

Thus, distance to the reflecting surface is specified up to the constant $c/2$. Information is available to moving and stationary observers. For a stationary perceiver, distance information exists in the specific frequency of the amplified tone. For a moving perceiver, information exists in the rate of change of the tone's frequency.

There is empirical support for the psychological reality of the previous analysis. Bassett and Eastmond (1964) showed that as predicted by acoustics, a predominant pitch is heard in reflected noise and that the pitch varies with distance from the reflecting surface. Participants held a speaker through which a broad spectrum sound ("thermal noise") was played. At the same time, a pure tone was played through a second speaker. The participant's task was to listen for the predominant pitch in the noise and walk toward or away from a reflecting panel until the pitch in the noise matched that of the pure tone. The frequency of the pure tone was varied from trial to trial. Bassett and Eastmond found that the distance selected for each pure tone was predicted by Equation 3.

⁵A qualification of Equation 3 should be noted. We use f to represent the lowest frequency enhanced at distance d . Because all integer multiples of f are also enhanced at f , substitution of the frequency of one of these harmonics of f would give an incorrect value of d .

This research did not involve echolocation because the sound source was external to the participants. However, the frequency of the source was fixed, and this was known to participants. Thus, they had information about the sound source that would not normally be available to nonecholocating perceivers. This may have produced an artifactual improvement in performance in the nonecho-location condition.

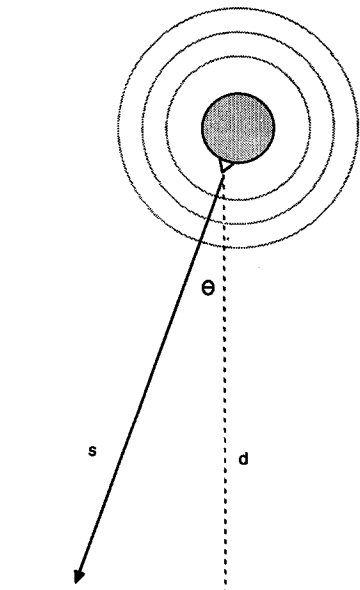
The second frequency-based source of information for distance requires relative motion between the surface and the observer. The following analysis is restricted to the case of perceiver-produced sound (as noted previously, it can be generalized to externally produced sounds; Wilson, 1966). Assume that there is a perceiver located at distance d from a wall and moving along a path at angle θ off the perpendicular to the wall and producing a broad spectrum sound (Figure 2). The distance to the wall along this path is symbolized as s .

Since $d = s \cos \theta$, then

$$f = c/2s \cos \theta. \quad (4)$$

As with Equation 4, by f we mean the lowest frequency enhanced at this distance. Also note that this analysis assumes that sound is reflected only perpendicular to the surface. This assumption is not physically correct; however, the results of Bassett and Eastmond (1964) suggest that it is the reflection from the perpendicular that gives rise to the predominant perceived pitch.

FIGURE 2 Frequency-based information for distance. An animal producing a multifrequency sound moves toward a wall along path s , which lies at angle θ from the perpendicular (i.e., the shortest path) to the wall. Constructive interference produces a predominant frequency at the animal's ear. This frequency is inversely proportional to d , the distance to the wall along the shortest path. Accordingly, functions of the frequency specify both d and the time-to-contact with the wall along path s . See text for explanation and equations.



Wilson (1966) used Equation 4 to show that the distance to the wall is specified by the ratio of the momentary frequency and the rate of change in frequency. Differentiating Equation 4 with respect to s gives

$$\Delta f / \Delta s = -(c/2\cos\theta)(1/s^2) \quad (5)$$

Therefore, the ratio of f to its rate of change specifies s , the distance to the wall along the path of motion; dividing Equation 5 by Equation 4 and solving for s gives

$$s = -(f/\Delta f)\Delta s \quad (6)$$

Equation 6 implies that a person could, in principle, perceive the distance to the wall by moving a small distance toward (or away from) it and detecting the relative change in the frequency of the reflected sound. Note that the distance s is specified as a multiple of Δs . In other words, if the listener moves a distance Δs toward the surface, then the ratio of frequency to change in frequency is the number of Δs -sized units it will take to reach the surface.

This analysis differs from that used in deriving optical τ because it differentiates with respect to distance rather than with respect to time, and because it provides information for distance rather than for time-to-contact. However, Wilson seems to have made an independent discovery of the underlying "trick" in the τ derivation—cancellation of terms by the use of derivatives. (Note that differentiation with respect to distance in the visual case would also lead to specification of distance.) A new acoustic τ , derived by differentiating Equation 4 with respect to time, is presented shortly.

Shape, Material Substance, Size, and Motion

Shape. Information about distance may be used to detect the three-dimensional shape of objects. Pulse-to-echo delay and pulse-to-echo frequency relations will differ for parts of objects nearer and farther from the point of observation. Bats appear to have considerable sensitivity to complex three-dimensional shape (Simmons & Chen, 1989) and can discriminate equal-volume cubes, pyramids, and cylinders (Schnitzler & Henson, 1980). It is likely that this ability arises, in part, from bats' extraordinary sensitivity to minute variations in distance (Simmons, 1989). Using echolocation, humans and trained bats can distinguish equal-area two-dimensional objects of different shapes (Rice, 1967; Simmons, 1989). The stimulus basis for this ability remains obscure (see Simmons, 1989).

In addition to relative time of arrival at the ears, pulse and echo can differ in relative intensity and relative frequency (and in details of frequency spectra). Many of these differences are well known in the literature on echolocation in

bats and dolphins (for a detailed discussion, see Simmons, 1989). There are also informative covariations among these three variables (e.g., Beuter, 1980). Variations in these relations are caused by physical properties of objects and surfaces and of their relation to the observer and to the physical surroundings. Consequently, pulse-to-echo relations provide information about a variety of properties in addition to distance and shape. Among these are the size and substance of objects, motion of the self relative to the acoustic environment, and motion of objects relative to the acoustic environment.

Substance. Substance is specified by the relative frequency spectra of pulse and echo. Physical surfaces absorb some frequencies and reflect others. For example, soft surfaces such as carpets tend to reflect only lower frequency sound waves, whereas rigid surfaces such as concrete blocks tend to reflect more energy in higher frequencies (Figure 3). A broadband pulse (one containing a wide range of frequencies) usually will give rise to a broadband echo. The frequency spectrum of the echo will contain gaps corresponding to frequencies absorbed by reflecting surfaces. Differences between outgoing and returning frequency spectra, then, will be related to the substantial makeup of distal surfaces. Both bats and dolphins can discriminate material substance via echolocation (Brill, Pawlowski, & Helweg, 1992; Whitlow, 1990; Whitlow & Turl, 1991); bats can discriminate food items (meal worms) from pieces of plastic of similar size (Simmons & Chen, 1989). Kellogg (1962) found that blind persons were able to discriminate reliably between a variety of materials when the materials were presented in paired comparisons: velvet, glass, denim, plain and painted wood, and metal.

Pulse-to-echo relations can provide information about substance that is not available in sounds generated by the distal objects. This is because a given externally generated sound wave can be generated by at least two physically

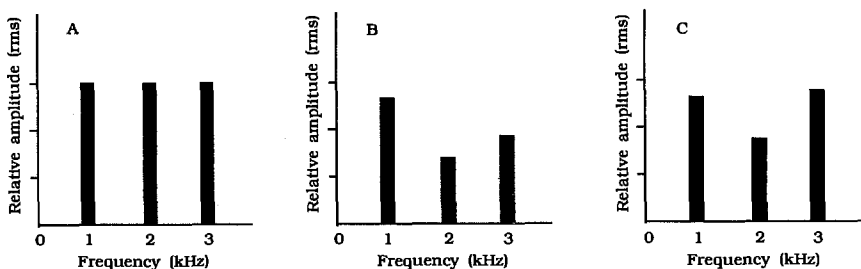


FIGURE 3 Frequency spectra of pulse (A) and echo. There is frequency-specific attenuation by the medium; the air preferentially absorbs higher frequencies. The "nominal" echo (B), then, will not reach the ears. After subtracting the effects of atmospheric attenuation, the remaining differences in relative frequency between pulse and echo (C) are caused by the reflecting surfaces. Relative amplitudes are root mean squares.

distinct sources (cf. Stoffregen, 1993). Any incoming sound wave that is not a reflection of self-generated sound could be generated by the "actual" event or by sound-reproducing devices like speakers. As the quality of audio technology improves it becomes more and more difficult to distinguish "real" from reproduced and other "simulated" events on the basis of externally generated sound. Self-generated pulses, however, reflect off the physical surfaces (the speakers), not off the objects whose sound is being simulated. Accordingly, the fact that an acoustic event is being simulated will be specified in relations between externally generated sound waves and self-generated pulse and echo. This should make it possible to discriminate "live" from reproduced sound (cf. Stoffregen, 1993).

Analyses of audition via externally generated sound sometimes focus on patterns of stimulation that specify the material nature of vibratory events. For instance, Gaver (1993b) discussed properties of acoustic wave forms that may permit differentiation of sound-producing events such as rolling, sliding, breaking, and so on. It is interesting to consider the differences that exist in the nature of information for object dynamics (such as substance) between pulse-to-echo relations and externally-generated sound waves. The two kinds of information are qualitatively different. Each must be understood and studied on its own terms.

Object size. Because larger objects reflect more acoustic energy, object size influences the intensity of echo relative to pulse. However, by themselves, intensity differences between pulse and echo provide no information. This is because an echo of a given intensity could be produced by an infinite number of reflecting surfaces of different sizes, substances, and distances. Information for the size of reflecting objects exists in a higher order relation between intensity, frequency, and delay. Pulse-to-echo delay disambiguates intensity with respect to distance. That is, delay determines how much of the intensity difference between pulse and echo is accounted for by distance. At the same time, frequency disambiguates intensity with respect to substance: Spectral relations of pulse and echo determine how much of the intensity difference is accounted for by the absorptive properties of the reflecting surface. Any remaining difference in intensity between pulse and echo is related to object size. This may account for reports of sensitivity to objects as small as 2.7 cm in humans (Rice, 1967). As just noted, neither Rice nor anyone else has carried out a thorough investigation of the information underlying the data reports. The analysis presented in this article suggests avenues for such an investigation.

Motion. Physical velocity of objects or surfaces relative to the point of observation induces changes in the spacing of successive acoustic wave fronts, producing a net change in frequency at the point of observation. This velocity-induced change in frequency is known as Doppler shift. The greater the velocity, the greater the change in spacing, and so the greater the Doppler shift. However,

for externally generated sound, Doppler shift is ambiguous with respect to velocity. This is because a given change in observed frequency could be caused by a change in the frequency of generated sound as well as by relative velocity. An example comes from sound reproduction: Speakers can simulate Doppler shift in the absence of any physical velocity. This ambiguity can be eliminated if the frequency of the pulse is known, which will be true when the pulse is generated by the animal. Velocity is specified by Doppler shift of the echo relative to the pulse. Certain species of bats are known to have extraordinary sensitivity to information in pulse-to-echo Doppler shift. For example, *Rhinolophus ferrumequinum*, which uses pulses of about 80 kHz, can detect pulse-to-echo Doppler shifts of as few as 30 Hz (Schnitzler & Henson, 1980), or 0.0375%.

Relative motion between the observer and the environment can arise from motion of objects relative to a stationary observer, from motion of the observer relative to a stationary environment, or from both. Pulse-to-echo Doppler shift can differentiate these distinct events. Motion of an object relative to the environment creates localized Doppler shift, that is, Doppler shift in a spatially localized portion of the echo (Camhi, 1984; Simmons, 1974). Motion of the self relative to the acoustic environment is specified by a spatially global Doppler shift of the echo relative to the pulse (similar to global optical flow). Echo-location-based sensitivity to changing position might be sufficiently refined to support compensatory postural sway in an acoustically reflective moving room. Finally, if perceivers can discriminate between local and global Doppler shifts, then Doppler shifts could be effective information for differentiating self-motion from object motion, even when the two occur simultaneously. There have been no empirical tests of these possibilities in any animals.

Velocity also influences the rate of change of the pulse-to-echo delay across successive pulse-echo pairs: If the distance between the reflecting surface and the perceiver is decreasing at a constant velocity, then the first time derivative of the pulse-to-echo delay function will be proportional to that velocity.⁶ Similarly, acceleration should be specified in the second time derivative of pulse-to-echo delay. We are not aware of any research on the sensitivity of echolocating humans to velocity (or any other parameter of motion). Similarly, we are not aware of any research on the sensitivity of any echolocating animal to acceleration.

Acoustic Time-to-Contact

Schiff and Oldak (1990; cf. Rosenblum, Wuestefeld, & Saldana, 1993) reported accurate judgments by inertially stationary humans of physical time-to-contact

⁶The two parameters that vary with velocity might be thought of as equivalent, redundant, or independent, such that an animal could choose among using one or another (cf. Cutting, 1986). We reject this approach. This is discussed in a later section on intermodal relations.

(T_c) from acoustic stimulation (externally generated sound). Shaw, et al. (1991; cf. Lee, 1990) attempted to identify a source of information in the acoustic array that might account for these data. They developed an acoustic variable based on changes in the intensity of sound arriving at a point of observation from a sound source that is in motion relative to the point of observation. This variable constitutes an intensity-based acoustic τ , or τ_i (as opposed to optic τ , τ_o), and can be used to generate time derivatives similar to those associated with τ_o (e.g., Lee & Reddish, 1981). Shaw, et al. (1991) referred to the echolocation literature, but they did not relate it to their analysis.

As presented by Shaw, et al. (1991), there are a number of important limitations to the utility of the τ_i variable and its time derivatives (cf. Guski, 1992). One of these limitations concerns the extent to which the production of sound is continuous over the period of observation. Specification of T_c , or at least the availability of the information, increases when sound is produced in a more nearly continuous manner: It should be more difficult to pick up τ_i for sound sources that emit only intermittently. This is a problem because many common sounds are intermittent. Consider, for example, an animal coming toward the observer. The animal may vocalize, but it may stop vocalizing or pause in its vocalization. A bipedal animal may or may not make noise with its hands (clapping or snapping fingers). There may be sound generated by footfalls, but it will be discontinuous, and the degree of discontinuity may vary with gait (walking, running, shuffling, number of legs, etc.). In addition, changes in sound intensity that provide information about T_c may be masked by unrelated intensity changes, such as those produced by heavier footfalls (e.g., stumbles). These discontinuities reduce the practical utility of τ_i . The observer must hope that the relevant information will be available at the right time, for a long enough time, to be useful.

A second limitation is more severe. In their discussion, Shaw, et al. (1991) considered only "the acoustic intensity field structure produced by an observer moving rectilinearly with respect to a sound source or, equivalently, a sound source moving rectilinearly with respect to an observer" (p. 257). That is, they assumed that the observer was silent, or that sound generated by the observer was irrelevant at best (such sound might hinder perception by masking sound generated by the object or surface). This assumption implies that the variable developed by Shaw, et al., can account for perception of T_c only when the observer is confronted with a noisy object or surface. In terms of daily life this is common, but it leaves out large classes of events for which the information available in τ_i might be useful if it were available. Most cases of physical closure arise from our own motion, and many of these involve closure with objects and surfaces that are silent; trees, rocks, doors, walls, parked cars, stationary people, and so on. As presented by Shaw, et al., τ_i provides no information about T_c for these events.

The foregoing limitations would seem to greatly reduce the range of situations

in which τ_i is informative about T_c . Accordingly, this variable appears to be much less general than t_o , which does not require luminous objects or surfaces, but works equally well with reflected light. The acoustic specification of T_c would have significantly enhanced generality if, like τ_o , it did not rely on energy generated by observed objects and surfaces. The assumption of a silent observer is not necessary, however. The intensity function described by Shaw et al. exists in returning reflections from self-generated sound. This means that animals can generate information in the acoustic array about T_c at will, even for motion relative to silent objects and surfaces (cf. Lee, 1990). Thus, the analysis of Shaw et al. is revealed to have been unnecessarily narrow. Intensity-based τ_i is available in far more situations than they considered.

Lee, van der Weel, Hitchcock, Matejowsky, and Pettigrew (1992) extended Lee's (1976) τ -dot strategy for visual control of braking of automobiles to control of locomotion by the use of information available through echolocation. The general strategy is to compute a τ function of a sensory variable that is a function of the distance between the perceiver and a surface. In traditional analyses, these functions are of interest when they specify time-to-contact. Lee, however, goes on to show that time derivatives of these functions can be used to control locomotion: If the organism moves to keep the derivative at a specific constant value, then it will bring itself to a halt just as it reaches the surface. Lee, et al. (1992) show that such analysis can be performed for three aspects of echoes (strictly speaking, the first of these is not a property of pulse-to-echo relations): (a) the angle subtended between any two elements on the surface and the organism's head, (b) the pulse-to-echo delay, and (c) the intensity (loudness) of the echo of a pulse of constant intensity. The τ based on intensity is similar to that developed by Shaw et al. (1991), and its use by Lee, et al. (1992) is consistent with our analysis of the advantages of echo-based acoustic τ . In fact, none of the parameters developed by Lee et al. (1992) is subject to the limitations that exist when acoustic τ arises from externally generated sound.

Guski (1992, p. 194) questioned the perceptual reality of the τ_i of Shaw, et al. (1991). Guski argued that τ_i would be effective only if the observing animal had independent information about the absolute intensity of the sound source. For externally generated sounds, such information is not available. But τ_i generated by way of echolocation would not be subject to this problem because with echolocation, the intensity of the sound source is known. This also applies to the intensity-based τ developed by Lee et al. (1992).

Another independent acoustic τ can be derived from our earlier discussion of reflected noise. As discussed earlier (in the section on information for distance from reflected frequency), Wilson (1966) noted that if frequency-based distance information is differentiated by distance, it provides information about dynamic distance. Now we show that by another transformation reflected frequency can provide information about T_c . Let Equation 4 be differentiated with respect to time:

$$\Delta f / \Delta t = -(c/2\cos\theta)(1/s^2)(\Delta s / \Delta t) \quad (8)$$

If the relative motion has a constant velocity v , then $\Delta s / \Delta t$ equals v . The ratio of the rate of change in frequency and momentary frequency specifies v/s , or T_c :

$$(\Delta f / \Delta t) / f = -v/s = T_c \quad (9)$$

This result seems to constitute a new τ . As with other τ variables, knowledge of distance and velocity are not needed to detect T_c . Notice also that the angle of approach to the wall does not appear in Equation 9. Thus, the perceiver would not need to know his or her orientation with respect to the wall to be able to know T_c . Finally, additional analyses like the ones for braking strategies (Lee, 1976) can be derived from Equation 9. In the following discussion we refer to this frequency-based variable as τ_f .

The τ_f variable exists with self-generated sound and also with externally generated sound reflected by distal surfaces. These two forms of the variable are not equally useful. When it is derived from externally generated sound, the τ_f variable is subject to severe limitations similar to those associated with the τ_i variable when it is based on externally generated sound. The τ_f variable will be available only when and for as long as externally generated sound is present and may depend on independent knowledge of the frequency of the external source (frequency information might not be available because the external source is moving relative to the observer, creating a Doppler shift).

This analysis reveals that the acoustic τ variables provide information about T_c for any situation in which the observer generates temporally heterogeneous sound that is reflected to the ear. This information is present in sonar whether produced mechanically or by animals. Something similar might be exploited for collision avoidance systems in automobiles. In principle, it is present in radar as well, but the great speed of electromagnetic propagation may render the information unavailable to biological perceptual systems. There have been no empirical evaluations of the sensitivity of humans to the information available in τ variables from self-generated sound. Lee, et al. (1992) conducted an initial study of bats' use of self-generated acoustic information about T_c in controlling flight. Bats flew freely down a tunnel toward an aperture. The timing of the bats' motion was consistent with the hypothesis that they were using information about τ -dot derived from echolocation. Future studies should examine sensitivity in both blind and sighted humans. The tapping of a cane on the ground is a good source of self-generated sound. We predict that blind people who locomote by using canes (or by snapping their fingers, or talking) should show sensitivity to time-to-contact with, for example, walls. The sensitivity may be sufficiently refined to aid in prospective control of locomotion (Supa et al., 1944; cf. Turvey, 1992) or in the avoidance of oncoming objects.

τ Variables Versus Distance/Velocity Calculation

Earlier, we described pulse-to-echo relations that provide information about both distance and velocity. These parameters exist in the acoustic array independent of the acoustic τ_s . In vision, estimates of distance and velocity (inferred from ambiguous optical stimulation) are sometimes thought to be building blocks of a cognitive calculation of T_c (Law, et al., 1993; McLeod & Ross, 1983). Our analysis shows that echolocating animals have available robust sources of information that would permit accurate calculation of T_c from d and v without recourse to estimates. At the same time, they have access to acoustic τ_s . Do they use d and v , or the τ variables? τ variables are specific to T_c only for constant velocity motion, yet most closure events are characterized by acceleration (e.g., Lee & Reddish, 1981; Lee, Young, Reddish, Lough, & Clayton, 1983). This means that information about distance and acceleration available in pulse-to-echo relations provides information about T_c that may be more accurate than that provided by the acoustic τ_s . Accordingly, it may be better for echolocating animals to ignore the acoustic τ_s in favor of d/v . In the absence of echolocation (when the observing animal is silent), neither d nor v is reliably available. Perhaps the acoustic τ_s are used when the animal is silent, and d/v when the animal is echolocating. This possibility is of direct relevance to the work of Lee et al. (1992) with bats. To conclude that bats are sensitive to direct information about T_c , it will be necessary to show that their timed behaviors are not based on calculations of T_c from d and v . This might be done by comparing their performance in constant velocity and accelerative flight.

What happens with animals that are sensitive to both optic and acoustic arrays (e.g., humans, but not bats)? Bats fly and intercept prey equally well when they are blinded (Camhi, 1984), but this is not true for humans. For us, visual-acoustic specification of the timing of the terminal phases of interceptive action may be the most common case. Research on the τ margin (Lee & Reddish, 1981) suggests that animals respond on the basis of τ_o even during accelerative interception, which would imply that they do not make use of echolocatory information for distance and velocity. However, the τ margin hypothesis originated in a study in which the motion of the behaving animal was silent (the flight of birds; Lee & Reddish, 1981). In the ball-punching experiment of Lee et al. (1983), participants' actions probably generated sound, making available echolocatory information about distance and velocity, but this was not under experimental control (the availability of such information would have varied depending on what each person was wearing, for example). This issue was not addressed by Lee et al. (1992).

The previous analysis implies that there may be considerable importance in an empirical evaluation of the perceptual basis of interceptive timing via echolocation. Bats employ prospective control during in-flight interception of prey: The movements of capture are initiated before physical contact (Webster

& Griffin, 1962). Presumably, this anticipatory control is based on sensitivity to T_c . However, except in the work of Lee, et al., sensitivity to T_c from any source, has not been considered or evaluated. For example, bats are thought to organize interceptive action solely on the basis of information about distance (e.g., Simmons, 1989).

ECHOES OF EXTERNALLY GENERATED SOUNDS

There are many sound sources in the natural environment. These give rise to acoustic energy that reaches the ears directly. Patterns in this acoustic energy are richly informative, as Gaver (1993a, 1993b) showed and can lead to precisely controlled behavior, for instance, in owls, which can capture prey in pitch darkness but do not use echolocation (Knudsen, 1981). In addition to reaching our ears directly from the source, sound that originates in one place may reach our ears after reflecting from other surfaces. This means that in most environments there will be both pulse and echo even when the observer is silent. Relations between externally generated pulses and their echoes can provide some of the information that exists when the pulse is self-generated (Lee, 1990). A common example is the ability to hear properties of large enclosures (e.g., caverns, concert halls) as other people move about within them. Although such "third party" pulse-to-echo information is present, it will often be less useful than relations between echoes and self-generated pulses. We have discussed some of these in earlier sections. Others are discussed here. For example, its utility will be influenced by the relative positioning of the sound source, the observer, and the perceived object or surface: If the object or surface is between the sound source and the observer, there may be no echoes from it to the observer. As noted earlier, with external sound sources the availability of information is contingent on the creation of pulses over which the observer has no control. Another consequence of this is that with externally generated pulses, the observer is unable to manipulate characteristics of the pulse as a means of exploring the acoustic environment as some bats are known to do. For example, the bat *Rhinolophus ferrumequinum* adjusts the frequency of the pulse to maintain a constant pitch of the echo (Schnitzler & Henson, 1980). Thus, the degree of pulse modulation required to maintain a constant echo pitch constitutes information for relative velocity as was explained in our earlier discussion of the Doppler shift. These limitations explain why echolocating animals generate their own pulses.⁷

There has been some research on human sensitivity to reflected sound and to

⁷Echolocating bats sometimes exploit externally generated sounds. For example, immature *Myotis lucifugus* appear to locate feeding sites by "eavesdropping," that is, listening to pulses and echoes generated by adults (Balcombe & Fenton, 1988).

relations between externally generated pulses and their echoes. Some studies have been conducted as direct comparisons with tests of echolocation. Rice (1967, p. 658) reported an experiment in which sound was generated by a speaker located close to the participant's mouth. Performance in this condition (detecting the presence of objects) was similar to echolocation conditions (discussed earlier). However, there was no variation in the rate, intensity, frequency, or location of these externally generated sounds. In an experiment reported by Supa et al. (1944), an experimenter walked toward the stationary target while holding a microphone. Participants sitting in an anechoic chamber listened to the output of the microphone over headphones. Performance in this experiment (avoiding collision with the target) was comparable with conditions in which the participant walked toward the target. In both of these experiments, the sound source was located close to the ear (or microphone), and its location was known to participants. In the Supa et al. study, the sound source (footballs) traveled with the microphone. These factors may have artifactually inflated judgment accuracy.

Mershon studied the effect of reflected sound on the auditory perception of egocentric distance (Mershon, et al., 1989; Mershon & Bowers, 1979; Mershon & King, 1975). In these studies, silent participants judged the distance to the source of a series of brief sound pulses. The distance of the speakers varied between 0.75 and 6.0 m; the smallest difference between speakers was 0.75 m. The independent variables included the reverberation time of the experimental room (manipulated by adding or removing acoustically absorbing material to the walls), levels of background noise, and so on. Judgments generally exhibited ordinal accuracy, but there was great variability across conditions. Distance judgments were strongly affected by changes in reverberation time (Mershon, et al., 1989; Mershon & King, 1975). In addition, judgment accuracy varied inversely with the level of background noise, which varied between 45 and 65 dB (cf. Ammons et al., 1953). Performance in these studies is not directly comparable to existing studies of distance perception on the basis of echolocation, in which objects were much closer to the point of observation (between 0.35 and 1.22 m; Kellogg, 1962). However, it is worth noting that Kellogg's blind participants showed robust and significant discrimination of surfaces (30.5 cm diameter disks) that differed in distance by as little as 8 cm. Kellogg did not evaluate possible effects of background noise or reverberation time. We might expect that the influence of reverberation time (material composition of the surroundings) would be minimal for echolocation because such variations would have no effect on the timing or intensity of echoes returning from an object (e.g., a person using echolocation to perceive an object located in an anechoic chamber).

Seki, Kajii, Ifukube, and Tanaka (1993) placed participants between two speakers, each of which presented pink noise. The noise streams coming from the two speakers were uncorrelated and were intended to suggest independent

sounding objects on either side of the observer. Within this context, Seki et al., generated an apparent surface (an obstacle) on one side that blocked part of the sound coming from that side. They did this by passing some of the noise from one speaker through to the other after adding a variable delay. The delay between the arrival of noise from one speaker and from the other was varied to simulate obstacles at different distances. Using the method of paired comparisons, Seki et al. found that blind participants were able to discriminate direct-to-reflected delays of 1, 2, 3, and 4 ms, corresponding to obstacles at distances of 0.17, 0.34, 0.51, and 0.68 m, respectively. This implies highly refined sensitivity to relations between externally generated sounds and their reflections similar to the sensitivity reported in juvenile bats (Balcombe & Fenton, 1988).

Guski (1990) studied the localization of external sound sources in an anechoic chamber. The main independent variable was the presence and location of a single acoustically reflecting surface between the sound source (speakers) and the participant. When the reflecting surface was present, externally generated pulse and echo were available to participants. The position of speakers was varied in azimuth, elevation, and distance relative to the point of observation. Lateral separation between speakers was about 12° . When asked to indicate which speaker had emitted a sound, participants responded accurately about 35% of the time. Accuracy was significantly greater when the reflecting surface lay flat on the floor, but was still rather low (41%). In the broader literature, auditory localization accuracy is greatest for targets that vary only in azimuth (horizontal position); under certain conditions participants can resolve angular differences as small as 1° . In Guski's study, accuracy in the horizontal plane was near 100% for all participants and was not affected by the presence or location of the reflecting surface.

Guski's (1990) research suggests that relations between externally generated pulse and echo play a modest role in localization in all spatial dimensions. The situation is different (in the horizontal dimension, at least) when the reflected sound has its origin in self-generated pulses. Using echolocating blind participants Rice (1967; 1969) varied target azimuth in 15° increments. Judgments of azimuth position were consistent and accurate, with a standard deviation of 10.1° (this implies nearly 100% accuracy, using Guski's metric). The target was a disk 10.2° in diameter. Measured accuracy may have been reduced by the use of a suboptimal dependent measure: Participants rotated their heads so that the perceived direction of the target was in front of their nose. Pointing tasks are known to yield spuriously low estimates of sensitivity to other spatial properties, such as the focus of radial optical outflow (Warren, Morris, & Kalish, 1988). Accordingly, the true level of sensitivity to spatial location via echolocation may be considerably greater.

Postural sway relative to the visual surround causes changes in the optic array that specify the sway, and these changes can exert a profound influence on the

control of posture (Lee & Lishman, 1975). Postural sway can also cause changes in the acoustic array. This has led some to suppose that stance might be modulated in response to appropriate acoustic stimulation. D. Ashmead (personal communication, 1994; cf. Lackner, 1977) attempted to induce compensatory postural sway with externally generated sound. Participants stood in a moving room that contained sound sources. Contrary to predictions, there was not a reliable relation between the postural sway and the motion of the room (we suggested earlier that "global acoustic flow" might lead to compensatory postural adjustments if the flow were generated via echolocation).

The studies reviewed in this section provide a very incomplete picture of human sensitivity to pulse-to-echo relations arising from externally generated sound. However, the evidence that is available suggests that such sensitivity may be substantially less than sensitivity to relations between self-generated sounds and their echoes. This is to be expected given the inherent limitations of externally generated pulse and echo.

HIGHER ORDER INFORMATION

Many common events are seen as well as heard and may also be felt, tasted, and/or smelled (Gibson, 1966, pp. 54–55; Jenkins, 1985). Traditionally, each of these is assumed to give rise to a separate percept, which is studied in isolation. For example, Lee (1990; Lee, et al., 1992; cf. Pack & Herman, 1995) discussed information for the control of locomotion that exists in the optic and acoustic arrays (including echolocation). However, he treated each array separately and did not address the possible existence of informative relations between them. Such an approach has led to the hypothesis that the stimulation of multiple perceptual systems gives rise to redundant sources of information, each of which is independently specific to the causal event (e.g., Fitzpatrick, Carello, Schmidt, & Corey, 1994). We refer to this view as the *independent specification hypothesis* (in the developmental and speech perception literatures it is commonly known as the hypothesis of *amodal specification*; e.g., Bahrack, 1992; Summerfield, 1987).

We see two weaknesses with the independent specification hypothesis. First, the hypothesis assumes that the information available to different perceptual systems is always identical with respect to the physical event in question. We believe that many exceptions occur. That is, although some variables often provide independent information for an event, they do not always do so. Stoffregen and Riccio (1991) provided examples of such exceptions for the perception of bodily orientation and motion. These exceptions are important because of their ubiquity (Stoffregen & Riccio, 1991) and because they show that perceptual processing cannot consist simply of picking up whichever of the purportedly independent specifiers happens to be preferred at the moment. Instead, the system must have some means of knowing which variable can be

used in the present context. In other words, exceptions to strict independence make impossible the simplicity of processing that is such an attractive feature of the independent specification hypothesis. The second weakness is that stress on individual variables has, in our opinion, led to neglect of higher order relations among these variables. We suggest that such relations contain information not available in the constituent variables and that perceptual systems are sensitive to these relations (Gibson, 1966, pp. 62–63; Stoffregen, 1990; Stoffregen & Riccio, 1988; 1991). Supporters of the independent specification hypothesis have not considered the possible existence of informative higher order relations between variables (i.e., emergent parameters that are qualitatively different from their constituent parts), and that perceptual systems may be sensitive to such higher order relations. The independent specification hypothesis would be true only if the information available to different perceptual systems was always identical with respect to a given physical event. That is, the hypothesis can be disproved for each physical event by the existence of a single exception. The rest of this section consists of examples of exceptions to strict independence and examples of higher order relations. We separately discuss higher order relations within the acoustic array and between acoustic and other forms of stimulus energy.

Informative higher order relations extend beyond acoustic energy. Our analysis has shown that the perception of distance from pulse-to-echo delay may depend on intermodal relations between stimulation of the auditory and (at least) somatosensory systems. We believe that much of the perception that is supported by patterns in the acoustic array is ultimately dependent on higher order intermodal relations between stimulation of the auditory and other perceptual systems (cf. Guski, 1992).

We noted earlier that the speed of sound is specified in temporal relations between the sight, sound, and feel of self-generated sounds (Equation 2). Relations between optics and acoustics also provide information for the distance of sound producing events, independent of any sound produced by the observer. The temporal relation between the arrival of photons and sound waves is specific to distance in the same way as the timing difference between pulse and echo: Distance is equivalent to the delay between the arrival of energy at the visual and acoustic receptors divided by the speed of sound.

When an echolocating animal observes an event or object that generates its own sound, there will be a higher order relation between pulse-to-echo delay (Equation 2) and sight-to-sound delay. In many natural situations, the relation between these will be one of identity: The pulse-to-echo delay will indicate the same object or event as the optic-to-acoustic delay. However, this will not always be the case. Differences between the two delays might indicate that the observer was making a perceptual error (looking at one event and, mistakenly, listening to another). Such differences might also specify that echo and photons were originating in different places. For instance, when a sound-producing event is viewed through glass, the sound it makes may not reach the ears. The relation

between seen event and lack of sound will be caused by and should (therefore) provide information about the intervening glass. The optic-to-acoustic delay will be infinite, whereas the pulse-to-echo delay will have a finite value: Perceiver-generated sound will reflect off the glass. The relation between the optic-to-acoustic delay and the pulse-to-echo delay will specify a distal event viewed through an acoustically opaque surface. The glass may or may not structure the optic array (e.g., through reflections, scratches, dirt, etc.). The self-generated acoustic information will be more generally available. Similarly, an event may be heard through an optically opaque but acoustically transparent surface. Examples would include a scrim (in a theater) or hearing a bird that is concealed by foliage. The ability to differentiate among such events would be evidence for sensitivity to these intermodal relations. Similar informative relations exist between sound and touch for example, during sanding, when the feel of the wood through the sandpaper will have an informative (unique) relation with the (self-generated) sound produced by the self-generated motion of the hand.

Atmospheric attenuation varies with certain climatic conditions, principally humidity. Sound "travels" well in dry air, but seems to be swallowed up by fog. This variation will affect echo frequency and intensity. A consequence of this is that the effects of atmospheric conditions on acoustic attenuation are specified intermodally. Atmospheric attenuation is given in relations between seen and felt actions that generate sound and the sound (pulse) that arrives at the ears. The visual and somatosensory systems give information about the location and the force or intensity of the sound-generated event. Relations between these systems and the intensity of sound waves arriving at the ear are specific to momentary local atmospheric attenuation. Similar relations may exist between pulse, echo, and nonauditory information for material substance: The intensity of the echo (from a given substance, which may be specified visually) relative to the pulse will decrease with increases in atmospheric attenuation.

As a final example, there should be informative higher order, intermodal relations between τ_i , τ_f , and τ_o (Stoffregen, 1990). A given closure event can yield different values for the acoustics τ_s and τ_o . As in the previous example, these variables will have different values if the approach is viewed through glass or if it is heard through an optically opaque but acoustically transparent surface. Research that accepts the reductionist assumption that specification exists within patterns of stimulation of individual perceptual systems cannot evaluate the perceptual reality of these intermodal relations (Stoffregen, 1990; 1993).

The intersensory version of the independent specification hypothesis has recently appeared in the echolocation literature. Pack and Herman (1995) reported that a bottlenosed dolphin was capable of "cross-modal recognition" through echolocation and vision. The animal exhibited immediate recognition of an object that could only be perceived through echolocation ("audible" through black plexiglas, which is transparent to aquatic sound) that had previously been perceivable only through vision. Pack and Herman interpreted

this as indicating that the dolphin perceived shape "through vision alone or through echolocation alone" (p. 731). This is consistent with the independent specification hypothesis. The methodology of Pack and Herman did not permit a test of sensitivity to information that might exist in relations between acoustic and optical stimulation. The experiments were designed to limit exposure of objects to one sense at a time. This effectively eliminated any higher order, optic-acoustic relations from the situation. Thus, the data of Pack and Herman cannot address the possible pickup of such higher order relations. It should be stressed that the excellent discrimination exhibited by the dolphin does not imply that the "unimodal" information it picked up was equivalent to higher order, intermodal information. Relations between optic and acoustic stimulation were specific to the fact that one of the "objects" was a nonphysical optical depiction (Stoffregen, 1993), whereas the other was physical, but optically occluded. These intermodally specified differences would have been highly consequential to the dolphin if it had been asked to interact with the objects beyond the level of observation. Such interactions if carried out adaptively would suggest that the animal was sensitive to informative optic-acoustic relations.

Our analysis of higher order information applies also to relations between variables within a single type of stimulus energy. A given event can influence the structure of several aspects of an energy field. It is now widely believed that these different aspects constitute "multiple sources of information" for the event, and that the animals can perceive the event with equal fidelity on the basis of any one of these (e.g., Montagne, Laurent, & Durey, 1995). Examples discussed in this article include separate aspects of pulse-to-echo relations that are related to physical velocity along with others that are related to distance and still others related to time-to-contact. These parameters can be analyzed independently, which has led to their being interpreted as independent, redundant sources of information (e.g., Cutting, 1986; Rosenblum, et al., 1987). Such an interpretation requires the assumption that these parameters have independent perceptual reality. Thus, the hypothesis of multiple sources of information appears to be motivated by assuming its own conclusion (Stoffregen, 1990). As one counterexample, see our earlier discussion of the specification of object size through higher order relations between pulse-to-echo intensity, frequency, and delay. If echolocating animals perceive object size on the basis of relations between these variables, the variables cannot be interpreted as having independent perceptual reality.

As another counterexample, consider Lee, et al. (1992), who presented three acoustic variables that are influenced by T_c —one based on divergence of elements on the approach surface, another on changes in pulse-to-echo delay, and a third on changes in echo intensity. Under many circumstances these three variables provide "the same information" about T_c , which might suggest that they are redundant. However, under other circumstances they do not. In fact,

Lee et al. (1992) created just such a situation in a condition in which they varied the size of an aperture through which bats were trained to fly. Usually, the aperture was of constant size, but sometimes the aperture expanded as the bat flew toward it. The intent (and effect) of this variation was to render the divergence variable uninformative about T_c . Thus, the three variables did not provide redundant information; the value of T_c "suggested" (falsely) by the divergence variable differed from that indicated by the other two variables. One implication of Lee et al.'s analysis was that the divergence variable was unreliable and should be ignored by the bats. However, taken together, the three variables formed a higher order pattern that was specific to the fact that the bat was flying with a particular time course toward an aperture of increasing size. This information should have been of interest to the bats: The initial aperture was intentionally set at "the minimum size that bat could reliably fly through," so that "the task required precise control of approach" (p. 566). Lee et al. did not address the possibility that the bats may have modulated their flight behavior on the basis of higher order information not only about when they would arrive, but also about the size aperture they would have to negotiate (cf. Peper, Bootsma, Mestre, & Bakker, 1994).

ADDITIONAL ISSUES

Last, we consider the consequences of three characteristics of sounds as they are typically encountered in everyday life—the intermittent nature of most perceiver-produced sound, the attenuation of intensity over distance, and the presence of other noises that may mask information-bearing sounds.

Earlier, we discussed a limitation on acoustic τ that can arise when sounds are generated intermittently. In that context we discussed the limitation as a characteristic of externally generated sound. In this section we address the issue in the context of echolocation. For there to be a pulse-to-echo delay there must be a pulse, that is, there must be a property of the generated wave form that is temporally discrete. A temporally homogeneous wave form emanating from the observer would lead to detectable echoes, but there would be no pulse-to-echo delay and therefore there would be no information that arises from relations between pulse and echo. The required discreteness can be in intensity, frequency, or in both. This requirement is not difficult to meet—in fact, it is rarely violated in nature. There are few biologically based sounds that do not vary in frequency and in intensity (bats are known to vary both the frequency and intensity of their pulses; Griffin, 1958). Thus, the information available in pulse-to-echo relations is, fundamentally, intermittent. This might seem to render such information less valuable or reliable. This may not be a problem, however, because outgoing pulses are generated by the animal, which means that they can be controlled to facilitate perception. Bats do just that (Simmons,

Fenton, & O'Farrell, 1979). In cruising flight they emit only a few pulses per s. When a target (e.g., prey) is detected, the rate of pulse emission rises dramatically. A similar effect may exist for the tapping of canes by the blind and for human echolocation in general (again, this has not been studied). The amount of information available or the temporal resolution of the information is under the control of the animal.

A second qualification arises from the fact that sound waves are attenuated by their medium (air or water). Pulse-to-echo relations provide information about objects and surfaces that are close enough to the point of observation that the pulses will reach them and the echoes will reach the ear. The limiting factor is the attenuation of the echo, whose intensity is several orders of magnitude less than the pulse and, thus, attenuates more rapidly. This means that pulse-to-echo information will be available over fairly short distances. An important aspect of this is that the air does not attenuate all sound equally. Attenuation depends on frequency: Higher frequencies are attenuated much more rapidly (i.e., over shorter distances) than are low frequencies. This places tight limitations on the utility of echolocation via ultrasound as practiced by bats. The spatial limit for bats is approximately 5 m (Camhi, 1984; Simmons, 1989). Frequencies in the range audible to humans propagate further, therefore humans may be sensitive to pulse-to-echo information over greater distances than are bats (humans are known to be sensitive to pulse-to-echo relations to distances of at least 5 m; Supa, et al., 1944).

The issue of echo strength is related to the existence of masking noise, or interference. Bats and dolphins emit trains of pulses. This means that a pulse could be emitted just as the echo from a previous pulse was arriving. For bats, at least, pulse does not mask echo despite the intensity differences and despite the fact that pulses and echoes often come in rapid succession. Rice (1967) recorded vocalizations of his participants and determined that even with the shortest of these (a tongue click), "in most instances . . . the echo returns before the click is finished" (p. 660). Yet "the data showed no difference between performance when considerable signal-echo overlap occurred and performance when there was no overlap" (p. 660). A similar issue arises from the fact that pulse and echo rarely are the only wave forms impinging on the ears (Passini et al., 1986; Ammons et al., 1953). Any externally generated sound has the potential to mask pulse-to-echo relations. Bats show extraordinary sensitivity to echoes in the presence of externally generated sounds, even though the echoes are very weak (Schnitzler & Henson, 1980). Bats avoid jamming from environmental noise through perception-action manipulations: They approach objects from oblique angles (to generate spatial separation between the source of interference and the target), and they increase the volume and duration of their pulses. The experiments of Ammons et al. (1953) suggest that human echolocation can be fairly robust in the presence of substantial extraneous noise. This possibility deserves further investigation.

The foregoing considerations suggest that the utility of information in pulse-to-echo relations will be limited to objects and events that are fairly close to the animal (cf. Shaw, et al., 1991) in either space or time. Frequencies within the range of human hearing travel farther than the ultrasound used by bats but are, nevertheless, subject to strong constraints arising from physics. The utility of self-generated sound should increase to the extent that perceivers exploit higher order relations between patterns in sound and patterns in other forms of energy.

CONCLUSION

We have suggested that humans may have considerable sensitivity to information in pulse-to-echo relations. We have further suggested that sighted humans may use this information on a regular basis. We have described a number of parameters of acoustic and acoustic-intermodal patterns of energy that, in principle, provide information to echolocating animals about consequential aspects of the animal-environment interaction. The sensitivity of animals, principally humans, to these sources of information is largely unknown, but past research indicates that both blind and sighted humans have echolocatory skills that merit careful investigation from a perception-action perspective. Such research may bring about an important expansion in our concept of auditory sensitivity and of the use of information in acoustic arrays for the control of action.

Echolocation and Active Touch

In echolocation, stimulus energy that is generated by the animal propagates into the environment, is structured by the environment, and returns to receptors. Relations between the outgoing and returning patterns of energy provide information that is, fundamentally, not available if either the pulse or echo is considered in isolation. We believe that generating information in pulse-to-echo relations is logically identical to the generation of information by active touch (e.g., Gibson, 1962, 1966; Barac-Cikoja & Turvey, 1991). In active touch, a structured pattern of force is generated by the animal. The pattern of force is transmitted to the environment (the felt object or surface) and "reflected" back to the haptic system in the form of a structured pattern of resistive force. As with echolocation, "incoming" force (whether resistive or imposed) is relatively uninformative (we do not learn much from being touched), whereas the relation between self-generated and resistive forces provides extremely rich information. It may be for this reason that perception is so much more accurate by active touch than by imposed stimulation of passive observers.

Echolocation as a Closed-Loop System

Echolocation is, profoundly, a closed-loop behavior. It is an activity in which action controls perception (cf. Powers, 1973). Analyses of closed-loop systems typically focus on perception controlling action. Echolocation is the reverse: Action is modulated to control perception. The same is true of active touch. Passive hearing by external sound is open looped. Granted, truly passive hearing is rare; most hearing, even with external sources, is not passive because the auditor moves, generating information (e.g., head movements in echolocation; Rice, 1967). But the role of "perceiver activity" has been studied very little for any form of human audition (e.g., not at all in any of the experimental studies of human audition cited in this article). Thus, we suggest that more attention be paid to action in audition, both with nonecholocation and with echolocation phenomena.

Research Issues

Our analysis has led to numerous suggestions for research, which are summarized in this section. The existing literature on human echolocation, most of which is several decades old, needs to be replicated using perception-action paradigms. Until this is done, we have only a vague idea of the true extent of echolocation abilities. Research should seek to identify the information that supports these abilities. Some candidate sources of information have been presented in this article. Others are available in the literature on nonhuman echolocation.

In addition to replicating previous work, new areas of perception and perception-action need to be addressed. There should be systematic research on the use of exploratory head movements in human echolocation. Research is needed in humans on echolocation-based sensitivity to self-motion and object motion and velocity and (in both humans and nonhumans) on sensitivity to acceleration. Echolocation should support perception of the size of enclosures and of the participants' location within them. We predict that echolocating humans should exhibit compensatory postural sway within an acoustically reflective moving room. We have identified a source of information in echolocation that should permit perceivers to discriminate "live" from reproduced sound regardless of the faithfulness of the reproduction. It should be possible by permitting or prohibiting echolocation to determine whether humans (and others) are sensitive to this information.

Our analysis has revealed two sources of information that may support the control of interceptive action. These are the new τ_f variable we developed in this article and the possible calculation of T_c from echolocation-based information for distance and velocity. Research is needed on the perception and use of each of these sources of information, in both humans and nonhumans.

Acute human sensitivity to information in pulse-to-echo relations might be exploited in the design of human-machine interfaces (e.g., flight control and simulation, process control in industry, and virtual environments). The potential utility of such an approach need not contradict with our assertion that echolocating animals should be able to discriminate live sound from reproductions: Operators can detect the simulation or reproduction as such and still pick up the presented information. Indeed, we do exactly this on a daily basis whenever we listen to the radio.

Last, we argued that higher order intermodal relations between acoustics and optics provide information about the distance of an event from an observer. Sensitivity to these higher order relations should be evaluated. These relations should also permit observers to detect invisible glass barriers between themselves and distal objects and surfaces. Similarly, research is needed to evaluate the perception-action utility of higher order relations between acoustic and optical sources of information about impending collision.

Echolocation exists in a wide variety of species, including humans, and can be used with extraordinary precision. The breadth of species exhibiting echolocation and the profound dependence of echolocation on tight coupling between perception and action would seem to make it a subject of natural interest to ecological psychologists. We believe that echolocation may be used regularly by humans in ordinary situations. Accordingly, echolocation may present substantial challenges to and substantial opportunities for the ecological study of audition in general.

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REFERENCES

- Ammons, C. H., Worchel, P., & Dallenbach, K. M. (1953). "Facial vision": The perception of obstacles out of doors by blindfolded and blindfolded-deafened subjects. *American Journal of Psychology*, 66, 519-554.
- Bahrick, L. E. (1992). Infants' perceptual differentiation of amodal and modality-specific audio-visual relations. *Journal of Experimental Child Psychology*, 53, 180-199.

- Balcombe, J. P., & Fenton, M. B. (1988). Eavesdropping by bats: The influence of echolocation call design and foraging strategy. *Ethology*, 79, 158-166.
- Barac-Cikoja, D., & Turvey, M. T. (1991). Perceiving aperture size by striking. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 330-346.
- Bassett, I. G., & Eastmond, E. J. (1964). Echolocation: Measurement of pitch versus distance for sounds reflected from a flat surface. *Journal of the Acoustical Society of America*, 36, 911-916.
- Beuter, K. J. (1980). A new concept of echo evaluation in the auditory system of bats. In R.-G. Busnel and J. F. Fish (Eds.), *Animal sonar systems* (pp. 747-761). New York: Plenum.
- Blauert, J. (1983). *Spatial hearing: The psychophysics of human sound localization*. Cambridge, MA: MIT Press.
- Boehm, R. (1986). The use of echolocation as a mobility aid for blind persons. *Journal of Visual Impairment and Blindness*, 80, 953-954.
- Bootsma, R. J., & van Wieringen, P. C. W. (1990). Timing an attacking forehand drive in table tennis. *Journal of Experimental Psychology: Human Perception and Performance*, 16, 21-29.
- Brill, R. L., Pawloski, J. L., & Helweg, D. A. (1992). Target detection, shape discrimination, and signal characteristics of an echolocating false killer whale (*Pseudorca crassidens*). *Journal of the Acoustical Society of America*, 92, 1324-1330.
- Burton, G. (1992). Nonvisual judgment of the crossability of path gaps. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 698-713.
- Busnel, R.-G., & Fish, J. F. (1980). *Animal sonar systems*. New York: Plenum.
- Cabe, P. N., & Pittenger, J. B. (1990, November). Sensitivity to auditory information for vessel fullness: Blind and sighted subjects. Paper presented at the meeting of the Psychonomic Society, New Orleans, LA.
- Camhi, J. M. (1984). *Neuroethology*. Sunderland, MA: Sinauer.
- Chan, T.-C., & Turvey, M. T. (1991). Perceiving the vertical distances of surfaces by means of a hand-held probe. *Journal of Experimental Psychology: Human Perception and Performance*, 17, 347-358.
- Cutting, J. E. (1986). *Perception with an eye for motion*. Cambridge, MA: MIT Press.
- Fitzpatrick, P., Carello, C., Schmidt, R. C., & Corey, D. (1994). Haptic and visual perception of an affordance for upright posture. *Ecological Psychology*, 6, 265-287.
- Gaver, W. W. (1993a). What in the world do we hear?: An ecological approach to auditory event perception. *Ecological Psychology*, 5, 1-29.
- Gaver, W. W. (1993b). How do we hear in the world?: Explorations in ecological acoustics. *Ecological Psychology*, 5, 285-314.
- Gibson, J. J. (1962). Observations on active touch. *Psychological Review*, 69, 477-491.
- Gibson, J. J. (1966). *The senses considered as perceptual systems*. Boston: Houghton-Mifflin.
- Griffin, D. R. (1958). *Listening in the dark*. New Haven, CT: Yale University Press.
- Guski, R. (1990). Auditory localization: Effects of reflecting surfaces. *Perception*, 19, 819-830.
- Guski, R. (1992). Acoustic tau: An easy analog to visual tau? *Ecological Psychology*, 4, 189-197.
- Handel, S. (1989). *Listening: An introduction to the perception of auditory events*. Cambridge, MA: MIT Press.
- Hausfeld, S., Power, R. P., Gorta, A., & Harris, P. (1982). Echo perception of shape and texture by sighted subjects. *Perceptual & Motor Skills*, 55, 623-632.
- Heine, W.-D., & Guski, R. (1991). Listening: The perception of auditory events? [Review of the book *Listening: An introduction to the perception of auditory events*] *Ecological Psychology*, 3, 263-275.
- Jenkins, J. J. (1985). Acoustic information for objects, places, and events. In W. H. Warren & R. Shaw (Eds.), *Persistence and change: Proceedings of the first international conference on event perception* (pp. 115-138). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Kellogg, W. N. (1962). Sonar system of the blind. *Science*, 137, 399-404.
- Knudsen, E. I. (1981). The hearing of the barn owl. *Scientific American*, 245(6), 112-125.
- Lackner, J. R. (1977). Induction of nystagmus in stationary objects with a rotating sound field. *Aviation, Space, and Environmental Medicine*, 48, 129-131.

- Law, D. J., Pellegrino, J. W., Mitchell, S. R., Fischer, S. C., McDonald, T. P., & Hunt, E. B. (1993). Perceptual and cognitive factors governing performance in comparative arrival-time judgments. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 1183-1199.
- Lee, D. N. (1976). A theory of visual control of braking used on information about time-to-collision. *Perception*, 5, 437-459.
- Lee, D. N. (1990). Getting around with light or sound. In R. Warren & A. H. Wertheim (Eds.), *Perception and control of self-motion* (pp. 487-505). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Lee, D. N., & Lishman, J. R. (1975). Visual proprioceptive control of stance. *Journal of Human Movement Studies*, 1, 87-95.
- Lee, D. N., & Reddish, P. E. (1981). Plummeting gannets: A paradigm of ecological optics. *Nature*, 293(5830), 293-294.
- Lee, D. N., van der Weel, F. R., Hitchcock, T., Matejowsky, E., & Pettigrew, J. D. (1992). Common principle of guidance by echolocation and vision. *Journal of Comparative Physiology A*, 171, 563-571.
- Lee, D. N., Young, D. S., Reddish, P. E., Lough, S., & Clayton, T. M. H. (1983). Visual timing in hitting an accelerating ball. *Quarterly Journal of Experimental Psychology*, 35A, 333-346.
- McFarland, D. (1987). *The Oxford companion to animal behavior*. New York: Oxford University Press.
- McLeod, R. W., & Ross, H. E. (1983). Optic-flow and cognitive factors in time-to-collision estimates. *Perception*, 12, 417-423.
- Mereshon, D. H., Ballenger, W. L., Little, A. D., McMurtry, P. L., & Buchanan, J. L. (1989). Effects of room reflectance and background noise on perceived auditory distance. *Perception*, 18, 403-416.
- Mereshon, D. H., & Bowers, J. N. (1979). Absolute and relative cues for the auditory perception of egocentric distance. *Perception*, 8, 311-322.
- Mereshon, D. H., & King, L. E. (1975). Intensity and reverberation as factors in the auditory perception of egocentric distance. *Perception & Psychophysics*, 18, 409-415.
- Montagne, G., Laurent, M., & Durey, A. (1995). Binocular optical invariant(s) and interceptive actions. In B. G. Bardy, R. J. Bootsma, & Y. Guiard (Eds.), *Studies in perception and action III* (pp. 371-374). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Okura, M. (1995, July). *A special perceptual technique of inspecting cans by tapping: A fieldwork*. Poster presented at the 8th International Conference on Perception and Action, Marseille, France.
- Pack, A. A., & Herman, L. M. (1995). Sensory integration in the bottlenosed dolphin: Immediate recognition of complex shapes across the senses of echolocation and vision. *Journal of the Acoustical Society of America*, 98, 722-733.
- Passini, R., Dupre, A., & Langlois, C. (1986). Spatial mobility of the visually handicapped active person: A descriptive study. *Journal of Visual Impairment and Blindness*, 80, 904-907.
- Peper, L., Bootsma, R. J., Mestre, D. R., & Bakker, F. C. (1994). Catching balls: How to get the hand to the right place at the right time. *Journal of Experimental Psychology: Human Perception & Performance*, 20, 591-612.
- Pittenger, J. B., Guskis, R., & Heine, W.-D. (November, 1994). *Non-visual information supports perception of number of moving objects*. Paper presented at the meeting of the Psychonomic Society, St. Louis, MO.
- Powers, W. T. (1973). *Behavior: The control of perception*. Chicago: Aldine.
- Rice, C. E. (1967). Human echo perception. *Science*, 155, 656-664.
- Rice, C. E. (1969). Perceptual enhancement in the early blind. *Psychological Record*, 19, 1-14.
- Rice, C. E., & Feinstein, S. H. (1965). Sonar system of the blind; Size discrimination. *Science*, 148, 1107-1108.
- Rice, C. E., Feinstein, S. H., & Schusterman, R. J. (1965). Echo-detection ability of the blind: Size and distance effects. *Journal of Experimental Psychology*, 70, 246-251.
- Rosenblum, L. D., Carello, C., & Pastore, E. (1987). Relative effectiveness of three stimulus variables for locating a moving sound source. *Perception*, 16, 175-186.

- Rosenblum, L. D., Wuestefeld, A. P., & Saldana, H. M. (1993). Auditory looming perception: Influences on anticipatory judgments. *Perception*, 22, 1467-1482.
- Schenkman, B. N., & Jansson, G. (1986). The detection and localization of objects by the blind with the aid of long-cane tapping sounds. *Human Factors*, 28, 607-618.
- Schiff, W., & Oldak, R. (1990). Accuracy of judging time to arrival: Effects of modality, trajectory, and gender. *Journal of Experimental Psychology: Human Perception & Performance*, 16, 303-316.
- Schnitzler, H. U., & Henson, O. W. (1980). Performance of airborne animal sonar systems: I. *Microchiroptera*. In R.-G. Busnel & J. F. Fish (Eds.), *Animal sonar systems* (pp. 109-181). New York: Plenum.
- Seidel, H. M., Ball, J. W., Dains, J. E., & Benedict, G. W. (1991). *Mosby's guide to physical examination* (2nd ed.). St. Louis: Mosby Year Book.
- Seki, Y., Ifukube, T., & Tanaka, Y. (1994). [Relation between reflected sound localization and the obstacle sense of the blind]. *The Journal of the Acoustical Society of Japan*, 50, 289-295.
- Seki, Y., Kajii, K., Ifukube, T., & Tanaka, Y. (1993). [On the relation between obstacle sense of the blind and variation of the sound field]. *Proceedings of the 19th Sensory Substitution Symposium, Tokyo* (pp. 9-15). Tsukuba, Japan: Association of Sensory Substitution.
- Shaw, B. K., McGowan, R. S., & Turvey, M. T. (1991). An acoustic variable specifying time-to-contact. *Ecological Psychology*, 3, 253-261.
- Simmons, J. A. (1989). A view of the world through the bats' ear: The formation of acoustic images in echolocation. *Cognition*, 33, 155-199.
- Simmons, J. A., & Chen, L. (1989). The acoustic basis for target discrimination by FM echolocating bats. *Journal of the Acoustical Society of America*, 86, 1333-1350.
- Simmons, J. A., Fenton, B. M., & O'Farrell, M. J. (1979). Echolocation and pursuit of prey by bats. *Science*, 203, 16-21.
- Stoffregen, T. A. (1986). The role of optical velocity in the control of stance. *Perception & Psychophysics*, 39, 355-360.
- Stoffregen, T. A. (1990, May). Multiple sources of information: For what? *ISEP Newsletter*, 4, 5-8.
- Stoffregen, T. A. (1993, November). "Natural," "real," and use of non-physical displays in perception-action research. *ISEP Newsletter*, 6, 4-9.
- Stoffregen, T. A., & Riccio, G. E. (1988). An ecological theory of orientation and the vestibular system. *Psychological Review*, 95, 3-14.
- Stoffregen, T. A., & Riccio, G. E. (1991). An ecological critique of the sensory conflict theory of motion sickness. *Ecological Psychology*, 3, 159-194.
- Strelow, E. R., & Brabyn, J. A. (1982). Locomotion of the blind controlled by natural sound cues. *Perception*, 11, 635-640.
- Summerfield, Q. (1987). Some preliminaries to a comprehensive account of audio-visual speech perception. In B. Dodd & R. Campbell (Eds.), *Hearing by eye: The psychology of lip-reading* (pp. 3-52). Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Supa, M., Cotzin, M., & Dallenbach, K. M. (1944). "Facial vision," the perception of obstacles by the blind. *American Journal of Psychology*, 57, 133-183.
- Turvey, M. T. (1992). Affordances and prospective control: An outline of the ontology. *Ecological Psychology*, 4, 173-188.
- Vicente, K. J., Christoffersen, K., & Pereklima, A. (in press). Supporting operator problem solving through ecological interface design. *IEEE Transactions on Systems, Man, and Cybernetics*, 25.
- Warren, W. H., Morris, M. W., & Kalish, M. (1988). Perception of translational heading from optical flow. *Journal of Experimental Psychology: Human Perception & Performance*, 14, 646-660.
- Warren, W. H., & Verbrugge, R. R. (1984). Auditory perception of breaking and bouncing events: A case study in ecological acoustics. *Journal of Experimental Psychology: Human Perception & Performance*, 10, 704-712.
- Webster, F. A., & Griffin, D. R. (1962). The role of flight membranes in insect capture by bats. *Animal Behavior*, 10, 332-340.

- Whitlow, W. L. (1990). Echolocation in dolphins. In M. A. Berkley & W. C. Stebbins (Eds.), *Comparative perception, Volume I: Basic mechanisms* (pp. 315–350). New York: Wiley.
- Whitlow, W., & Turl, C. W. (1991). Material composition discrimination of cylinders at different aspect angles by an echolocating dolphin. *Journal of the Acoustical Society of America*, 89, 2448–2451.
- Wilson, J. P. (1966). Obstacle detection using ambient or self-generated noise. *Nature*, 211(5045), 218.
- Wood, A. (1940). *Acoustics*. London: Blackie & Son.
- Yost, W. A., Hill, R., & Perez-Falcon, T. (1978). Pitch and pitch discrimination of broadband signals with rippled power spectra. *Journal of the Acoustical Society of America*, 63, 1166–1173.

APPENDIX

Specification of Distance in Pulse-to-Echo Delay: Case 3

This analysis applies to the situation in which the source of the sound is not at the ear or on the line which is perpendicular to the wall and intersects the ear. A related analysis has been presented by Seki, Ifukube, and Tanaka (1994). Let point A be at the ear and point B be at the sound source (Figure A1). As shown in the figure, H is the vertical distance from the source to the ear, d_p is the horizontal distance from the source to the ear, and d_w is the distance from the ear to the wall.

P is the point on the wall from which the sound can be considered to be reflected. It is located so that it constitutes the shortest path from B to the wall and back to the ear. The shortest path occurs for P such that the angle from B

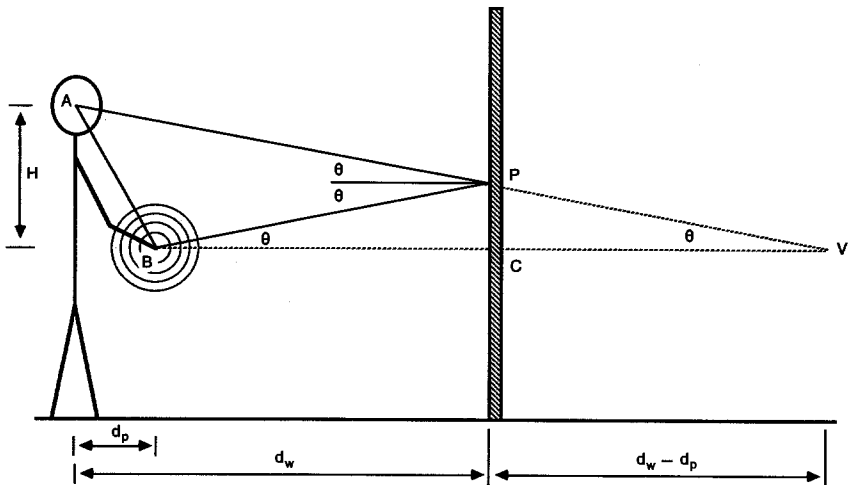


FIGURE A1 Information for distance from pulse-to-echo delay (Case 3).

to the perpendicular to the wall at P is the same as from A to the perpendicular. The size of these angles is θ . A virtual auditory image of the reflected sound is constructed at V as the intersection of a line parallel to the ground and passing through B and as an extension of the line AP . Note that the angle PVC is of size θ . Triangles BCD and VCP are, therefore, similar. Thus, the distance of V to C is equal to $d_w - d_p$.

Using this construction, we can compute the length of the echo path and, thus, the echo time. The echoing sound must travel from B to P and back to A . This distance is the same as that from V to P to A . Therefore, the distance the echo travels is

$$\{[d_w + (d_w - d_p)]^2 + H^2\}^{1/2}. \quad (1)$$

After reorganization and division by the speed of sound, c , this shows that the echo time t_e is

$$t_e = (4d_w^2 d_p + d_p^2 + H^2)^{1/2}/c. \quad (2)$$

The pulse time, t_p , is equal to the pulse distance divided by c :

$$t_p = (d_p^2 + H^2)^{1/2}/c. \quad (3)$$

To solve for d_w , the distance to the wall, we first compute the difference between the squares of these times:

$$t_e^2 - t_p^2 = 4d_w(d_w - d_p)/c^2. \quad (4)$$

Setting this equation to zero and using the quadratic formula to solve for d_w gives

$$d_w = \{d_p + [d_p^2 + c^2(t_e^2 - t_p^2)]^{1/2}\}/2. \quad (5)$$

Thus, d_w is specified by the difference in the squares of the pulse and echo times, the constant c and the parameter d_p . Note that for a source in the plane passing through the ear and parallel to the wall (e.g., when the hand is held out to the side of the body) $d_p = 0$ and the equation simplifies to

$$d_w = c(t_e^2 - t_p^2)^{1/2}/2. \quad (6)$$