# *Space in Sound:*

*Human active echolocation*

## Final Term Paper

## PSYC 501 – Auditory Perception

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The use of self-generated acoustic emissions by animals as a means of perceiving and localizing objects within their environment is a well-studied phenomenon. Through acoustic comparison of a perceiver-generated wavefront (pulse) and its reflection off a surface (echo) an organism can access information on the spatial characteristics of its surroundings. This form of auditory-spatial perception, known as *echolocation*, was first identified in 1938 by zoologist Donald Griffin. At Harvard University, Griffin became intrigued by the mechanisms underlying bat navigation, particularly after reading "elementary accounts of Spallanzani's experiments showing that blinded bats flew normally" (Squire, 1998, p. 73). His own subsequent investigations (Griffin, 1940) confirmed ultrasonic ranging as the basis of bat navigation and earned him the reputation of the pioneer of echolocation research. Since then, observation and documentation of the echolocative capacities of bats (see Simmons, 1989 for a review) as well as porpoises (Kellogg, 1961), whales and select terrestrial mammals (Stoffregen & Pittenger, 1995, p. 182) have contributed to the formation of a sophisticated and ample body of literature.

One species that is not an immediately obvious user of echolocation is our own. However, it has been demonstrated that both blind and sighted people can, and do, utilize this form of perception (Ammons, Worchel & Dallenbach, 1953; Kay, 1974; Kellogg, 1962; Rice, 1967; Teng & Whitney, 2011). In fact, echolocation may play a far more prominent role in human spatial perception than is generally supposed. This paper seeks to illuminate these capacities through a brief review of current knowledge on the topic of human active echolocation. Following this, potential mechanisms and sources of information that underlie particular discriminative capacities will be presented in reference to specific experiments. Finally, this paper will discuss modern perceptual aids, the product of a dynamic discipline combining engineering and psychology. It is from this point that suggestions about future directions in the field will be elaborated.

## I. Where the field stands: human echolocation in the literature

For those involved in the field of perceptual psychology, human active echolocation may not be a completely alien concept. Anecdotes involving blind individuals riding bicycles (Rosenblum, 2009), skating and playing sports (Schorn, 2009) are present in many lectures and textbooks on human perception. Indeed, echolocation has found its place even within popular culture. For instance, Marvel

Comic's super-hero *Daredevil*, rendered blind in a radioactive accident, is bestowed with enhanced perceptual powers enabling him to fight crime. What these examples demonstrate is a general awareness of the use of sound to characterize space. What they *do not* demonstrate is an empirical, quantitative approach to understanding these capacities. This section will outline the history of such investigation.

The first observation of retained spatial perception in blind people was by French philosopher Denis Diderot in the 18th century. Diderot (1789) described astonishment at a blind acquaintance's "amazing ability" to perceive and avoid objects. Numerous theories arose to explain this phenomenon[1], the foremost of which was the facial vision hypothesis. Proponents of this theory attributed blind spatial perception to an enhanced tactile acuity on the skin of the face. Hyper-sensitivity to perturbations in air currents, temperature and pressure could hypothetically guide navigation. While in retrospect this may seem ponderous, there is a certain sophistication in this theory of somatosensory enhancement. It acknowledges perceptual gains often observed in preserved modalities when individuals lose a sense – so called sensory substitution (e.g. Rauschecker, 1995). The facial vision theory of object detection would remain popular for two centuries.

Empirical investigation of obstacle detection by the blind began in the 1940s. Supa, Cotzin and Dallenbach (1944) performed a series of experiments on spatial discrimination abilities in the blind. By systematically disrupting either facial tactile sensitivity or auditory sensitivity, they proved that it was auditory perception of echoes reflected from surfaces that enabled obstacle detection when approaching a vertical board. As such, they effectively disproved the facial vision hypothesis and demonstrated audition to be the modality underlying detection. Ammons et al.(1953) replicated the findings of the Cornell studies conducted by Supa with two interesting distinctions. Firstly, they addressed potential issues of ecological validity by performing the experiment out-of-doors, in the presence of ambient noise and environmental distractions. Secondly, the participants were *sighted* individuals. Their findings were congruent with Supa et al., demonstrating a high degree of task competency despite their differing design and experimental group.

Arias (1997) identified "two basic modalities" of human echolocation. The first involves simple detection of obstacles within the environment, whereas the second is concerned with discriminating

[1] Described at length by Hayes (1935) who researched and identified fourteen independent explanations of the period ranging from the pragmatic (and correct) auditory perception hypothesis to occult and supernatural theories.

physical characteristics of that which is detected. With detection proven (Supa et al., 1944; Ammons et al., 1953), research in the 1960s turned its focus to the second modality in hopes of identifying particular object features discernable through echo perception. Kellogg (1962) was the first to apply traditional psychophysical techniques and obtain quantitative measures of echo-perception. In a series of experiments, it was demonstrated that individuals could reliably detect differences in object distance, texture and size. Importantly, they reported that, while blind subjects tended to excel, sighted subjects rarely performed above chance. However, a series of studies performed in subsequent years suggested that echo-perception was not unique to the blind. Rice (1967) found both blind and sighted people (to a slightly lesser extent) are able to detect targets monaurally, to discriminate simple shapes and to locate targets in space. Other experiments on sighted subjects confirmed findings of obstacle detection (Ammons et al., 1953), simple shape and texture discrimination (Hausfeld, 1982), and accurate spatial localization (Teng & Whitney, 2011).[2] In fact, it seems Kellogg's (1962) findings of chance performance in sighted subjects represent the exception. It appears that with little training both blind and sighted subjects can localize objects and perceive specific physical characteristics. General observations common to the studies above include:

i. Quantitative results that were highly consistent with psychometric functions observed in other sensory modalities for detection tasks, generally appearing sigmoidal (see Figure 1). This is true of both blind and sighted participants.

ii. Ceiling performance was rapidly achieved. For instance, Hausfeld (1982) observed near-optimal performance by trial block number two of ten with little subsequent improvement thereafter. Also noted by Rice (1967) and Teng and Whitney (2011)

iii. Certain tasks proved more difficult than others – for instance, discrimination of size was far worse than that of texture, distance or position (Kellogg, 1962)

iv. Blind subjects consistently outperformed the sighted. However, exceptional skill was observed in some sighted participants. Teng and Whitney (2011) reported on a naive

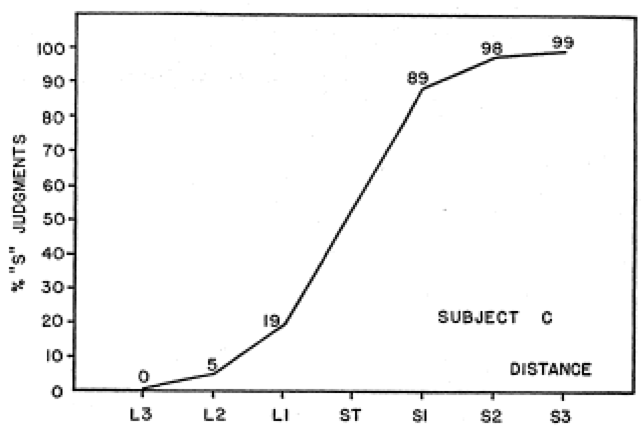


*Fig. 1 – psychometric function of a subject on distance discrimination paradigm (Kellogg, 1962, p. 401)*

2 Teng and Whitney (2011) utilized a form of the vernier acuity task (McKee & Westheimer, 1978) adapted to the echo-perception domain to test the fine-grained limits of spatial localization.

sighted subject whose precision approached that of a congenitally blind expert.

v. Large variations in individual performance were observed despite normal audiometric profiles in all participants. Firstly, individual techniques differed between subjects. For instance, when generating pulses, most subjects employed either discrete clicks or prolonged hissing but other pulse varieties were often reported.[3] Furthermore, it is likely that pre-existing aptitude differences existed as well, evidenced by the high degree of performance stability within subjects.

vi. Blind participants spontaneously produced exploratory head motions, a behaviour absent among the sighted. Interestingly, this behaviour has also been observed in porpoises as they perform undersea ranging (Kellogg, 1959; Norris *et al.*, 1961). Deemed auditory scanning it is thought to combine echo ranging and binaural localization. The lateral head oscillations help accentuate the differences in echoes received between the two ears by continuously modulating the inter-aural intensity and phase differences (Kellogg, 1961),

## II. Proposed mechanisms underlying echolocation

The body of literature summarized above demonstrates empirically that humans do possess echolocative capabilities. As the study of auditory perception has progressed so too has our understanding of the physics of sound. While this paper does not endeavour to address the complex mathematics of acoustic interactions, a practical understanding of the mechanics relevant to echo-perception is fundamental to appreciating this modality. This section will address how distance, texture, size and motion can be coded in sound. Each description will be supplemented with reference to experimental paradigms. Lastly, the use of intermodal cues in auditory spatial perception will be acknowledged.

*Distance Discrimination:*

Capacity to detect distance is of primary importance to any perceptual system involving spatial relations between an observer and his surroundings. This is accomplished by comparing stimulus characteristics of a self-generated pulse with those of its echo. The result is a representation of physical surroundings in the form of an object space.

3 Most investigators did not compare performance between those who used clicks and hisses. Rice (1967) found both signal types "sufficient to provide information on the presence or absence of an object."(p. 660) Furthermore, when forced to switch from clicks to hisses and vice-versa, individuals demonstrated a decrement in performance. This suggests that no signal is superior and that preference is idiosyncratic. However, Arias (1997) suggested broadband hissing may provide a pulse that is superior to clicks because of its continuous nature.

The most immediately obvious cue of distance is that of the pulse-to-echo (P-E) delay (Stoffregen & Pittenger, 1995). Essentially, assuming the speed of sound through air to be relatively constant[4], the time delay between when the original pulse and its echo are perceived is a function of the distance between the reflecting surface and the ear.

Consider a situation in which a person facing a reflecting surface(wall) snaps his or her fingers with their arm at distance $d_p$ in front of them.

Let $d_p$ = distance from pulse's point of origin to ear, $d_w$ = distance from wall to ear and c = speed of sound through air

$time_{pulse}$ (time it takes the pulse to reach the ear)= $d_p/c$

$time_{echo}$(time it takes for the pulse to reach the wall and reflect back to the ear) = $(2d_w – d_p)/c$, as wave must travel from pulse source to wall and back

P-E delay = $t_e – t_p = 2(d_w – d_p)/c$

$d_w = [c(t_e-t_p)/2] + d_p$ (see figure 2)

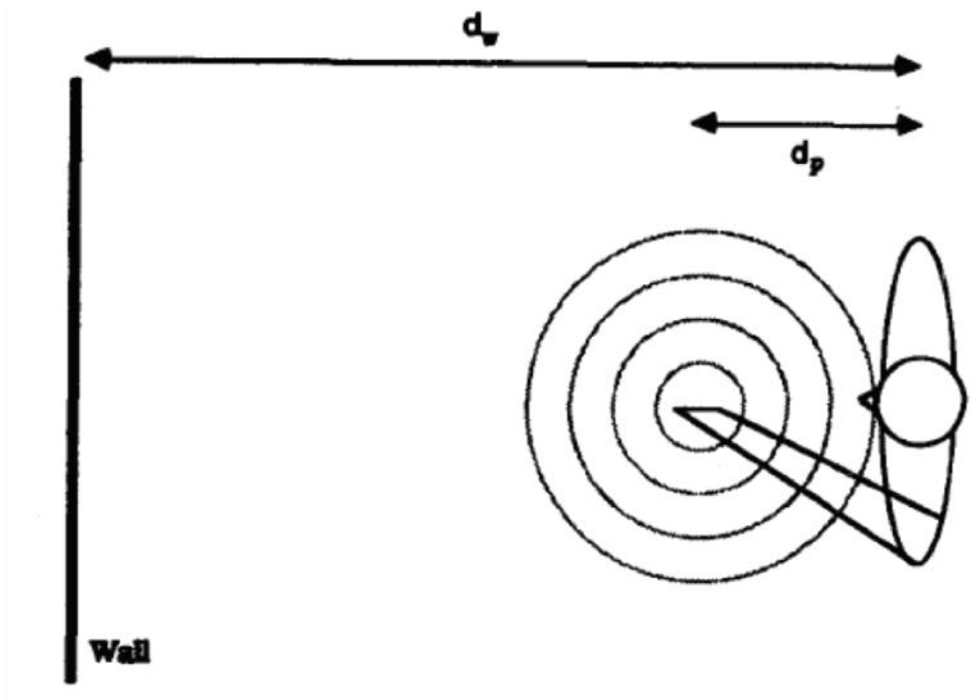


*Fig. 2 – A schematic diagram demonstrating the principal of Pulse-Echo Delay (Stoffregen & Pittenger, 1995, p. 188).*

Thus, the distance to the reflecting object, $d_w$, can be derived if information regarding the distance of the original pulse source from the ear and the speed of sound are accessible. For humans performing echo-perception, pulses are generated as utterances from a consistent location (i.e. the vocal tract) at a well-

[4] Speed of sound at 0°C is approximated at 334 m/sec (Camhi, 1984).

known distance from the ears. To calibrate the speed of sound, Stoffregen and Pittenger (1995) acknowledged the necessity of an intermodal cue. For instance, the delay between when a perceiver feels the somatosensory feedback of producing a vocal click and the pulse's arrival can disambiguate the speed of sound.[5] P-E delay is well-demonstrated in Kellogg's 1962 distance-discrimination paradigm. Subjects were asked in a paired comparison whether the second of two identical wooden disks was located nearer or further than the first placed at a standard distance (two feet). A more distant test disk would generate a larger P-E delay. Subjects demonstrated extremely high sensitivity to very minute delays, in some cases on the order of approximately 0.0003 s.

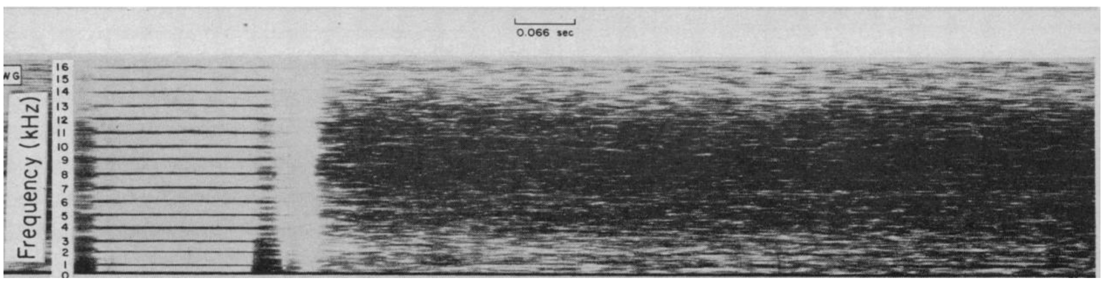


*Fig. 3 – The frequency spectrum of a human hiss. Similar to 'white noise', it contains a wide range of frequency components (Y axis) over time (X axis) (Rice, 1967, p.660).*

A second fundamental cue in distance discrimination is based upon the frequency relations between pulse and echo (see Wilson, 1966). Clicks and hisses are both broadband noises containing a wide range of frequencies within their spectra (see figure 3). If two sound waves are in phase with one another, an amplification effect is observed that increases the intensity of sound at their shared frequency. Thus, at various distances different frequency components of a pulse would be enhanced by the echo, resulting in specific increases in the perceived loudness of those components.

That distance is represented by:

$d = c/2f$, where $f$ is a given frequency

Bassett and Eastmond (1964) were among the first to investigate the phenomenon in which a predominant pitch arises through the interaction between a pulse and echo. This pitch varies with

[5] This notion is supported through an observation by Rice (1967) that certain subjects struggled to perform echo-perception tasks when their self-generated clicks were supplanted by artificial, externally generated clicks from a speaker. However, this effect was not universal within the experimental group.

distance from the reflecting object. Participants held a speaker outputting broadband noise while a pure tone was played through a second distal speaker. Facing a reflecting panel, they were instructed to listen within the broadband noise for the predominant pitch that emerged. Once identified, subjects had to walk towards or away from the board until the emergent pitch matched the pure tone sample. They found that the distance considered to match the pure tone was accurately predicted by the equation above. Thus, if frequency component amplification exists in a fixed relationship with distance, the frequency relations between a pulse and echo could certainly cue distance.

The cue discussed above was discovered by Thurlow and Small (1955) and is known as a repetition pitch or rippled noise pitch. It was observed that when individuals listen to a pair of identical trains of pulses slightly offset in time, a pitch emerged that was "equal to the reciprocal of the smallest time separation between leading edges of proximal pulses of the two trains."(Arias, 1997) An echolocative pulse and its echo are likewise identical sound stimuli slightly offset in time. The tone that emerges as a result of pulse-echo interference varies inversely with distance as some frequencies are cancelled and others enhanced. This cue is evidenced by Ammons et al.(1953) who reported that blindfolded subjects experienced "a change of sound in their footsteps" as they approached a vertical board. Presumably, if interference patterns can be detected in discrete sonic events such as footsteps, a continuous signal would provide an even better cue. For this reason, Arias (1997) posits that continuous broadband hissing should provide the best signal. To date, however, no comprehensive comparison has been performed to test this.

*Texture Discrimination:*

Another object feature that can be readily discriminated using echo-perception is texture. The physical composition of objects determines their sonic absorption properties such that some frequencies will be absorbed and others reflected. By comparing the relative frequency spectra of pulse and echo, texture is disambiguated. Rigid surfaces such as glass will reflect more high frequency waves while soft surfaces such as cloth tend to reflect the low. Kellogg (1962) had individuals attempt to discriminate between six equally sized disks made of various materials (glass, painted wood, denim, velvet, metal and plain wood). In paired comparisons, subjects could discriminate sixteen of the twenty-one combinations at an average accuracy of 94.5%. Only in pairs of substances with similar densities (e.g. glass and metal) was performance at chance.

Texture discrimination provides another explanation for the popularity of clicks and hisses in echo-perception. Both pulses employ broadband noise which would provide a diverse sample of frequencies across the spectrum. By observing which spectral aspects are attenuated through absorption, a clear idea of an object's composition can be determined.

*Size Discrimination:*

The cue that is most fundamental to discriminating the size of a reflecting object is the relative intensity of the pulse and echo. Larger obstacles occupy more space and will therefore reflect a greater amount of acoustic energy. That being said, Kellogg (1962) found that subject performance was far worse on tasks involving the discrimination of different sized disks at a fixed distance than on tests of distance or texture discrimination.

Stroffregen and Pittenger (1995) call attention to the fact that "by themselves intensity differences… 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" (p. 194). As discussed above, the difference in pulse and echo intensity is also affected by object distance and composition. Segregating the specific proportion of intensity change that can be attributed to each quality - size, distance and texture – may be difficult. The ambiguity could potentially be overcome if intensity differences are in some way cross-referenced with both delay information, disambiguating distance, and frequency spectrum information, disambiguating substance. Still, simultaneous calculation of these factors is resource intensive and subject to error which may explain subject difficulty on size detection tasks.

*Motion Discrimination:*

A motion cue that is particularly tangible, even for the sighted, is one most people experience daily: the Doppler shift. First noted by Austrian physicist Christian Doppler in 1842, it is the net change in a perceived frequency at a specific point of observation caused by the movement of objects relative to that point. This frequency shift is caused by changes in the spacing of each successive wave front such that approaching objects produce a systematic increase in frequency while receding objects produce a decrease in frequency. The sliding ascent and descent in frequency we experience when a motorcyclist approaches and passes us is a good demonstration of this. In the case of echolocation, if an individual generates a pulse of known frequency, the velocity of an approaching or receding object can be determined based on Doppler shifting in the echo fronts. Schnitzler & Henson (1980) have studied this cue in bats, specifically *Rhinolophus ferrumequinum*, who utilize pulses fixed around 80 kHz and are capable of detecting Doppler shifts as small as 0.0375% (30Hz).

*Intermodal Cuing:*

All the capacities discussed in this section are supplemented by information encoded by other perceptual systems other than audition. Over-dependence on a single system when navigating environments with potentially harmful obstacles is a poor strategy for survival. Thus, while a blind individual may tap with his cane to produce echolocative pulses, added tactile feedback confirms what is below his feet and what lies before him.

Intermodal cuing does not end with the sense of touch. In Ammon et al.'s (1953) outdoor echolocation experiment, it was demonstrated that individuals could detect obstacles even in complex environments replete with distractions (e.g. 30-70 dB ambient noise, traffic, construction, wind). The task involved approaching a wooden board from an unknown distance until they had perceived or collided with it. Interestingly, they reported instances in which subject performance was substantially aided by use of tactile and olfactory cuing. Wind was used in two ways:

1. When walking against the wind, subjects could detect its absence when the object acted as a wind shield.
2. When walking with the wind, subjects could detect the board by reflected air currents.

Participants used sunlight in a similar way, using the temperature decrease when the board occluded the sun and cast them into shadow and temperature increases when the light was reflected. Use of a Masonite board enabled the use of olfactory cues as well, as it gave off a distinct odour when exposed to direct sunlight. The researchers observed that these cues were used with particular frequency during the early stages of learning when participants would rely on any and every piece of information that would serve them in the task. Of course, to confirm that their results were not confounded by the use of these cues, subsequent experiments were performed. Subjects performed the same tasks at night and with nose-plugs, eliminating tactile and olfactory cues, and still demonstrated excellent echolocative proficiency. Thus, these intermodal cues were supplementary but not necessary for detection.

With simple cues such as pulse-echo delay, frequency, and intensity differences a variety of conclusions about the objects in one's environment can be made. Presumably, detection of the minute temporal and intensity differences necessary for the application of these mechanisms is well within the capabilities of our auditory system. Even naïve subjects rapidly grasp tasks. The ease with which subjects acquire tasks could be taken to suggest that while humans are rarely dependent upon audition for navigation, we constantly encode and utilize these cues throughout our lives. Making associations between how a carpeted room looks and how it sounds is most likely happening all the time outside our awareness: an intriguing thought.

## III. Where bat meets man: modern perceptual aids

Since the 1960s, improvements have been made in our understanding of human audition and the essential factors underlying the masterful echolocation of bats. Bridging these two bodies of knowledge, mechanical engineers have had marked success in creating perceptual aids for the blind. This section will review the essential characteristics of perceptual aids, primarily by examining the work of Dr. Leslie Kay, a distinguished researcher in the field.

Development of perceptual aids began in the 1950s. An early question was which sensory system (somatosensory or auditory) was optimal for presentation of spatial information. Tactile imaging displays use digital processes to convert optical information into an output perceived by touch. Generally this involves the use of a rectangular array of pins positioned on the user's finger with which the information is presented. The enhanced tactile sensitivity of the fingers provides the discriminatory accuracy necessary to make use of this information. Tactile displays have proven to be very useful in reading aids (Bliss, 1970), enabling the conversion of written content into something not dissimilar to Braille. However, Bliss (1970) found that modifying this technology to work as an environmental sensor has yielded poor results. Even simple form detection and tracking tasks appear overly complex for tactile display systems.

It is not surprising, then, that the vast majority of blind mobility aids utilize auditory displays. Devices such as the Pathsounder (Russell, 1965), Mowat Sensor (Pressey, 1977) and Tri-Sensor (Kay, 2000) all use sound to encode space with surprising efficacy. The earliest aids (Cooper, 1950; Kohler, 1964; Shroger & Susskind, 1964) were designed for simple obstacle detection. Thus, they generally functioned to make users aware of imminent collisions at relatively short distances within a narrow angular range. However, given that many blind people make use of a cane or guide-dog and presumably also employ echolocative cues, simple obstacle detection devices hardly seem useful.

A more ambitious program is seen in the work of Dr. Leslie Kay, who has spent over six decades in the field (see Kay, 1946; 1966; 1974; 1976;. 1980; 2000; 2001). Unlike basic obstacle detectors, Kay's aids seek to provide highly detailed spatial representations. His approach is unique in that he believes it is best to "present to the brain the maximum amount of environmental information which the auditory sensory channel could effectively transmit" and have users learn to "disregard both redundant and unwanted information merely by switching [their] attention" (Kay, 1974, p. 608). Much like we select our points of focus in vision, a user would learn to hone in on relevant sonic features. Kay calls this process sonocular perception.

The recently-developed Trisensor (Kay, 2001), one of Kay's many devices, will provide a representative example. The Trisensor is an ultrasonic spatial sensor worn on the head. It functions by first emitting pulses of ultrasonic noise (70-140kHz) from one central and two peripheral transmitters. The echoes produced are subsequently recorded and processed by on-board electronics. This information is converted into an audible code, which is output binaurally through headphones at frequencies within the audible human range. The information coding occurs on two dimensions:

1. *Distance* is coded with frequency such that as the distance of a reflecting surface increases, the frequency used to represent it increases. The frequency range spans 20 – 5000 Hz and codes objects at up to 5 metres from the unit.
2. *Direction* is mapped binaurally using interaural intensity difference (IID). For instance, an object located to the left of the sensor on the azimuth will be presented at a higher intensity to the left ear. This is particularly intuitive for users as IID is already a fundamental cue used in every-day auditory source localization.

Through these two features, the user can produce a mental map in which the multiple tone complexes reflect various objects in the environment (see figure 4). As subjects reorient their head, the tone complexes change in frequency and move laterally in synchrony with head movement. Intuitively, users begin to connect the tone complexes with objects existing in space.

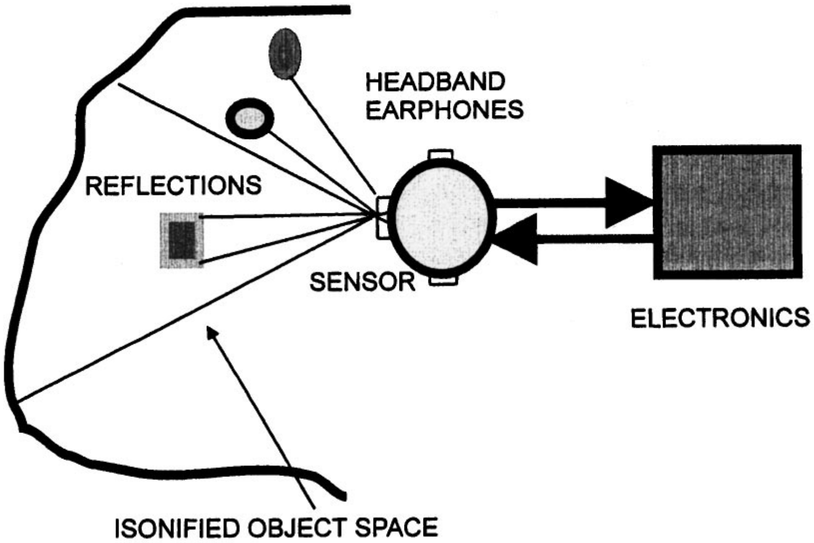


*Fig. 4 – A schematic diagram illustrating a TriSensor user observing an 'object space' (Kay, 2001, p.804).*

The use of ultrasonic pulses in the Trisensor confers a distinct advantage. The extraordinary echolocators of the animal kingdom such as bats have evolved to use very high frequency pulses (Kay, 1962). This is explained by the process of diffraction, the change that occurs in the direction of waves of energy as they pass around an obstacle. The degree to which a wave's direction is affected is directly proportional to its wavelength. Thus, high frequency waves experience the least diffraction. Waves with sufficiently small wavelengths will only be able to reflect directly back upon encountering an obstacle. Thus, the use of ultrasonic pulses in perceptual aids greatly enhances the quality of the information that is received. It is important to note that using ultrasonic pulses necessitates that the echo signal be demodulated into the human audible range. This is performed through a digital process that shifts the frequency of a target wave (i.e. the echo) into a useful range. By combining the original carrier wave, f1, with a wave of another frequency, a new beat frequency is produced equal to the difference between the two. This new beat frequency retains the original signal of f1, but at a lower frequency. Through demodulation, the Trisensor can use high frequency pulses and enjoy limited diffraction while still being able to present a functional auditory output to users.

The three forehead-mounted sensors that give the device its name function in a way that is analogous with vision. The dual peripheral fields focus on the areas to the left and right of the azimuth. Acting like peripheral vision, they 1) enable detection of objects in their respective fields and 2) guide user movement through acoustic flow (similar to global optic flow) in which motion of the user relative to the acoustic environment manifests itself as a global Doppler shift (Stoffregen & Pittenger, 1995). Finally, the direction coding (based on IID) in these peripheral sensors allocates 1 dB of intensity change per angular degree. In comparison, the central field is akin to the fovea of the visual system. The central sensor allocates 2 dB of intensity change per degree which greatly improves its ability to code small spatial differences. Using these two regions in tandem, an object initially detected in the periphery can be inspected more closely by placing it in the central field and performing a neck saccade.

The utility of Kay's devices is buttressed by both anecdotal and experimental evidence. Dr. Kay has been prolific, publishing frequently on his work. That being said, the majority of his papers do not involve any form of rigorous psychological experimentation. His tendency has been to provide his devices for no charge to a cohort of blind individuals who integrate it into their day-to-day experience. Afterwards, they provide suggestions or comments. This investigative style conforms to his primary objective: to optimize his devices and best improve the quality of life of users. His publications contain reports of such capacities as:

1. Navigating distances of 1 km by different routes including a quiet suburban area, a busy residential area and a business intersection (Kay, 1974). This included avoiding pedestrians, following sidewalks based on texture cues and crossing the street.
2. Differentiating between the sides of a USA penny through recognition of the different tone complexes associated with the "head" and the "memorial" sides (Kay, 2001).

Generally, blind participants reported feeling highly proficient within the first week using the device. Furthermore, in one cohort, 90% felt they had benefitted from their perceptual aid and 80% opted to keep their device following their week-long trial (Kay, 1974). While this evidence is subjective, it seems clear that the Trisensor is capable of conferring real benefits to blind users.

Empirical tests of these devices have also occurred. Kay (2001) conducted an experiment to quantify the minimum angular spacing between equidistant identical rods necessary for object resolution. 13 naive sighted subjects were asked to locate

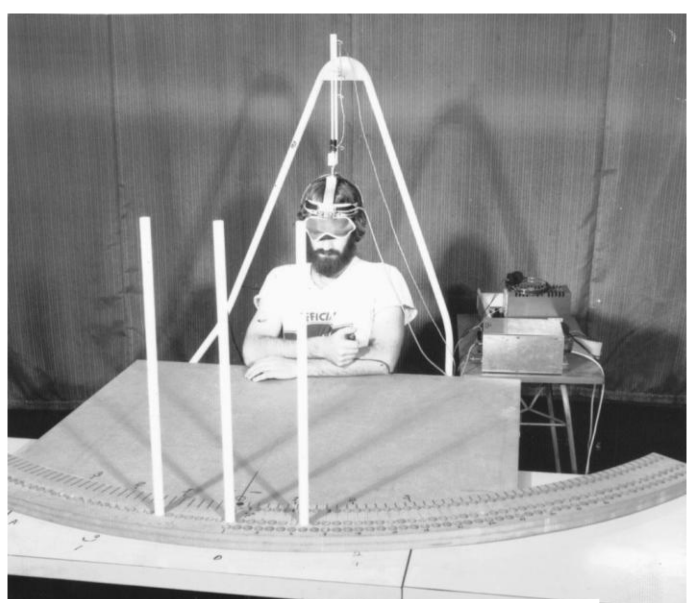

*Fig. 5 –The apparatus used in Kay (2001, p. 804).*

a target rod placed between two masking rods at the same radial distance (see Figure 5). This arrangement is particularly difficult as each rod was equidistant and no distal pitch cue was usable. Thus, the subjects could only use IID. All subjects could resolve at 8-10° of spacing, 10 were capable at 6°, and 4 were capable at 4°. A similar experiment involving rod counting performed with blind children aged 7-11 (Hornby, Kay, Satherlay & Kay, 1985) yielded similar results. In a sensory substitution study (Strelow, Warren, Sonnier & Riesen, 1987), neonate macaque monkeys blinded at birth were raised for 1 to 3 months while continuously wearing the Trisensor. The animals demonstrated head-scanning and 'looking' with the device by the third or fourth week. For example, animals would orient the sensor's field of view to include target objects while performing reaching behaviours. When placed in novel environments, they rarely collided with obstacles. Lastly, when experimenters turned off the device, the animals were hyperactive, producing mannerisms and loud vocalizations in a display of stress. They concluded that animals reared with the device "are active, and reasonably normal, with good mobility" (p. 740).

In sum, perceptual aids such as Leslie Kay's Trisensor can be effectively used by blind and sighted subjects to navigate and engage with their environment. Bio-mimicry of the mechanisms used by nature's master echolocator, the bat, enhances existing human capacities to use sound to perceive space.

## IV. Future directions

The study of human active echolocation is interesting in that it has been largely dormant for half a century. The majority of experiments investigating human active echolaction occurred in the 1960s, with few since. It could be presumed that this is because there is not a great deal of utility in investigating how sighted people can learn to tell different disks apart using only tongue clicks. The findings were robust enough to conclude that this capacity exists, but did not open many new avenues for research. Further study of this phenomenon, unless from a truly novel perspective, is unnecessary.

That being said, the continued improvement of perceptual aids is highly worthwhile. At this point, these devices are rarely used by the blind population. This is partially attributable to the difficulty in promoting them within the community (Kay, 1974). A closed system of blind mobility experts and pedagogues continue to insist use of traditional methods, namely guide-dogs and long cane navigation. Along with this exists the mistaken notion that perceptual aids are costly devices. Interestingly, a synergistic effect has been observed when using perceptual aids in addition to traditional aids such that training time for both can be reduced (Kay, 1974). If this is the case, money saved on reducing training with certified specialists could be used to offset the cost of the device. Kay's latest aid, the K-Sonar, retails at slightly over $1000 which is less than the cost of some of the available cane training programs. In order to augment the popularity of such devices, engineers and researchers should attempt to form partnerships with blind mobility specialists. This would open up new experimental cohorts, bolstering the experimental literature and potentially clarify certain cost misconceptions.

The aids themselves should continue to be improved. Potential directions include:

1. Minimizing the degree to which the device affects users' normal perception of the auditory environment. Users should continue to be able to conduct conversations and analyze the auditory scene even with the device enabled. This can be achieved through continuing to improve earphone design to minimize the impact on natural hearing (see Morland & Mountain, 2008).
2. Reducing the size of devices while not compromising battery life.
3. Improving the field of view to include further distances and wider angles.
4. Considering inclusion of different dimensions other than distance and direction. Though it would present a substantial challenge, perhaps aspects such as colour could be represented with a code based in timbre.
5. Continuing to use animal models to test the effects of early intervention. Strelow et al.'s (1987) study with macaques found no evidence that intense exposure to the device interfered with normal development. Still, they insisted that much more research is necessary before similar trials are performed with humans.

## V. Conclusion

In sum, it is clear that humans make use of sound when navigating their environment with or without conscious awareness. This paper has reviewed past research and suggested potential mechanisms underlying this ability. While sighted individuals can quickly learn to use echolocative cues, the population for whom active echolocation is most important is the blind. Efforts to enhance these capacities have culminated in the development of modern perceptual aids, a field with significant potential to improve the quality of life of users.

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