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Directional Guidance Method for the Blind Using Time Separation Pitch Discrimination of Triple Pulse Signals

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INTRODUCTION

One of the most difficult problems in orientation and mobility training with blind people is that subjects veer either to the left or to the right while attempting to walk a straight path. This veering tendency is most pronounced when attempting to traverse an open area in the absence of consistent tactile or auditory cues (Cratty, 1971; Schaeffer, 1921). Blind people veer while walking on city sidewalks even in the presence of traffic noise. Correcting the problem is particularly difficult because the magnitude and direction of a person's veering tendency are unrelated to hand preference, leg length, or habitual tilting of the head (Cratty, 1971).

Untrained blind subjects who attempted to walk along a straight path, 61 meters long, on an athletic field were an average of 18.3 meters from the nearest point on the line when they finished (Cratty, 1971). Between trials, Cratty allowed each subject to inspect a board with two wires, one straight representing the correct path, and one bent into the shape of the subject's path. This training method enabled a group of blind people to reduce veer from 18.3 to 12.2 meters. Most mobility instructors discourage blind people from crossing open areas without external cues, because more accurate training methods are not available. A training method is needed in which a blind person can detect and correct veer, based on information from only gait and body movements.

We propose a training method in which a blind person receives continuous feedback while walking along a predetermined line. A subject would attempt to follow this line, defined as a straight, horizontal path. Deviations from the line would be measured as the distance between the final position and the closest point on the line. This method was designed to allow immediate recognition and correction of deviations from the straight path. The laboratory simulation of the training method involved detecting delays between sound pulses by observing changes in time separation pitch (TSP).

TSP is a perceived pitch resulting from hearing at least two highly correlated, broad-band pulses. (For example, the pulses could have the same shape or the second pulse could be the inverse of the first.) The pitch is matched most often to a frequency equal to the reciprocal of the interpulse interval. A pitch can be heard even when the frequency spectrum of the pulses has no energy at the TSP frequency. In previous experiments, researchers have examined either pulse trains (Yost, Hill & Perez-Falcon, 1978; Warren & Bashford, 1981), pulse pairs (McClellan & Small, 1967), or interactions of two pulse trains (Thurlow & Small, 1955; Small & McClellan, 1963; McClellan & Small, 1965). The literature contains little information about TSP perception in distinct pulse triplets (Ceruti, Floyd & Martin, 1982; Ceruti, Martin & Floyd, 1983).

The following is a description of the pulse transmitter system simulated in the experiments reported here. We hypothesized that an observer could follow a line by listening to the TSP perceived from two stationary, spatially separated and synchronized pulse

transmitters, one producing the first and third pulses and the other transmitter producing the second pulse, thus forming a pulse triplet (figure 1). The interpulse interval of pulses 1 and 3 would be held constant, while the second pulse would be exactly in the center of the fixed-pulse doublet when the observer is on the line. The observer would receive signals with unequal interpulse intervals if he or she deviated from the line and would perceive these deviations as a change in TSP. Altering the relative timing of the pulses from the transmitters would change the orientation of the line.
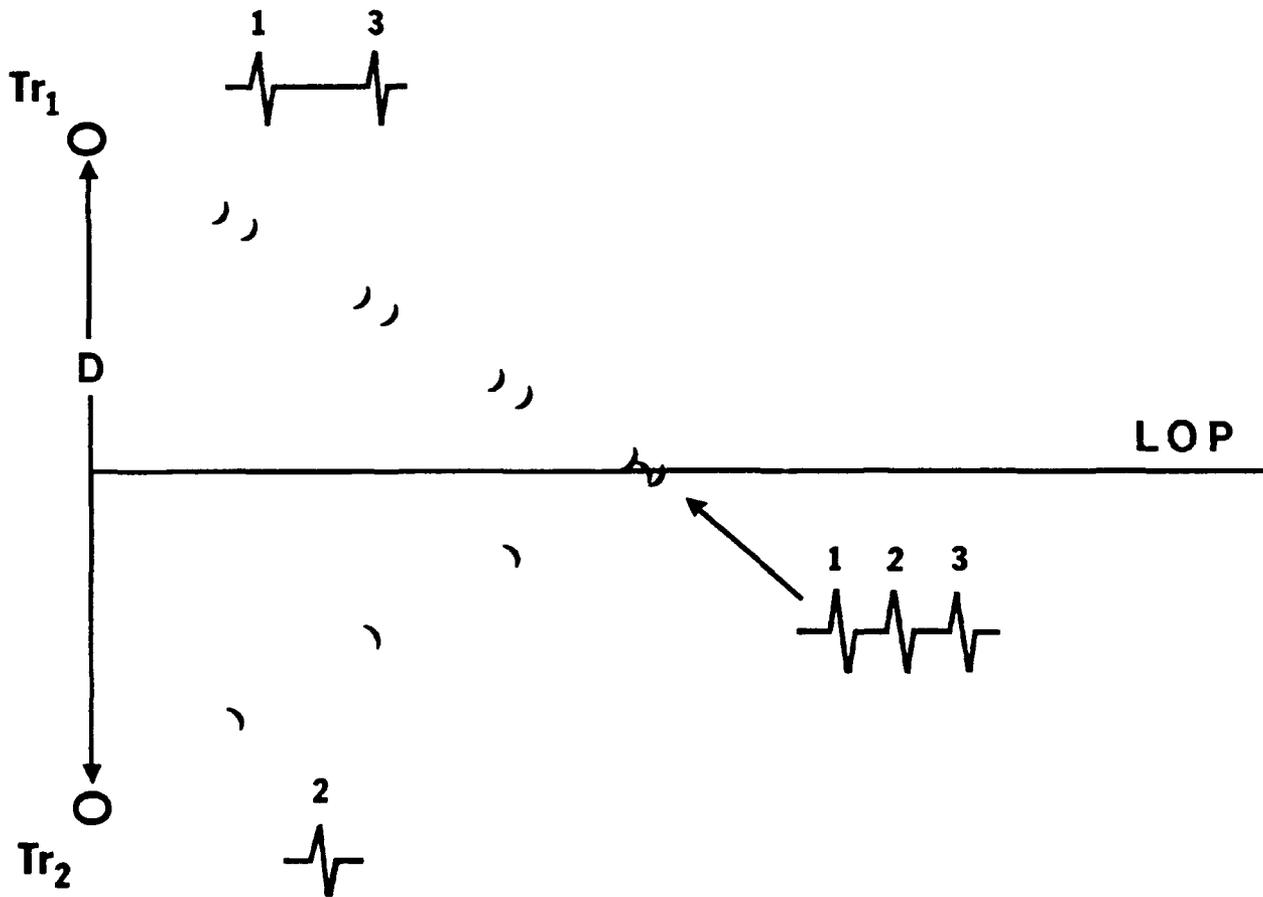
Figure 1. Schematic diagram of two synchornized pulse transmitters, Tr_1 and Tr_2 separated by distance D. TR_1 broadcasts pulses 1 and 3 while Tr_2 transmits pulse 2. A triple-pulse signal is formed with equal interpulse intervals along with the line of position (LOP).

The success of such a direction-finding system for the blind depends on the ability of the subject to recognize deviations from the line and to return to the line. We performed psychoacoustic experiments using signals simulating stimuli that a subject would hear while traveling on or near the line defined by three coordinated pulses.

A simulation was performed to test the concept of using TSP cues as an aid to blind navigation and to indicate whether field tests were justified because actual field tests with blind subjects would be costly. The results of these simulations are necessary to design tractable field tests because considerably more variance is expected in field tests than in the laboratory.

The objectives of these experiments were to determine the following:

1. Can human listeners distinguish a triple-pulse stimulus with equal interpulse intervals (standard) from a stimulus that was the same except for unequal intervals (test)?

2. Can listeners equalize the interpulse intervals by manipulating the signal and listening to the changes in TSP?

Positive results in both experiments would indicate the possibility of a directional system of navigation based on TSP.

If pulse 2 occurred before the center of the 4.0-ms, fixed-pulse doublet, the signal was called a negative-displacement test signal. Similarly, if pulse 2 followed the doublet's center, this was called positive displacement. The results of a signal discrimination experiment (1) and a signal-manipulation experiment (2) are presented in terms of the subjects' discrimination and equalization performance on both standard and test signals. The discussion includes the subjects' pitch perception of the stimuli and how this relates to correcting veer.

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EXPERIMENT 1—SIGNAL DISCRIMINATION

METHOD

Subjects

The four subjects (S_1 through S_4) were adult civilian or military personnel at the Naval Ocean Systems Center, Hawaii Laboratory. S_1 and S_2 were experienced psychoacoustic listeners, whereas S_3 and S_4 had little listening experience.

Stimuli

Signal parameters of the stimuli are summarized in table 1, and examples of the signals are illustrated in figure 2.

The time between the first and third pulses was fixed at 4.0 ms for both standard and test signals. For test signals, a DEC PDP 11/40 computer controlled the timing of the second pulse.

The standard signals were designed to produce a TSP frequency near 500 Hz, as this is the region where TSP strength is greatest (Yost & Hill, 1978). Two subjects matched a sine wave to the TSP of standard signals yielding a mean frequency of 485 Hz. TSP perception requires successive pulses to be broadband and highly correlated (McClellan & Small, 1965, 1966, 1967; Yost, Hill & Perez-Falcon, 1978). Therefore, the same pulse was repeated for all signals in both experiments. A test signal consisted of three identical pulses (figure 2), with interpulse intervals ranging from 1.5 to 2.5 ms. Ten positive and 10 negative test signals were tested in random order against the standard.

Apparatus and Procedure

A PDP-11/40 equipped with a DEC Laboratory peripheral system (LPS-11) was used in both experiments. Signals were played diotically to the subjects through earphones in an audiometric chamber. In each session, 50 test and 50 standard signals were presented randomly to the subject. The number of positive-displacement and negative-displacement test trials presented during a given session varied with the session. Stimuli were repeated at 10 pulse triplets per second.

Each subject could practice with identified standard and test signal trains before the start of each session. Because TSP perception does not seem to vary significantly with signal sound pressure level (Small & McClellan, 1963; McClellan & Small, 1966; McClellan & Small, 1967; Yost & Hill, 1978; Yost, 1982), the subjects were allowed to adjust the sound volume to a comfortable working value at the beginning of each session.

STANDARD

$T_1 = T_2$

(= 2.0 ms)

TEST

$T_1 > T_2$
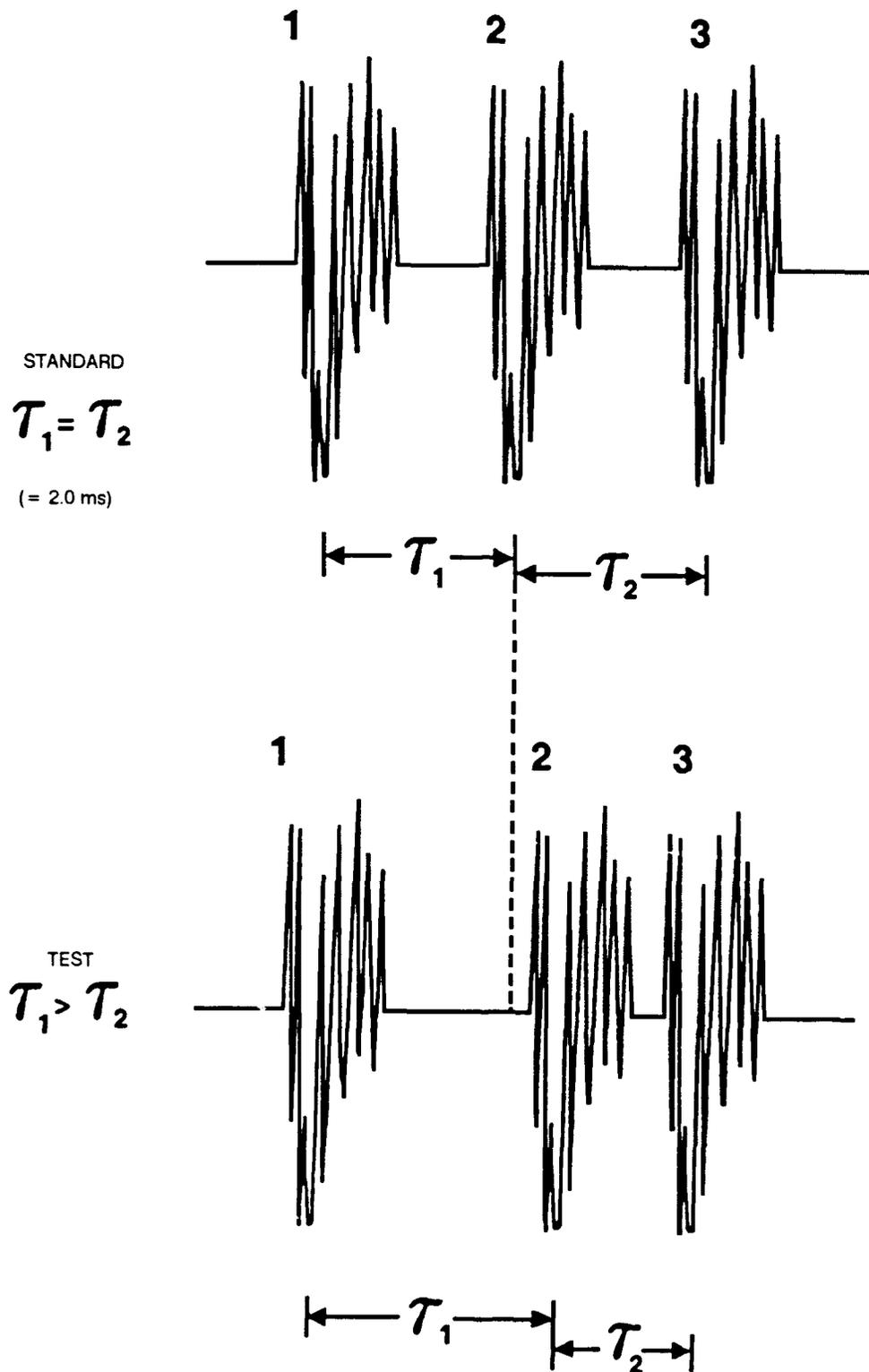
Figure 2. Examples of time waveforms of the acoustic stimuli, each stimulus containing three identical broadband pulses. In standard signals, the two interpulse intervals, τ_1 and τ_2 were always 2.0 ms. An example of a positive-displacement test signal is shown here.

Table 1. Conditions of signal-discrimination (1) and -manipulation (2) experiments.

Experimental Parameter	Experiment 1	Experiment 2
Range of variable-pulse displacement from fixed doublet center	−0.5 to +0.5 ms	−6.7 to +6.7
Smallest incremental displacement off doublet center*	0.5 ms	1.0 ms
Time between first and third pulses	4.0 ms	4.0 ms
Pulse duration	1.0 ms	1.0 ms
Pulse center frequency	2.4 kHz	2.4 kHz
TSP frequency, standard	485 Hz	485 Hz
Pulse triplet stimulus repetition rate	10 Hz	9 Hz
Standard trials per session	50	———
Range of positive-displacement test trials per session	23 to 27	———
Range of negative-displacement test trials per session	23 to 27	———
Total trials per session	100	27
Sessions for Subject 1	25	50
Sessions for Subject 2	25	50
Sessions for Subject 3	25	38
Sessions for Subject 4	25	31

*Note: Excludes trivial case of zero-displacement.

During the sessions, the computer program randomized the order of the signal presentations between positive and negative test signals, and between test signals and standard signals on a trial-to-trial basis by a Gellermann series (Gellermann, 1933). The subjects were instructed to respond by pressing buttons identifying either a test or a standard stimulus. The maximum duration of each stimulus was 15 seconds in each trial, and subjects had to respond within this time period. After the response, the computer discontinued the signal and provided immediate feedback to the subject.

RESULTS

Performance on test trials is shown in figure 3. For each subject, the percent correct detection is plotted against the absolute value of the interpulse interval difference within that particular test signal. The curves are visual fits to the data points. Data for positive and negative test signals were analyzed separately. Table 2 displays interpulse interval discrimination thresholds at the 70-percent correct detection level for positive and

negative displacement test signals measured by comparing interpulse intervals between test and standard signals. For example, for S_1, positive-displacement test signals, with interpulse intervals differing from 2.0 ms by at least 0.14 ms, were discriminated from the standard signal.

Subjects responded correctly to 82.5 percent of the standard signals presented, based on a total of 10,000 trials. The subjects' performance improved an average of 6.6 percent on standard trials, but performance on test trials did not vary systematically with time.
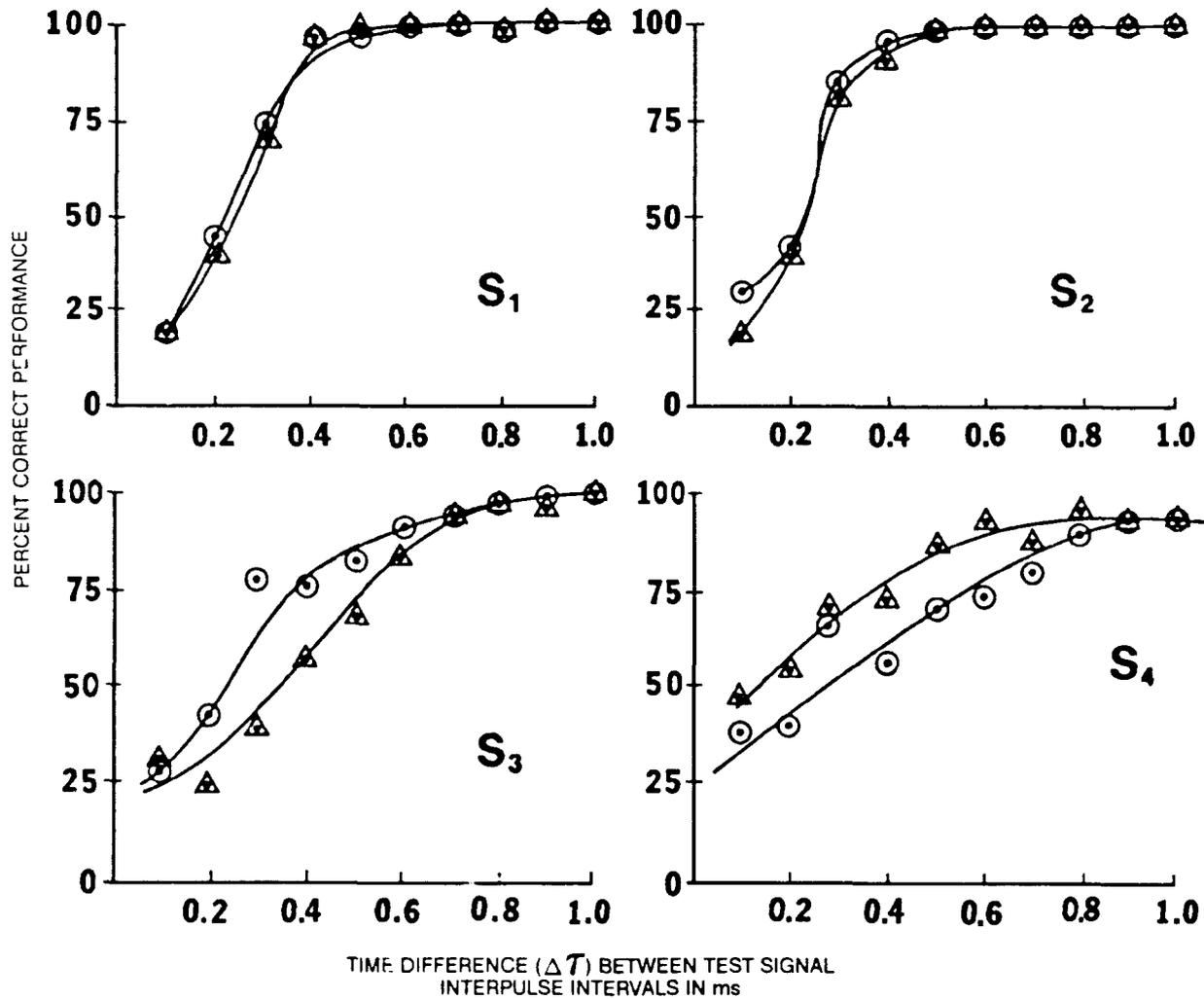
Figure 3. Psychometric functions for the signal-discrimination experiment for each subject. Circles represent positive-displacement test signals, and the triangles, negative-displacement test signals. The absolute value of each test signal interpulse interval difference is plotted on the abscissa.

Table 2. Experiment 1 results expressed as interpulse interval discrimination thresholds in milliseconds at the 70-percent correct detection level. Just-noticeable differences are between test and standard interpulse intervals (half the value from figure 3, showing interval differences within test stimuli).

Subject	Just-Noticeable Difference, Positive Displacement	Just-Noticeable Difference, Negative Displacement
1	0.14	0.16
2	0.13	0.13
3	0.17	0.24
4	0.25	0.15

We calculated the magnitude of positive deviation from a theoretical line of position for various distances, D, between two pulse transmitters (figure 1). A time resolution of 0.14 ms, the just-noticeable difference for positive-displacement test signals for S_1, and a sound velocity of 300 m/s were assumed throughout the entire range. Linear solutions were not expected because an analytic solution was not possible. The results of the calculation are shown in figure 4.
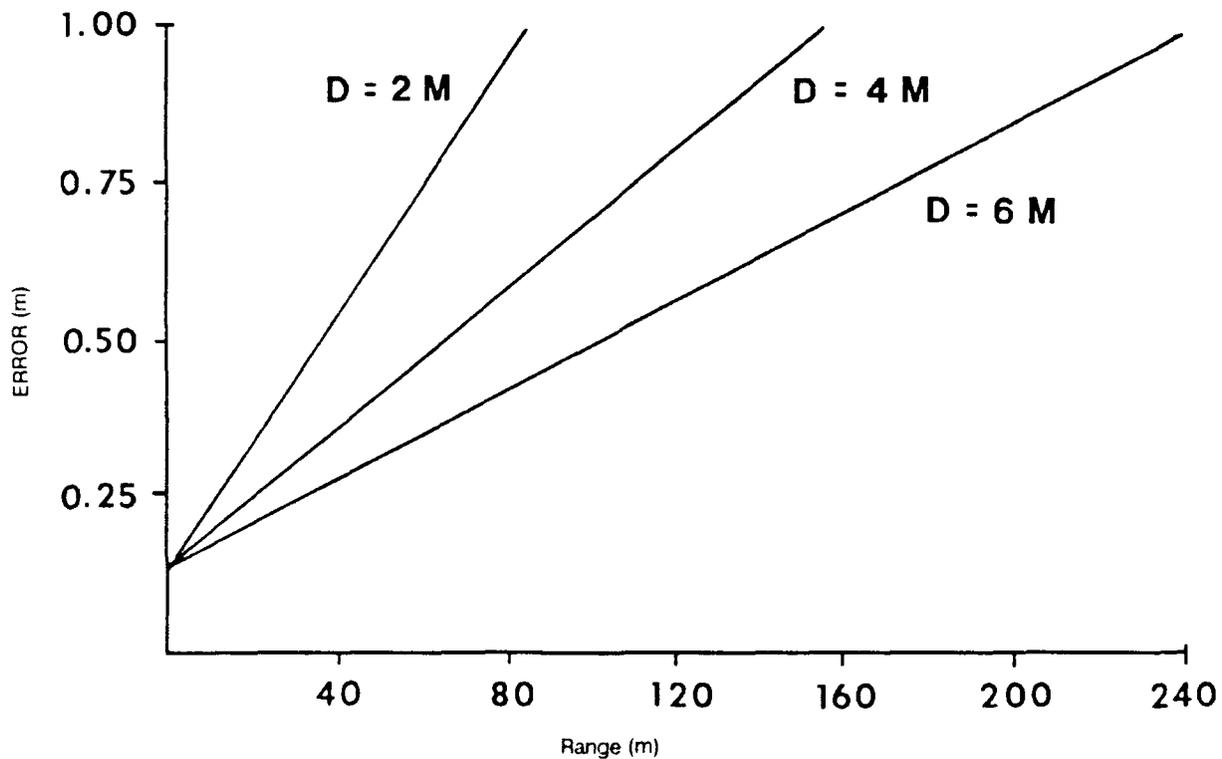
Figure 4. Deviation from the line versus guidance system range for sound transmitter separations, D of 2, 4, and 6 meters.

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DISCUSSION

These results show that experienced listeners could distinguish in a low-noise environment, a line defined by the standard signal, from a deviation from the line in either direction, represented by test signals. For the worst case shown in figure 4, corresponding to a transducer separation, D, of 2 meters, a subject could detect simulated deviations from the line that were about 0.4 meter over a range of 30 meters. In contrast, Cratty (1971) measured veering tendencies in trained blind subjects. He determined that veering less than 6 meters from a straight line over a range of 30 meters represented good performance for adult subjects.

Differences in the two training methods are at least partially responsible for the order-of-magnitude difference in deviations from the line. Cratty's method did not provide feedback on the subjects' distance from the correct path while they were walking. His subjects were informed of their performance after the trial was completed. In contrast, we provided continuous feedback to subjects during each trial, thereby allowing realtime error correction.

Most subjects' performance on test signals with interpulse interval differences of 0.1 and 0.2 ms in either direction was below 50-percent correct because these test signals resembled the standard more than any other test signal (figure 3). Because all test signals were equally likely on a trial-to-trial basis, the subjects' performance on standard signals was enhanced by selecting the standard response when the signal was not obviously a test signal. The subjects had to put forth more effort and concentration to achieve correct responses on test signals with small interpulse interval differences.

EXPERIMENT 2—SIGNAL MANIPULATION

METHOD

Subjects

Subjects included three of the four subjects (S_1, S_2, and S_4) who participated in experiment 1. S_3 was not an experienced listener.

Stimuli

The triple-pulse stimuli presented initially to the subjects, contained variable time displacements of pulse 2 from the center of the fixed-pulse doub`. Table 1 contains details of stimuli and other experimental conditions.

The just-noticeable difference in TSP, as indicated by discrimination thresholds at the 70-percent performance level between test and standard signals in experiment 1, was used to determine the smallest possible change subjects were allowed to make in a signal. Two requirements for stimuli in this experiment were as follows:

1. The smallest change that a subject could make should be the same for both positive- and negative-displacement test signals.

2. The signal changes resulting from turning the potentiometer should appear continuous to the subjects.

Therefore, we chose 0.1 ms as the the smallest incremental change for both directions, because this value is smaller than any observed just-noticeable difference in table 2. The signal produced during a correct response was identical to the standard in experiment 1.

Apparatus and Procedure

As in experiment 1, a PDP-11/40 computer produced the signals and recorded the data. For each session, we instructed the subjects to manipulate the time delay of pulse 2 (figures 2 and 5) by turning a precision 10-turn potentiometer connected to the A/D converter of the LPS-11. Subjects were instructed to produce a standard signal (figure 2) with the potentiometer by listening to the TSP. This differs from experiment 1, in which subjects simply chose test or standard from signals with fixed interpulse intervals.

The control program divided the voltages from the potentiometer into 135 equal sectors corresponding to 135 possible locations of the 4.0-ms pulse doublet with fixed interpulse interval (pulses 1 and 3). At the start of a trial, the time delay of the pulse doublet was randomized relative to the pulse to be varied by the subjects (pulse 2). All pulse

centering was done by listening to only the generated TSP. The program compared the subjects' sector selection to the actual sector position of the center of the fixed 4 0-ms doublet. This center position would coincide with pulse 2 in a standard signal. To avoid fatigue, each session was limited to 27 of the 135 locations. The control program randomly selected each of the 27 locations without replacement.

a   b

POTENTIOMETER
TURNS
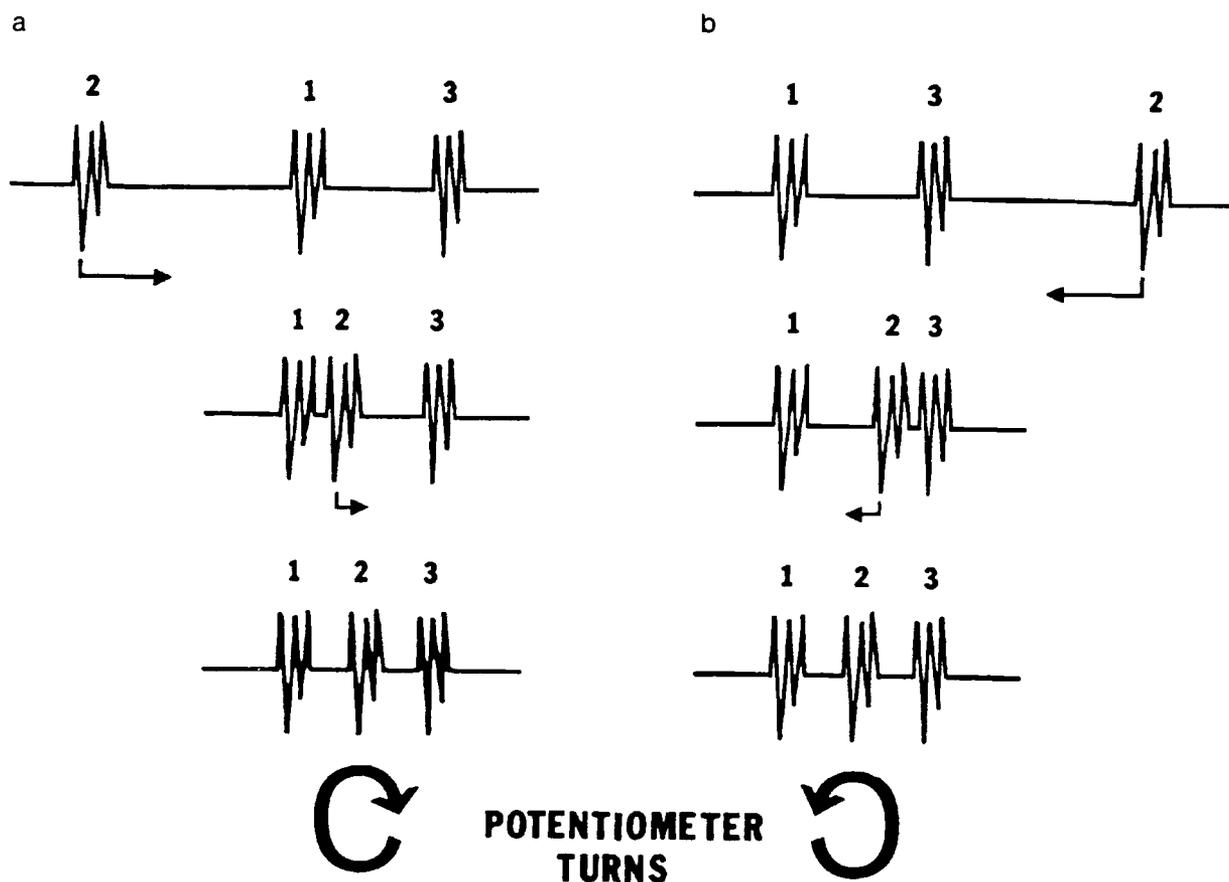
Figure 5. Examples of the procedure for adjusting the stimuli to produce a standard signal in experiment 2 (signal manipulation). (a) If pulse 2 preceded the doublet, the potentiometer was turned clockwise until pulse 2 was centered between pulses 1 and 3. (b) Turning the potentiometer counterclockwise, brought pulse 2 to the center if pulse 2 followed pulse 3 in the initial stimulus.

We did not control the initial position of the variable pulse before the start of each trial, because the program randomly selected the location of the pulse doublet. The variable pulse remained in the last position of the previous trial. Therefore, subjects often observed an initial stimulus in which the variable pulse either preceded pulse 1 or followed pulse 3 of the fixed-pulse doublet. The pulse the subjects varied was called

"pulse 2" or the variable pulse, although most of the time it was initially out of sequence with pulses 1 and 3. We chose this terminology because pulse 2 occurred between pulses 1 and 3 in the standard, correct response.

Stimuli were presented to the subjects at the rate of nine triplets per second. Subjects had unlimited time to respond for each trial. The computer program informed subjects of their progress during the session according to the differential feedback schedule in table 3. The program also recorded the final sector of each trial, corresponding to the subjects' responses.

Table 3. Differential feedback schedule for experiment 2, signal manipulation.

Final Response Offset	Description of Feedback
0 (Correct response)	Three tone beeps and/or three light flashes
-2, -1, 1 or 2	Two tone beeps and/or two light flashes
-4, -3, 3 or 4	One tone beep and/or one light flash
beyond + or -5	No feedback

RESULTS

Figure 6 presents data analyzed for each subject. Here, histograms depict how frequently subjects responded with a given accuracy. For example, a variable-pulse displacement of zero indicates the subject set pulse 2 in the center of the 4.0-ms pulse doublet, thereby forming two equal 2.0-ms intervals. This was the correct response. Similarly, a response offset of +2, or equivalently, a variable-pulse displacement of 0.2 ms after the center, was observed if a subject responded when the potentiometer was set two sectors following the position necessary to produce the standard. In this case, the longer inter-pulse interval preceded the shorter one, as in positive-displacement test signals used in experiment 1.

Subjects produced the correct response signal by equalizing the two interpulse intervals to 2.0 ms each on 41 percent of the trials. On an additional 33 percent, subjects responded when the variable pulse was displaced one sector in either direction from the center, each interpulse interval differing from 2.0 ms by 0.1 ms.

In figure 6, all 1350 trials contributed to the histogram for S_1. The histograms of S_2, S_3, and S_4 represent 1344, 956, and 833 trials, respectively, because some responses with the variable pulse outside the range between -0.5 and +1.0 ms are not shown. Note the differences in vertical scales for the histograms. Here, 4458 of 4563 trials are represented because in 105 trials, the subjects responded when the interpulse interval differences were greater than +1.0 ms or less than -1.0 ms.
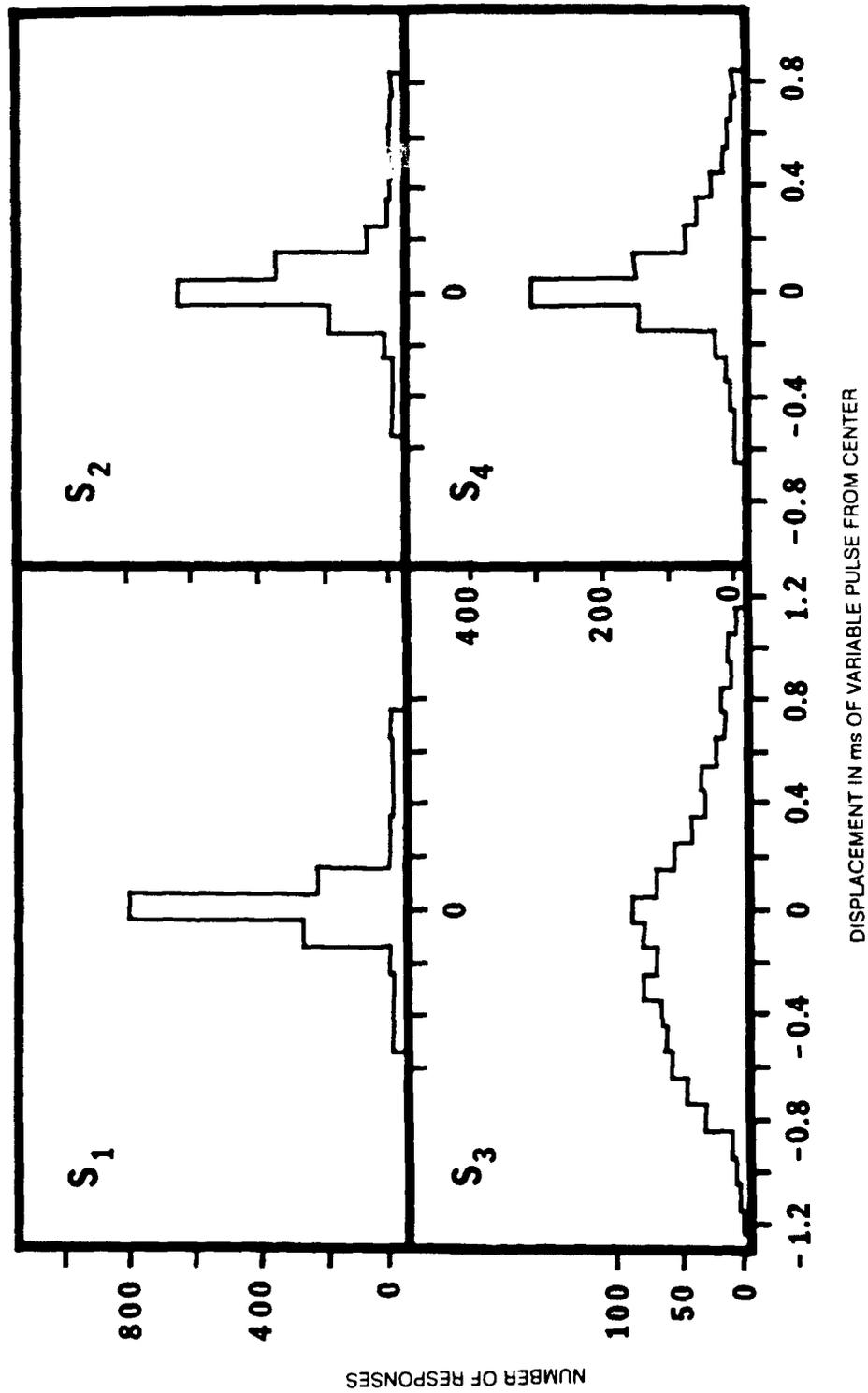
Figure 6. For each subject, distribution of responses over final offsets of pulse 2, expressed as the displacement in milliseconds of the variable pulse from the center of the 4.0-ms pulse doublet.

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GENERAL DISCUSSION

The distribution histograms reveal the accuracy with which subjects performed the task; the more narrow and peaked the distribution, the better the performance. Subjects improved their performance with time.

The signal manipulation results for S_4 in figure 6 are consistent with the psychometric functions for S_4 in figure 3. S_4 responded as if positive-displacement test signals sounded more similar to the standard than did negative-displacement test signals in both experiments. In a direction-finding system for the blind, this result implies that subjects attempting to follow a line may make systematic errors predominantly in one direction when deviating from the line. If these errors are systematic, a subject aware of a directional bias could compensate by moving either to the right or to the left to return to the line.

Most subjects reported they obtained repeated confirmations of the correct response before indicating their response. They did this by repeatedly scanning a small region within two or more sectors of the correct response. The fact that subjects could obtain repeated confirmations of the correct response by making relatively small deviations to either side of the correct response demonstrates a self-correcting procedure potentially beneficial in training to minimize veer. Feedback allowing immediate recognition that veering had occurred is likely to help a subject recognize properties of gait or body movements that contributed to the veering.

We noticed unexpected features in the function describing the variation in perceived pitch of the stimulus with the position of the variable pulse relative to the fixed-pulse doublet. Although all subjects did not participate in tone-matching measurements, they all reported information leading to the following hypothesis. A curve describing the approximate relative perceived pitch as a function of variable pulse displacement is somewhat symmetrically peaked in the vicinity of zero displacement, the correct response.

Similarly, in experiment 1, subjects generally reported they perceived both the positive- and negative-displacement test signals at a lower pitch than that of the standard. Thus, the longer interval appears to have determined the TSP. The subjects also reported that, starting from negative offsets of the potentiometer and moving toward the correct response, the pitch of the stimulus would rise monotonically until an offset of about −2.0 ms. At this position, the variable pulse is superimposed on the first pulse of the fixed doublet. Subjects reported the TSP dropped abruptly and rose again to a local maximum at the correct response, when they continued to move the variable pulse toward the center of the interval between pulses 1 and 3. A similar phenomenon occurred when approaching the correct response from the positive-displacement direction.

Only one interpulse interval could give rise to a TSP when the variable pulse was superimposed on either pulse 1 or pulse 3. All other possible stimuli contained two interpulse intervals. These singularities may be related to the rapid pitch variations the

subjects noticed. More experiments are needed to characterize this pitch function completely. These local maxima at +2.0 ms and −2.0 ms were not ambiguous, because most subjects quickly learned to scan beyond them and concentrate their efforts on displacements near the correct response, as figure 6 demonstrates. This capability suggests that a false line arising from signal anomalies would not be likely to lead blind subjects astray.

CONCLUSIONS

We measured the just-noticeable difference in periodic versus nonperiodic pulse presentations in stimuli consisting of pulse triplets. In the best case, S_2 discriminated signals with interpulse intervals differing from the 2.0 ms by at least 0.13 ms. The highest discrimination threshold was 0.25 ms for S_4. Subjects noticed that the highest and strongest TSP was associated with signals with equal interpulse intervals because the direction of pitch change was a salient feature of the signals. For signals with unequal intervals, the longer interval resulted in the dominant perceived pitch. In a signal-manipulation experiment using stimuli similar to those of the signal-discrimination experiment, subjects adjusted signals containing three pulses, to make both interpulse intervals equal to 2.0 ms. Subjects equalized these intervals to within 0.05 ms in 41 percent of the trials. In an additional 33 percent of the trials, subjects produced signals with intervals that both differed from 2.0 ms by 0.1 ms each.

The results of this simulation suggest that nearly an order-of-magnitude improvement in reducing veer is possible with well-trained subjects. In addition, the causes of veering should be easier to identify and correct in training situations using this method because subjects immediately detected small deviations from the simulated line. Whereas these simulated tests do not prove the veer problem is solved, a directional guidance system based on TSP cues appears to be a feasible potential aid to blind subjects crossing open spaces with no other cues to navigation. Field tests using actual pulse transmitters and blind subjects are required to validate this training method.

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13 ABSTRACT *(Maximum 200 words)*

This document reports the simulation of a guidance system for the blind using time separation pitch (TSP). Listeners estimated a simulated straight-line course perpendicular to and bisecting a line between two horizontally separated transmitters, one transmitting a pulse doublet and the other, a single pulse. The course was represented by the coincidence of the single pulse with the doublet's center, forming a triplet of identical broadband, evenly spaced pulses. In test signals simulating deviations from the course, changes in the timing of the second pulse caused variations in interpulse intervals. The subjects' ability to discriminate pulse separations in triplets was measured. Next, subjects manipulated the timing of the second pulse of test signals to produce a triplet containing two equal intervals. The subjects' ability to discriminate and manipulate signals suggests that a trained listener could correct veering by observing changes in TSP.

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