Quantitative Comparison of Alternative Sensory Displays for Mobility Aids for the Blind

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Abstract—This paper proposes a method to compare quantitatively various auditory display schemes communicating the course a blind traveler should follow to comply with information a blind mobility aid has acquired, and the optimal scheme is sought for that traveler. A computer system emulates different display devices which use amplitude modulation to indicate the error of a subject's location from the indicated course. The real-time Selspot-based TRACK system measures the location of the human subject in real time, and the error is presented to the subject via each of the emulated devices. The indicated course, human trajectory, and error are recorded in computer disk memory. The performance of the human in each task is evaluated by calculation of a transfer function of the human with each display and then using this transfer function as the criterion for comparison. The feasibility of designing the display schemes of blind mobility aids using this procedure is demonstrated. Thus, an optimal choice for the specific blind person can be made via this system before committing a particular mobility aid design to the lengthy development process.

INTRODUCTION

SUPPOSE that a device which directs or guides a blind individual has somehow acquired information about the direction of, and width of, the path along which it should lead the blind individual. The choice of sensory display of the path and the individual's position on it, appropriate for presentation to the remaining exterioreceptive senses of the blind individual, becomes the limiting problem.

This kind of situation occurs, for example, when a blind individual uses the guide dog robot [1]. The robot has an internal map of the environment, is guided by landmarks on the road, and can detect obstacles using on-board sensors. The robot communicates to the blind individual the clear path to follow, with the speed of the robot controlled by the travel velocity of the blind individual. Another example is a device which receives radio beacon signals transmitted by several stations and thereby guides a blind individual according to the information received [2].

Various display methods for such communication to the blind have been proposed and employed in several devices for the blind, e.g., the sonic guide uses a binaural display which includes the dimensions of range, azimuth, and ultrasound reflection texture [3].

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All of these, however, represent ad hoc solutions and offer no practical suggestions for a generalized design procedure to define optimal displays for specific applications.

The central features of such a design capability must include a method to quantify the motion or movement of an unhampered blind individual walking in a real or mock-up physical environment, and the means of feeding back to the individual, in real time, the path information and/or error from the path by means of a very adaptable and potentially rich psychophysical sensory display code. Such a system would retain the human's *a priori* uncharacterizable ability to interpret and implement an arbitrary code describing obstacle and environment cues. The system would also provide quantifiable information on the human's trajectory before and after the presentation of the sensory display information. Thus, the efficacy of different sensory displays could be compared efficiently and optimal choices made before committing a particular design to the lengthy development process entailed in a field-worthy, practical, reliable mobility aid for the blind. Furthermore, an aid could be "custom tailored" to the specific attributes of an individual human.

The importance of this mobility environment simulation approach was first proposed by Mann in 1965 [4]. Brabyn has reported [5] on a scheme involving pretensioned cables—three in number—one end of each attached to the subject's head or back and the other connected to a take-up reel on the walls of a 17 m by 11 m laboratory. Cable-length transducers on the reels and triangulation permitted calculation of subject position. Cable stretch, sag, and dynamics limited accuracy to about 2.5 cm in position, and frequency response to about 1 Hz.

The system used in this study couples the high-speed, low-cost laboratory minicomputer with the high-performance, multichannel, point-monitoring and data-transferring device called "Selspot." The resulting hardware/software system is dubbed "TRACK" (telemetered real-time acquisition computation kinematics). Feasibility was demonstrated by Conati in 1977 [6], real-time capability was implemented on a DEC computer PDP 11/40 under the RT-11 operating system by Tetewsky [7], and the overall system has been brought to practical use by Antonsson [8], [9], operating under RSX 11-M on a DEC computer PDP 11/60.

Using this new system, the performance of human subjects employing different auditory display schemes communicating the course they should follow is quantitatively compared. A method for the quantitative comparison is also proposed: an optimal auditory display scheme is sought, by measuring the movement of a human subject responding to a random course

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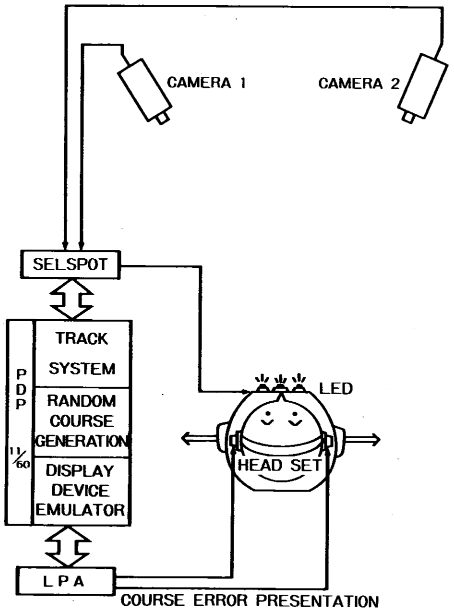

Fig. 1. Experimental arrangement for real-time evaluation of sensory display devices for the blind.

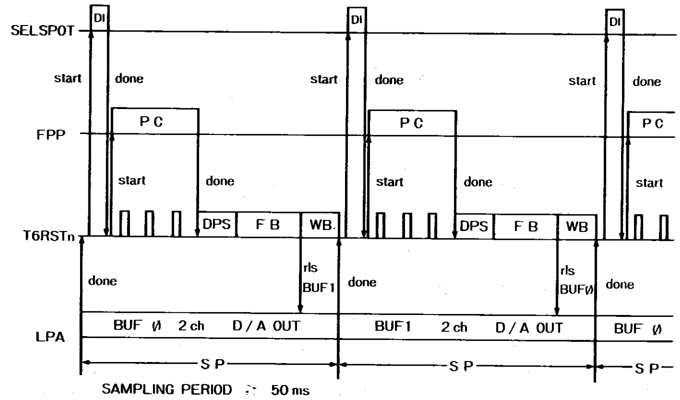

Fig. 2. Timing diagram of the display device emulator.

(generated by the computer) which displays to the subject the course error from the desired course in real time. The transfer function of the subject employing each of several different display schemes is estimated. The effective gains and the effective time delays of the transfer functions for the several display devices are calculated according to the crossover model. Using the sum of the effective gain and the reciprocal of the time delay as the criterion of optimality, the optimal display scheme is sought, and the consequences of differences between the alternative display schemes are quantitatively evaluated.

Experimental Apparatus

Fig. 1 shows the experimental arrangement. The movement of the human subject is measured by the newly revised TRACK system. The system consists of the raw-data acquisition and handling device, Selspot I, marketed by Selcom AB of Sweden, a PDP 11/60 minicomputer, and an auditory display device which is linked to the computer through a laboratory peripheral accelerator (LPA).

The Selspot system uses cameras with lateral photoelectronic plates at their image planes which are sensitive to infrared illumination. Each plate detects the position of the image of a light-emitting diode (LED) and thereby provides two-dimensional position data from each camera for up to 30 LED's which are multiplexed at a frame rate of 315 Hz.

The two cameras are positioned accurately in laboratory coordinates and their two-dimensional image position data are manipulated trigonometrically by the computer to yield three-dimensional data of the LED's. By arranging three or more LED's on a plane attached to a segment of a moving human (in this case the abdomen), the location and orientation of the human subject are tracked in real time. The calibrated system position accuracy is less than 1 mm when two cameras observe a viewing volume approximating a cube 1 m on a side. Orientation accuracy (not used in this experiment) is less than 1°.

Band-limited random noise is generated by the computer and is used to define the course which the subject should follow. Error in the human's location relative to the indicated course is fed back to the subject via auditory signals through a headset (Electrostat-Dynamic Systems k-340) through the LPA's D-to-A converters.

Fig. 2 gives the timing diagram of the software and the hardware used. A real-time clock in the LPA activates the sampling subroutines of the Selspot which is in the program T6RSTn ($n = 1, \cdots, 12$), running in the CPU of the PDP 11/60. The Selspot in turn returns the data in the direct memory access (DMA) mode, and the three-dimensional position is calculated, primarily by the floating point processor (FPP) in the 11/60.

Two buffers are used to output the position data as an auditory stimulus through the LPA. The portion of the program (T6RSTn's) which sets the display parameters differs from one program to another; thus, different types of auditory display devices can be emulated. This experiment will quantitatively evaluate the effectiveness of these different displays.

Experiment Goal and Method

The computer system emulates several display devices which use auditory amplitude modulation to indicate an error in a subject's location from the desired course. The TRACK system measures the location of a human subject in real time and the error signal is presented to the subject through one of the emulated devices. The desired course, the human's trajectory, and the error are recorded in computer disk memory.

The performance of the human in each task is evaluated by calculating a transfer function of the movement of the human with each display and then using this transfer function as the criterion for comparison.

Fig. 3 shows in general terms the auditory display methods compared in this study. They are categorized as amplitude modulation displays controlled by the error, i.e., only the error signal is presented, corresponding to compensatory display as defined in ordinary tracking experiments in manual control. The error is used to modify the amplitude of a fixed frequency tone.

Three attributes of this tone are to be compared: 1) whether the tone is continuous or discrete [i.e., continuous tone and tone burst as in Fig. 3(a)]; these alternative display schemes will be called type-C and type-D, respectively; 2) whether the

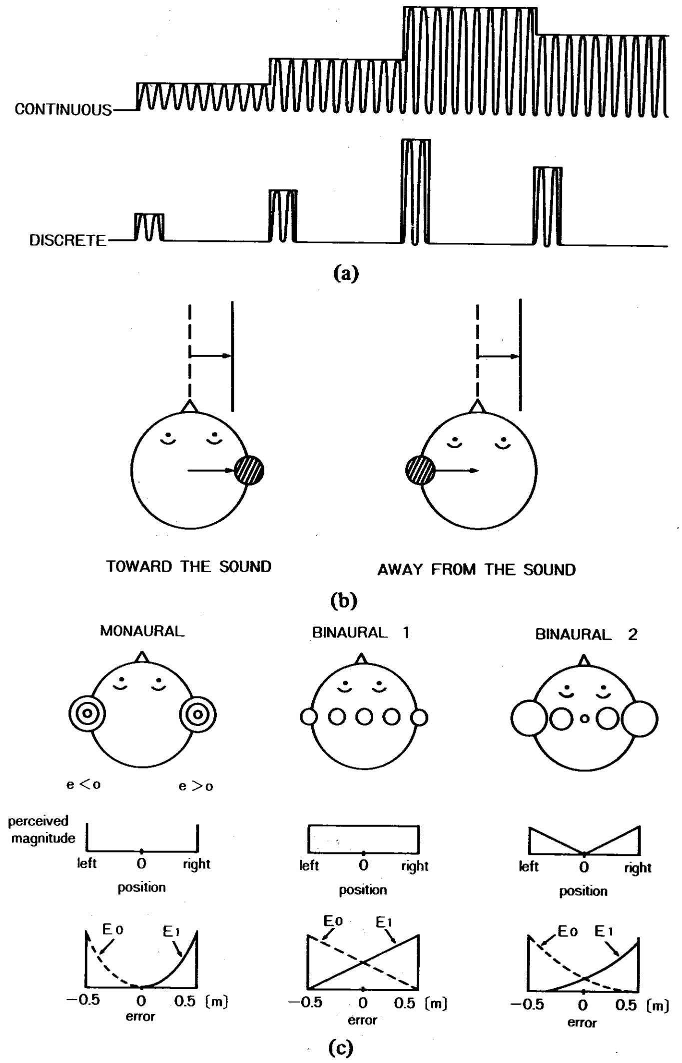

Fig. 3. Comparison of alternative amplitude modulation displays. (a) Continuous (type-C) and discrete (type-D). (b) Toward the sound (type-T) and away from the sound (type-A). (c) Monaural (type-M), binaural 1 (type-B1), and binaural 2 (type-B2).

subject is instructed to move toward the sound (e.g., an error to the left is presented to the right ear) or move away from it (e.g., an error to the left is presented to the left ear); those two alternative display schemes are shown in Fig. 3(b) and will be called type-T and type-A, respectively; and 3) whether the presentation is monaural or binaural (i.e., only one ear is stimulated at a time or both are stimulated simultaneously) as shown in Fig. 3(c).

In the monaural presentation, the inverse logarithm of the absolute value of the error signal is presented to either of the human ears and will be called type-M. In the binaural presentation, two amplitude modulation signals are generated according to the course error signal. These signals are presented to both ears of the subject simultaneously to produce a fused image, the perceived location of which is proportional to the course error.

The binaural presentation scheme is subdivided into two parts: one uses only the position cue as an indication of the course error (type-B1) and the other uses the positional and the loudness cues simultaneously (type-B2).

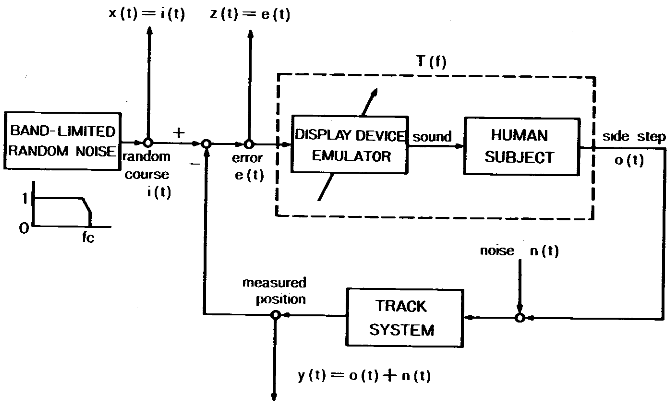

Fig. 4. Block diagram of the compensatory system including human subject and position monitoring display emulator.

All combinations of these display attributes are compared using an experimental procedure as follows.

A subject is asked to sidestep (right or left) within the TRACK's viewing volume according to the auditorily presented error of his location from the indicated random course generated by the computer.

Fig. 4 shows the block diagram of this compensatory system and display. The $i(t)$ is the input Gaussian white noise with cutoff frequencies f_c's of 0.16, 0.32, and 0.64 Hz with a zero mean.

Thus, the observed input $x(t)$ is

$$x(t) = i(t)$$

$$E[x(t)] = E[i(t)] = 0 \tag{1}$$

where E indicates an ensemble mean.

The $y(t)$ is the observed output of the system. It consists of the human subject's response to each of the emulated devices $o(t)$ and the additive noise $n(t)$. The noise consists of the random component of the human response and the measurement error of the TRACK system. These are combined and described as $n(t)$ with a zero mean:

$$y(t) = o(t) + n(t)$$

$$E[y(t)] = E[o(t)] + E[n(t)] = 0. \tag{2}$$

We further assume that we can measure the difference between $i(t)$ and $y(t)$:

$$z(t) = e(t) = i(t) - y(t). \tag{3}$$

The transfer function $T(f)$ of each of the emulated devices as interpreted by the human subject is calculated by the following formula:

$$T(f) = \frac{\Phi xy}{\Phi xz} = \frac{\Phi iy}{\Phi iz} = \frac{E[I(f)^* \{O(f) + N(f)\}]}{E[I(f)^* E(f)]}$$

$$= \frac{E[I(f)^* O(f)]}{E[I(f)^* E(f)]} = \frac{O(f)}{E(f)} \tag{4}$$

where Φ is the cross spectrum between signals $x(t)$, $y(t)$, $i(t)$, and $z(t)$ which are indicated as subscripts. The signals $x(t)$, $y(t)$, and $z(t)$ are measured during a finite time in order to determine their Fourier transforms. Upper case letters denote the Fourier transform of the corresponding lower case letters, e.g., $E(f) = \int_{-\infty}^{\infty} e(t) \exp(-2\pi jft)dt$. The asterisk denotes the complex conjugate.

The frequency of the modulated tone is fixed at 500 Hz, and the sampling frequency at 10 Hz. FFT's (fast Fourier transforms) of 1024 points are employed and the cross spectrum is measured using the frequency averaging technique for each of the emulated devices. This process is repeated three times to obtain an ensemble average of the cross spectrum, and then the transfer function is estimated as the ratio of the averaged cross spectrum for each emulated device.

Experimental Results

Preliminary experiments were conducted to determine the optimal bandwidth of the random input. The monaural-toward-continuous-type (MTC-type) display was chosen tentatively and the course was computer-generated using Gaussian white random noise with a bandwidth f_i of 0.18, 0.32, or 0.64 Hz. All subjects complained that random courses generated by random noise with an f_i of 0.64 Hz were too fast to follow. With random courses generated with an f_c of 0.18 Hz, it was difficult to determine the crossover frequency of the open-loop transfer function because the gain was always greater than unity for all input frequencies. As a result, random noise with an f_c of 0.32 Hz was used throughout the study.

All display schemes, i.e., monaural (M), binaural 1 (B1), or binaural 2 (B2), toward the sound (T) or away from the sound (A), and continuous (C) or discrete (D), were combined. Thus, 12 display devices were emulated, which were called MTC-, MTD-, B1TC-, B1TD-, B2TC-, B2TD-, MAC-, MAD-, B1AC-, B1AD-, B2AC-, and B2AD-type, respectively. In the feasibility study reported here, two subjects (TS, a student, age 26, and NA, a researcher, age 41) used these 12 emulated displays to follow the random courses generated by the computer. Since no actual pathway exists by means of which the subjects can establish their absolute position and since the computer-generated course varied randomly, performance was not significantly influenced by whether or not vision was occluded. Each sensory display device trial lasted 3 min. The order of presentation of the various displays emulated was randomized.

Open-loop transfer functions of each subject with each of the 12 emulated devices were calculated using formula (4). Fig. 5(a) and (b) shows amplitude and phase of the transfer functions of subject TS with emulated devices MTC and MTD, respectively. Similar transfer functions were estimated for all 12 emulated devices used by the two subjects.

Our results for the sidestep task described herein are very similar to results for manual compensatory tracking experiments of position vehicle K_c obtained by McRuer *et al.* [10], although our crossover frequency is much lower because of the larger inertia of the body compared to the hand.

Thus as a first-order approximation, the crossover model can be applied to our sidestep version of compensatory tracking experiments. According to the crossover model of McRuer, the transfer function $T(f)$ in the region of the crossover frequency can be described as follows:

$$T(f) = \frac{\omega_c \exp\{-j\omega T_e\}}{j\omega} \quad (5)$$

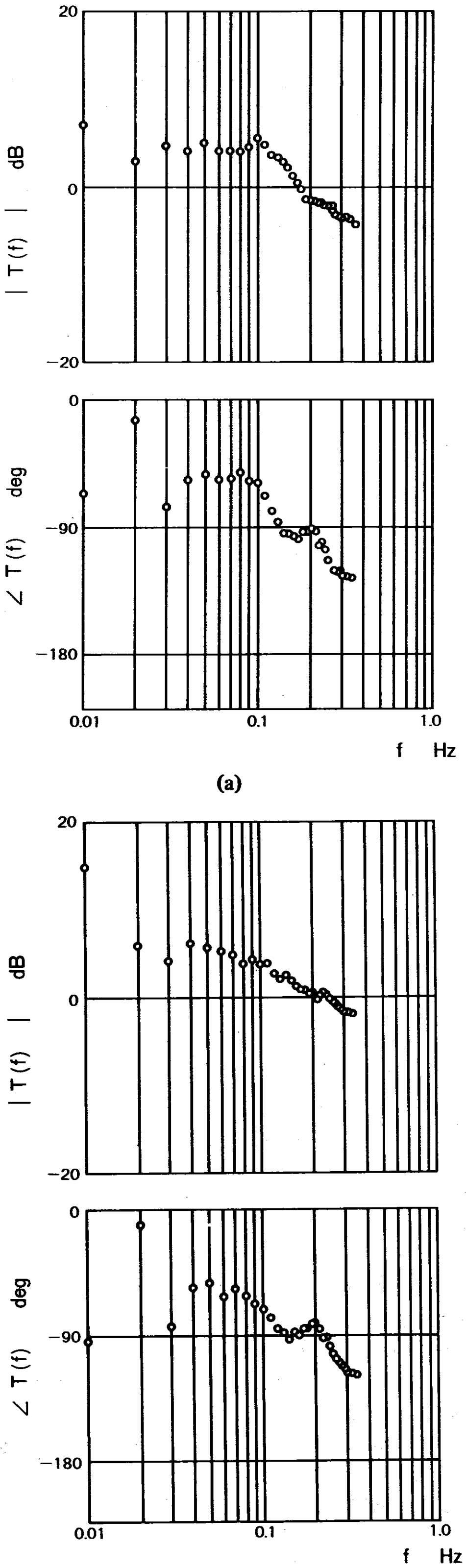

Fig. 5. Examples of the open-loop transfer function. (a) MTC-type for subject TS. (b) MTD-type for subject TS.

where ω_c is the crossover frequency corresponding to the sidestepping human's gain compensation K_e using the emulated device, and T_e is the effective time delay due to both reaction time and neuromuscular dynamics.

TABLE I
EQUIVALENT GAIN K_e, EQUIVALENT TIME DELAY T_e, AND EVALUATION VALUE $EV = K_e + 1/T_e$ OF 12 DISPLAY SCHEMES FOR TWO SUBJECTS

		MTC	MTD	B1TC	B1TD	B2TC	B2TD	MAC	MAD	B1AC	B1AD	B2AC	B2AD
TS	K_e	1.26	1.38	0.63	0.82	0.82	0.82	0.94	1.13	0.50	0.44	0.75	0.82
	T_e	1.26	1.17	3.06	2.29	1.82	1.77	1.78	1.51	3.06	3.41	1.67	1.32
	EV	2.05	2.23	0.96	1.25	1.37	1.38	1.50	1.79	0.83	0.73	1.35	1.57
NA	K_e	1.51	1.32	0.57	0.94	1.70	2.26	1.63	1.63	0.88	0.88	0.94	1.19
	T_e	0.78	0.85	2.56	1.98	1.18	0.99	1.14	1.19	1.79	1.61	1.56	1.33
	EV	2.80	2.50	0.96	1.45	2.54	3.27	2.51	2.48	1.44	1.50	1.58	1.95

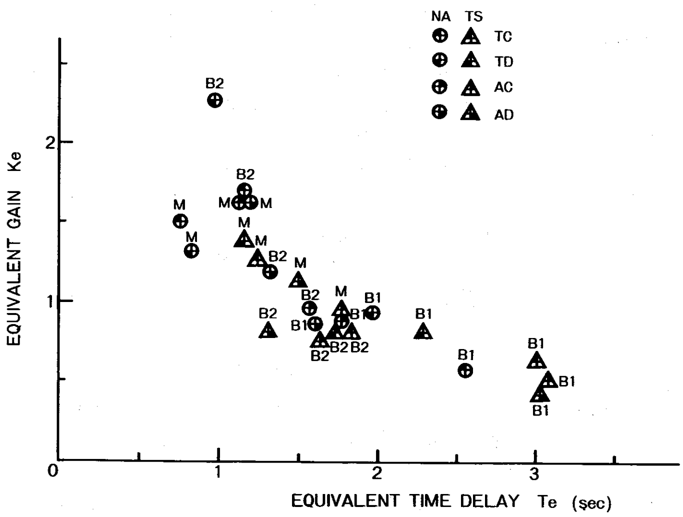

Fig. 6. Performance comparison of all 12 display types for two subjects.

For the model, overall performance is improved for higher equivalent gain and smaller equivalent time delay. The two parameters K_e and T_e describe the overall characteristic of the human sidestepping in response to the emulated device. Thus, the quantity

$$EV = K_e + 1/T_e \tag{6}$$

is selected as the measure or criterion to determine and evaluate quantitatively the effectiveness of each emulated device.

In order to estimate the effective gain and the effective time delay, a line with slope of -20 dB/decade was fitted to the amplitude of the transfer function near the crossover frequency, and using the least squares method, the crossover frequency f_c was measured for each of the 12 display schemes. The phase margin ϕ_m was measured as $\phi_m = 180 - P_c$, where P_c is the phase value at the crossover frequency.

The effective gain K_e and the effective time delay T_e were calculated using the following formula based on the fitting method usually applied to a position vehicle [11]:

$$K_e = 2\pi f_c$$

$$T_e = 1/K_e \left(\pi - \phi_m \cdot \frac{\pi}{180}\right). \tag{7}$$

Table I shows the results for two subjects with each of the 12 display schemes. These two parameters K_e and T_e are plotted in Fig. 6, which clearly shows that display B2TD is most effective for subject NA while MTD is best for subject TS.

To study differences between display attributes in order to determine which of the alternative display schemes we should employ in a real device, the following statistical procedure was applied.

First, 24 values of EV are divided into n classes according to the attributes to be compared. The n classes are called $\alpha_1, \alpha_2, \cdots, \alpha_n$ (e.g., α_1 is the class of display methods which use type-T and α_2 is the class of display methods which use type-A when we compare the alternative attributes of T and A).

The attributes of the members of each class are named $\beta_1, \beta_2, \cdots, \beta_m$ according to attributes which will not be compared (e.g., β_1 is MC, β_2 is MD, $\cdots, \beta_{12}$ is B2D when we compare the alternative attributes of T and A).

The variances due to the attributes which should be compared, $\sigma_1^2, \sigma_2^2, \cdots, \sigma_n^2$, are separated from the variance due to other factors using the following formula:

$$\sigma_i^2 = \frac{1}{(n-1)(m-1)} \left\{ n \left(\sum_{j=1}^{m} y_{ij}^2 - \frac{SA_i^2}{m} \right) - \left(\sum_{j=1}^{m} y_{ij} SB_j - \frac{SA_{iT}}{m} \right) \right\} \qquad (i = 1, \cdots, n) \tag{8}$$

where y_{ij} is the EV value when the emulated device type of $\alpha_i\beta_j$ is used,

$$SA_i = \sum_{j=1}^{m} y_{ij}, \quad SB_j = \sum_{i=1}^{n} y_{ij},$$

and

$$T = \sum_{i=1}^{n} \sum_{j=1}^{m} y_{ij}.$$

Using the above formula, the variances due to the alternative attributes were calculated for the two subjects. The standard deviation due to each attribute corresponding to each emulated device type was also calculated. These are named s.d.A, s.d.T, s.d.C, s.d.D, s.d.M, s.d.B1, and s.d.B2, respectively. The two standard deviations associated with the two attributes to be compared were averaged to yield the average standard deviation s.d. $\alpha_i\alpha_j$.

$$\text{s.d. } \alpha_i\alpha_j = \tfrac{1}{2} (\text{s.d. } \alpha_i + \text{s.d. } \alpha_j). \tag{9}$$

The average difference of the EV values between the two attributes to be compared was then divided by the associated average standard deviation to yield the normalized distance between the two attributes.

TABLE II
AVERAGE DIFFERENCE, AVERAGE STANDARD DEVIATION, AND NORMALIZED DIFFERENCE OF TWO ALTERNATIVE DISPLAY ATTRIBUTES BEING COMPARED

	Average difference	Average standard deviation	Normalized difference
T-type versus A-type	0.29	0.34	0.85
C-type versus D-type	0.19	0.19	−0.96
M-type versus B1-type	1.09	0.16	6.67
M-type versus B2-type	0.36	0.40	0.88
B1-type versus B2-type	−0.74	0.35	−2.12
Between subjects	0.66	0.29	−2.33

$$ND_{ij} = (AEV_i - AEV_j)/\text{s.d. } \alpha_i \alpha_j \quad (10)$$

where AEV_i is the averaged EV value of the class α_i.

These normalized distances were used as a measure to quantify the effect of the two different types. Table II shows the normalized distances between types A and T; types C and D; types M and B1; types M and B2; and types B1 and B2.

The same procedure was applied to evaluate the effect of differences between the subjects. This result is also included in Table II.

Differences between the three alternative attributes M, B1, and B2 are most significant. The monaural display and the binaural 2 display are far better than the binaural 1 type display (99 percent and 89 percent confidence at least; Chebyshev's inequality). Little difference appears between M and B2. The differences between C and D and T and A are also small; however, D and T are consistently superior.

Differences between subjects are noticeable. However, superiority of one display attribute relative to another is independent of subject.

CONCLUSIONS

The performance of human subjects employing simulations of different auditory display devices which present the error from a desired course was measured in real time by using the Selspot-based TRACK system.

A method was proposed to quantitatively compare alternative displays and thereby determine the optimal display scheme. The sum of the effective gain and the reciprocal of the time delay was calculated based on the estimated open-loop transfer function of the subjects using each of the displays. The normalized distance between the alternative display schemes was calculated statistically and used as the measure to determine the quantitative superiority of one alternative display scheme relative to another.

For the small number of subjects involved and for the compensatory task and auditory display schemes experimented with in this paper, the monaural-type (loudness cue only) and the binaural-2-type (position cue plus loudness cue) are superior to the binaural-1-type (position cue only).

The monaural-toward-discrete type display was found to be superior for one subject, while the binaural-2-toward-discrete type was best for the other. Differences between the two subjects were significant. The superiority of one alternative display scheme relative to another, however, was almost independent of subject.

The procedure reported in this paper is shown feasible for designing display schemes for mobility aids. Clearly, the thorough scrutiny of any prospective mobility-aid concept would mandate more thorough experimentation with more subjects, including those with vision impairments. Thus, this human–computer-interactive simulation system could define rigorously the optimal choice of display *before* committing a particular mobility aid to the lengthy design and development process. Moreover, the method reported herein permits custom-fashioning the display scheme to the specific sensory perception attributes of a particular blind person. One can imagine, first, identifying that generic display which best satisfies the attributes of a range of potential users and then in "fine-tuning" the generic display to each specific person's attributes and capabilities.

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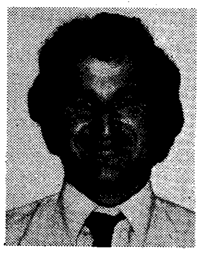

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