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Frequency Encoded Auditory Display of the Critical Tracking Task

James Stevenson

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ABS: The use of auditory displays for selected cockpit instruments was examined. In auditory, visual, and combined auditory-visual compensatory displays of a vertical axis, critical tracking task were studied. The visual display encoded vertical error as the position of a dot on a 17.78 cm, center marked CRT. The auditory display encoded vertical error as log frequency with a six octave range; the center point at 1 kHz was marked by a 20-dB amplitude notch, one-third octave wide. Asymptotic performance on the critical tracking task was significantly better when using combined displays rather than the visual only mode. At asymptote, the combined display was slightly, but significantly, better than the visual only mode. The maximum controllable bandwidth using the auditory mode was only 60% of the maximum controllable bandwidth using the visual mode. Redundant cueing
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Frequency Encoded Auditory Display of the Critical Tracking Task

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SUMMARY

The great demand for visual attention out-the-window suggests exploration of the use of auditory displays for selected cockpit instruments. In this experiment, auditory, visual, and combined auditory-visual compensatory displays of a vertical axis, critical tracking task were studied. The visual display encoded vertical error as the position of a dot on a 17.78-cm, center-marked CRT. The auditory display encoded vertical error as log frequency with a six-octave range; the center point at 1 kHz was marked by a 20-dB amplitude notch, one-third octave wide. Asymptotic performance on the critical tracking task was slightly but significantly better when using combined displays rather than the visual-only mode. At asymptote, the combined display was slightly, but significantly, better than the visual-only mode. The maximum controllable bandwidth using the auditory mode was only 60% of the maximum controllable bandwidth using the visual mode. Studies of other single axis auditory displays have produced enhancement of visual displays. They have shown that redundant cueing increased the rate of improvement of tracking performance, as well as the asymptotic performance level. This enhancement increases with the amount of redundant cueing used. In conclusion, this effect appears most prominent when the bandwidth of the forcing function is substantially less than the upper limit of controllability frequency.

INTRODUCTION

Pilots are frequently confronted with the requirement to monitor cockpit instruments (such as those describing heading, altitude, turn and bank, and their rates of change) and the outside visual scene at the same time. This problem is particularly acute for helicopter pilots when the outside visual workload is very high. At such times there are competing needs (1) to look out the window for purposes of navigating, avoiding obstacles, and making precise maneuvers and (2) to monitor cockpit instruments. These conflicting demands on the pilot's attention make display methods that decrease visual workload highly desirable.

Auditory displays that could supplement or replace instruments in future cockpits may help to provide information relevant to this kind of flying task. As will be discussed below, there is preliminary evidence that auditory and visual displays of the same information may improve tracking performance in manual control tasks. In addition, there is theoretical interest regarding the effects of displaying the same information by auditory and visual means and the ways in which different sensory modalities process the information.

Clearly, auditory and visual presentations of the same information are separable dimensions and do not combine into a single percept in the manner of Garner's integral dimensions (Garner, 1974). Although the visual system is usually dominant, Posner et al. (1976) have reviewed evidence that the auditory system produces a quicker alerting response. It is therefore plausible that simultaneous auditory and visual display of the same information may improve some aspects of control performance.

I wish to acknowledge the assistance of Ms. Roberta Cortilla for operation of the experimental equipment and assistance with the subjects.

PREVIOUS WORK

Several investigators have attempted to compare visual displays with auditory displays of the same information. The studies relevant to these investigations have used continuous (rather than discrete) auditory displays which attempt to maximize information transfer in the auditory domain (Forbes, 1946; Katz et al., 1966; Mirchandani, 1972; Pitkin and Vinji, 1972). These continuous auditory displays have been compared with well designed continuous visual displays which attempt to maximize information transfer in the visual domain.[1] They have compared auditory, visual, and combined auditory-visual displays in manual control tasks. Unfortunately, some of these investigators have failed to present sufficient information on the characteristics of the forcing function (particularly its frequency spectrum) to permit detailed analysis of performance using the different display modes (Forbes, 1946).

Mirchandani (1972) presented subjects with two simultaneous tracking tasks. The primary task was the control of a second order plant (acceleration control: transfer function given by km/sec^2; the secondary task was the control of a first-order plant (velocity control: transfer function given by km/sec). The plant errors for the two tasks were shown on separate visual displays by pointers. The primary acceleration task was controlled by the horizontal motion of a spring loaded joystick in the right hand; it was displayed by the horizontal motion of a vertical line on a 12.7-cm cathode ray tube (CRT) located near the right hand. The secondary velocity task was controlled by the vertical motion of a spring loaded joystick in the left hand; it was displayed by the vertical motion of a horizontal line on a 12.7-cm CRT located near the left hand. The input forcing functions in Mirchandani's study were sums of 16 sinusoids with a break frequency of 2.8 rad/sec, the 8 high-frequency sinusoids being attenuated by 20 dB, as is commonly done in manual control studies. The forcing functions for the two displays were presented separately and out of phase. An auditory display was used to supplement the secondary task on half of the runs. The frequency of the display was proportional to the vertical deflection (error in the secondary task), and the amplitude of the display was proportional to the vertical distance from the center point. The center frequency of the auditory display was 1250 Hz. The zero position amplitude at this frequency was slightly above the operator's threshold of hearing; the maximum level was less than 100 dB SPL, although the exact amplitudes were not specified. The minimum frequency was 500 Hz, which corresponded to an indicated error of -3 cm; the maximum frequency was 2000 Hz, which corresponded to an error of +3 cm.

To study the effects of adding the auditory display to the visual display, Mirchandani obtained two performance measures: (1) the integral of the squared error (ISE) and (2) the describing functions of the human operator. Statistical analysis of the ISE measures indicated that when the secondary task was supplemented with an auditory display, there was a significant improvement in performance on that

[1]Making a potentially continuous auditory or visual display into a discrete finite-state display results in loss of information from quantization effects.

task: for three of the four subjects there was an average decrease in tracking error of 62%. The auditory display of the secondary task improved the performance of the primary task significantly for only one of the four subjects with an average decrease in tracking error of 23%. In all cases, the variances of the ISE values decreased for both the tasks, indicating a more consistent behavior with the auditory display. The describing function analysis showed that supplementing the secondary task with the auditory display increased the low-frequency (<1 rad/sec) gain of the human operator by an average of 6 dB for this task. The describing functions for the primary task showed no apparent changes.

Katz et al. (1966) presented subjects with a one-dimensional tracking task and a simultaneously presented target acquisition task. All subjects saw the targets that were to be identified in a background noise of similar targets. In addition, the lateral position of the target could be presented either acoustically through binaural loudness and phase cues or visually through the position of a meter needle, mounted above the target display. The binaural cues modulated a 500-Hz tone, which was interrupted four times per second to decrease habituation and improve the perception of the arrival-time differences. Subjects who received auditory augmentation or auditory and visual augmentation of the lateral position of the target reacted more quickly and accurately to the target acquisition task than did subjects who received only visual augmentation. No differences were found on the simultaneous tracking task. This suggests that auditory information about the presence of nearby obstacles might augment attention to the visual scene and produce quicker obstacle-avoidance maneuvering without interfering with other flying tasks.

Pitkin and Vinji (1972) compared the auditory, visual, and combined performance on four subjects using the critical tracking task. Their auditory display encoded error in the horizontal axis by stimulating the ear, on the side on which the error occurred, with a frequency equal to $330+64|\%e|$ Hz, where 100% error corresponded to the visual display limit, and an auditory frequency of 6730 Hz. Four visual displays were compared. The display yielding the best performance employed a vertical line moving on a 12.7-cm-CRT grid. The other three visual displays (not discussed further here) yielded inferior performance; they utilized various discontinuities at the center to simulate the discontinuity in the stimulated ear at the center of the auditory display. At asymptote, the average improvement from adding the auditory display to the best visual display was 12.9%. The auditory display alone was 82.2% as effective as the visual display alone.

The studies mentioned above suggest that a well-designed auditory display will, under certain conditions, improve tracking performance when used simultaneously with a visual display of the same information. They also suggest that an auditory display alone is not as effective as a visual display alone. However, previous studies have not examined the effect of combined auditory and visual displays of the same information on learning rate. It is possible that combined displays could facilitate the learning of a psychomotor skill; however, there may be an extra workload imposed in fully utilizing the combined display, and the possibility of enhanced learning may not be realizable.

PRESENT INVESTIGATION

In the present study, I examined the performance of auditory, visual, and combined displays using a manual control task of progressively increasing difficulty (critical-tracking task). This task has been shown to be a sensitive measure of differences in display and a variety of intersubject variables (Jex et al., 1972; Allen and Jex, 1973; Allen et al., 1974; Allen et al., 1978). The hypotheses of this study are:

1. The simultaneous audio and visual display (AV condition) used in this experiment will produce asymptotic performance superior to that of the visual display alone (V condition) which will produce superior asymptotic performance to the auditory display alone (A condition).

2. The combined auditory and visual display will produce a faster learning rate than will the visual or auditory display alone.

METHOD

Subjects

Four paid subjects, all of whom were right handed and had self-reported normal hearing and vision that was either normal or corrected to normal, participated in the experiment. The subjects were students in their early twenties; none were pilots or had extensive experience with the tracking tasks and displays used in this experiment.

Apparatus

The visual display consisted of a dot moving vertically on a 17.78-cm CRT with a circle marking the center; the circle was just large enough to contain the dot. The CRT was positioned about 1 m from the subject (with some variability from the subject's chair position, which was self-adjusted for comfort) and its elevation was adjusted by the subject for optimum viewing. The auditory display consisted of a tone of variable frequency presented to both ears. The center point of the scale was 1 kHz. Full-scale deflection down was indicated by 125 Hz and full-scale deflection up by 8 kHz. Thus, the display was linear in log frequency with a three-octave range on either side of center. The 1-kHz center point was marked by a 20-dB amplitude notch with a linear amplitude increase on either side to 80 dB SPL at 1/20th of the full-scale deflection. Outside of this amplitude notch, the display amplitude remained constant at 80 dB SPL. At the center of the amplitude notch, the amplitude was 60 dB SPL, and the frequency was 1 kHz. The displays were controlled by a force stick (Measurement Systems, Inc., Norwalk, Conn.), mounted 45 cm from the table edge and in front of the subject.

The auditory and visual displays were generated by an EAI 2000 analog computer driven by a DEC 11/34 digital computer. The total delay in the system was less than 20 msec at all frequencies.

Procedures

The critical tracking task requires a subject to control an increasingly unstable element with the forcing function proportional to the instantaneous error. The equation for this system is $\dot{E} = E\lambda + k\lambda\Delta$, where E is the instantaneous error, λ is the instability parameter, k is the stick gain, and Δ is the stick input. As the trial progresses, λ increases linearly from its initial value λ_0, until control is lost. This occurs at the maximum value of E, at which the display reaches its limit. This is represented in the machine implementation at the maximum value of 10 V, which is the limit of the EAI 2000 analog computer. This corresponds to an 8.9-cm deflection on the visual display and 3 octaves on the auditory display. For each trial, the value of λ where this occurred was called the critical value λ_c. This value is proportional to the maximum frequency that the subject can control (McDonnell and Jex, 1967). In the present experiment, $\dot{\lambda}$ was initialized at $\lambda_0 = 0.5$ rad/sec. The fast mode was employed (defined by $\dot{\lambda} = 0.2$ rad/sec) until the first time that $\dot{E}$ exceeded one-third of the maximum error. The slow mode was used (defined by $\dot{\lambda} = 0.05$ rad/sec) after E first exceeded one-third of the maximum error. The use of the fast mode during the initial part of the trial when the errors were small decreased the total trial time and subject fatigue. The slow mode was used when, near the end of a trial, the task became more difficult and errors became larger. This allowed for a more accurate estimate of λ_c at the trial's end. Each trial consisted of the determination of one critical value λ_c.

Four subjects were trained to asymptote on the critical tracking task. The critical value of λ was the score for each trial. Trials were grouped into blocks for the purpose of repeated measures analysis. Blocks were grouped in repeating sets of three conditions. The first block in each set used the auditory and visual display (AV condition); the second block in each set used the visual display alone (V condition); the third block in each set used the auditory display alone (A condition).

The first six sets consisted of six trials per block. The remaining 30 sets consisted of eight trials per block to produce more stable estimates of the variability between trials. Subjects were tested on 2 or 3 days per week. Each day's runs usually consisted of three sets and lasted between 2 and 2.5 hr, including 1-min breaks between blocks and 10-min breaks between sets. Occasionally, subject-reported fatigue required that only two sets be run per day (this did not occur during the last six sets). All subjects completed 36 sets (828 trials per subject).

By set number 30, all subjects had seemingly achieved asymptotic performance on all displays. There was only random variation in the graphs of the block means.[2] This procedure allowed for analysis of asymptotic performance and learning rates, comparing all display modes within subjects.

The conditions were rotated cyclically in fixed order to permit intrasubject comparison of display modes and learning rates and to facilitate the learning phase of the experiment. The order of conditions was not counterbalanced. In spite of

[2]For the AV condition, the difference between adjacent block means for the last six sets differed by >5% only twice, with a maximum of 6.5%. For the V condition, the difference between adjacent block means for the last six sets differed by 7.5% six times, one of which was slightly greater than 10%. The adjacent block means for the A condition were more unstable. They differed by >5% eleven times and by >10% five times with a maximum of 17.5%.

Unfortunately, the standard deviations of the eight numbers within each block were much less stable for all conditions. They frequently differed by a factor of 1.5 or more. Fortunately, analysis of variance is robust against this degree of variability in the within-cell standard deviation. This variability in standard deviation indicates either unusual instability for this task or a failure to achieve asymptotic performance which was not reflected in the fluctuation of the means.

the lack of counterbalancing, it is still possible to compare learning rates and asymptotic performance between conditions through additional statistical analysis to correct for the major known effects of order. The AV condition was run first in each set to familiarize the subject with the correspondence between the two displays during the learning phase of the experiment. In the AV condition, subjects were asked to pay attention to the auditory and visual displays simultaneously.

RESULTS

To help interpret the following results, it is worth mentioning the subjective reaction to the auditory display. On the A condition, subjects reported trying to imagine the position of the cursor, which did not appear on the visual display. For this A condition, all four subjects reported initial difficulty conceiving the position of the cursor. On the first few A trials, the subjects were frequently uncertain about the direction of the cursor near the center. This confusion resulted in excess control inputs and occasionally reversed control. These errors were very infrequent after the third set.

In order to analyze asymptotic performance, a four-way analysis of variance (subject, by condition, by block, by replication within blocks) was performed on the critical tracking scores for the last six sets (31-36). These results are presented in table 1. The significant effects were as follows: subject $F = 65.88$, $df = 3,21$, $p < 0.00005$; condition $F = 44$, $df = 2,6$, $p < 0.01$ (using the more robust subjects x conditions as the error term, instead of the usual conditions x replications); subject-by-condition $F = 40.74$, $df = 6,42$, $p < 0.00005$; subject-by-block-by-condition $F = 2.38$, $df = 30,210$, $p = 0.0002$.

To test the hypothesis that the AV condition produces superior performance to that of the V condition, which produces superior performance to that of the A condition, contrasts were performed comparing these conditions. For the AV vs V comparison, $F = 12.390$, $df = 1,14$, and $p < 0.01$ (using the condition x replication error term from the complete analysis of variance (ANOVA) in table 1). This comparison is also significant using the more robust subjects x conditions as the error term from table 2 (which compares conditions in pairs); $F = 20.9937$, $df = 1,3$, $p = 0.020$. For the V vs A comparison, $F = 5281$, $df = 1,14$ and $p < 0.00005$.

Because the conditions were run in cyclic order, it is necessary to test the hypothesis that the superiority of the AV condition to the V condition might be due to warm-up or fatigue effects. The superiority of the V condition over the A condition is so large that this test is not necessary. To test for the effects of fatigue, the contrast was performed eliminating the first run of the AV condition and the last run of the V condition from each of the last 2 days. This left the AV condition from blocks 32, 33, 35, and 36 compared with the V condition from blocks 31, 32, 34, and 35: $F = 24.389$, $df = 1,14$, $p < 0.001$. This is also significant using the subjects x conditions as the error term from table 2: $F = 43.054$, $df = 1,3$, $p < 0.001$. To test for the effects of warm-up, the contrast was performed eliminating the last run of the AV condition and the first run of the V condition from each of the last 2 days. This left the AV condition from blocks 31, 32, 34, and 35 compared with the V condition from blocks 32, 33, 35, and 36: $F = 9.190$, $df = 1,14$, $p < 0.01$. This is also significant using the subjects x conditions as the error term from table 2: $F = 16.224$, $df = 1,3$, $p = 0.028$.

These tests suggest that the AV vs V improvement was not caused by warm-up or fatigue effects.

In order to compare conditions more accurately and to determine the source of the interactions, an analysis of variance was performed on the three pairs of two conditions. These results are presented in table 2. For the AV vs V condition, significant effects were found for subject, condition, and subject by block. None of the other interactions approach significance. For the AV vs A condition, V vs A condition, and for the complete ANOVA of table 1, significant effects were found for subject, condition, subject-by-condition, and subject-by-block-by-condition. Interestingly, there is no three-way interaction when comparing the AV and V conditions. This interaction occurs only when comparing the AV and V conditions with the A condition (discussed below). The subject-by-block interaction appears in the AV vs V comparison; the subject-by-condition and subject-by-block-by-condition interactions appear in the AV vs A and in the V vs A comparisons. These interactions remain significant when the tail probabilities are multiplied by 3 to correct for the problem of multiple inference (three pairs of two conditions on the same data). The probabilities shown in table 2 are the uncorrected probabilities computed from the individual F statistics.

Examining the interactions from the analysis of variance reveals additional information concerning the ways in which subjects were able to utilize the three combinations of displays. For the AV vs A, V vs A, and the complete ANOVA, a significant subject-by-condition interaction was found. This indicates differential efficacy between subjects for the auditory display relative to the visual display. For the AV vs V comparison, the subject-by-condition interaction did not approach significance. This indicates uniform enhancement of the AV display relative to the V display alone across subjects. For the AV vs V condition, there was a significant subject-by-block interaction. This may indicate that for some subjects, there was a small deviation from asymptotic performance which was not apparent from inspection of the block means. The three-way subject-by-block-by-condition interaction was significant for the AV vs A and for the V vs A comparisons, and for the complete ANOVA, but was not significant for the AV vs V comparison. This may indicate a failure of the A condition to reach asymptote relative to the other two conditions, for some of the subjects.

Table 3 presents the means and standard deviations by subject and condition in groups of six blocks. In addition, it lists the ratio for the AV and A condition to the V condition. This table illustrates the results of the analysis of variance, namely, that the asymptotic values for the AV condition are slightly above those of the V condition for all four subjects. The asymptotic AV/V ratio showed remarkable uniformity between subjects. It also showed the variability of the A/V ratio between subjects for the asymptotic and learning phases of the experiment. The AV condition also produces a somewhat higher learning rate than the V condition, as indicated by the AV/V ratio throughout the experiment. Furthermore, all subjects showed an increased ability to use the auditory display alone relative to the visual display alone, as indicated by the increase in the A/V ratio as the experiment progressed. Subject 3 seemed to show this learning later in the experiment (the A/V ratio did not show a marked increase until blocks 19-24).

To examine the learning phase of the experiment, the data for each subject and condition were regressed on the function $\lambda_c = c - ae^{-bn}$. This function was chosen in an attempt to model an asymptotic learning curve with negative acceleration, as is done in Bower's model (Atkinson et al., 1965) of simple learning experiments. Here, λ_c is the cutoff value of λ, where control was lost on each trial; c is the asymptote set equal to the mean of the last six blocks for each subject and condition; b is a measure of learning rate; c-a is a measure of early performance before training; and n is the block number. The free parameters fitted by the model BMDP3R nonlinear regression program are a and b.

In these regressions, trials were treated as replication observations within blocks. The values of the regression coefficients and their asymptotic standard deviations for each subjects and condition are presented in table 4. Although the distribution of coefficients is not known, table 4 indicates that the asymptotic standard deviations for the estimates of b are sufficiently homogeneous to justify the paired T test, which is reasonably robust against non-normality; $T = 3.954$, $df = 3$, $P < 0.02$. This indicates a significantly faster learning rate for the AV condition relative to that of the V condition. The nonlinear regression gives a larger value of b for the AV condition than for the V condition for all four subjects. The b values for the AV and V conditions are more than two standard deviations apart for all four subjects. Unfortunately, there is no clear relationship between the learning rates for the V condition and the A condition.

DISCUSSION

This study confirms the efficacy of the combined auditory and visual display in producing superior asymptotic performance relative to that of the visual display alone. The auditory display in the present study was not as effective as the Pitkin and Vinji display in improving performance. In the current study, at asymptote the average improvement in performance of the simultaneous auditory and visual display over that of the visual display alone was only 2%. The auditory display alone was only 60% as effective as the visual display alone. This is contrasted with the findings of Pitkin and Vinji where the addition of the auditory display to the visual display was 12.9%. Their auditory display alone was 82.2% as effective as the visual display alone. The lower effectiveness of the auditory display of this experiment is likely due to the inability of the subjects to use the amplitude notch as an accurate mark of the center position. In fact, all subjects complained of difficulty in determining distance from the center and, to some extent, difficulty in determining the exact position of the center, using the auditory display alone. Pitkin and Vinji's display used ear of stimulation to indicate the direction of the error from center; that probably accounts for the improved performance of their binaural display.

It is instructive to compare this study's auditory display with Mirchandani's results. His display was also frequency encoded, but it utilized amplitude modulation throughout the frequency range; the display of this study, on the other hand, used a narrow amplitude notch to mark the center. Although Mirchandani reported that the AV display produced a 63% reduction in rms error over the V display, he attributed this reduction to a 6-dB increase in the low frequency gain of the human operator. In the current study, the AV display produced only a 2% increase in λ_c (high frequency cutoff) relative to the V display. The most likely explanation of this difference is that the critical tracking task measures only the highest frequency that the subject can control and is a different measure than rms error. It would seem important for future research on combined auditory and visual displays to use tasks and analytic methods such as pilot-describing functions, which permit comparison of the displays as a function of the frequency spectrum of the disturbance to be tracked.

The current study and the above comparisons support the idea of supplementing a visual display of a compensatory tracking task with an auditory display of the same information. However, the exact characteristics of the display (amount of redundant cueing necessary and optimal marking of center points) require further study. Some improvement in precision of control might be expected under conditions of an unstable control law. The frequency of the disturbance at which this improvement might occur also requires further research. Additionally, the current study indicates that auditory displays may be useful when continuous attention in the visual display is not possible, if some loss in high bandwidth controllability is acceptable. Future research should also explore the possibility that an auditory display of the information given by instruments in present or future cockpits could increase the time available for the pilot to attend to the visual scene.

CONCLUSION

A frequency encoded auditory display was compared with a CRT visual display to indicate the vertical error for a compensatory critical tracking task. Used in combination with the visual display, the auditory display produced a slight but significant increase in performance over that achieved with the visual display alone. The current auditory display alone was only 60% as effective as the visual display. Evidence from other experiments indicates that greater improvement can be expected from auditory displays utilizing redundant cueing. In addition, frequency encoded auditory displays have proved more useful when the bandwidth does not approach the subject's upper limit of controllability.

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TABLE 1.- FOUR-WAY ANALYSIS OF VARIANCE

Source[a]	Degrees of freedom, df	Mean square	F	Tail probability
S	3	11.90413	65.88	<0.00005
SxR	21	.18069		
B	5	.19674	1.18	.3402
BxR	35	.16718		
SxB	15	.22692	1.32	.2043
SxBxR	105	.17209		
C	2	348.17243	3699.77	<.00005
CxR	14	.09411		
SxC	6	7.91811	40.74	<.00005
SxCxR	42	.19434		
BxC	10	.27198	1.54	.1441
BxCxR	70	.17673		
SxBxC	30	.32172	2.38	.0002
SxBxCxR	210	.13524		

[a]B = block; C = condition; R = replications,
S = subject.

TABLE 2.- ANALYSIS OF VARIANCE BY CONDITIONS IN PAIRS

Source[a]	Degrees of freedom, df	Mean square	F	Tail probability
Conditions: AV, V				
S	3	21.04022	116.88	<0.00005
SxR	21	.18002		
B	5	.26624	2.01	.1020
BxR	35	.13274		
SxB	15	.43541	2.50	.0034
SxBxR	105	.17421		
C	1	1.16600	15.87	.0053
CxR	7	.07346		
SxC	3	.05331	.29	.8330
SxCxR	21	.18464		
BxC	5	.40644	1.89	.1209
BxCxR	35	.21486		
SxBxC	15	.14018	.84	.6319
SxBxCxR	105	.16692		
Conditions: AV, A				
S	3	5.23336	29.34	<.00005
SxR	21	.17835		
B	5	.09048	.48	.7914
BxR	35	.18997		
SxB	15	.15947	1.02	.4407
SxBxR	105	.15631		
C	1	546.33199	4446.05	<.00005
CxR	7	.12288		
SxC	3	12.38701	63.39	<.00005
SxCxR	21	.19542		
BxC	5	.13486	.92	.4790
BxCxR	35	.14643		
SxBxC	15	.43117	3.48	.0001
SxBxCxR	105	.12377		

TABLE 2.- CONCLUDED.

Conditions: V, A				
S	3	5.45280	27.63	<.00005
SxR	21	.19736		
B	5	.30874	1.64	.1755
BxR	35	.18839		
SxB	15	.18067	1.21	.2735
SxBxR	105	.14890		
C	1	497.01929	5780.71	<.00005
CxR	7	.08598		
SxC	3	11.31402	55.74	<.00005
SxCxR	21	.20298		
BxC	5	.27464	1.63	.1789
BxCxR	35	.16891		
SxBxC	15	.39381	3.42	.0001
SxBxCxR	105	.11504		

[a]B = block; C = condition; R = replications; S = subjects.

TABLE 3.- MEANS AND STANDARD DEVIATION FOR SIX BLOCK GROUPS

	Blocks					
	1-6	7-12	13-18	19-24	25-30	31-36
Subject 1						
Mean AV	4.56	5.10	5.51	5.51	5.86	5.77
V	4.35	4.94	5.12	5.25	5.62	5.68
A	2.30	2.98	3.37	3.48	3.74	3.80
Std. dev. AV	.71	.63	.39	.49	.36	.43
V	.47	.60	.56	.43	.39	.43
A	.58	.44	.32	.36	.39	.35
AV/V	104.8%	103.2%	107.6%	105.0%	104.3%	101.6%
A/V	52.9%	60.3%	65.8%	66.3%	66.5%	66.9%
Subject 2						
Mean AV	3.94	5.55	6.11	6.26	6.46	6.33
V	4.09	5.30	6.13	6.12	6.27	6.21
A	1.49	1.94	2.46	2.68	2.96	3.08
Std. dev. AV	.95	.52	.42	.40	.48	.45
V	.69	.49	.40	.44	.51	.49
A	.46	.45	.53	.47	.34	.40
AV/V	96.3%	104.7%	99.7%	102.3%	103.0%	101.9%
A/V	36.4%	36.6%	40.1%	43.8%	47.2%	49.6%
Subject 3						
Mean AV	4.20	4.66	5.04	5.32	5.72	5.68
V	4.31	4.59	4.95	5.23	5.42	5.51
A	2.12	2.10	2.19	2.33	2.86	3.01
Std. dev. AV	.47	.36	.46	.36	.30	.33
V	.36	.43	.53	.38	.38	.37
A	.42	.39	.50	.42	.49	.41
AV/V	97.9%	101.5%	101.8%	101.7%	105.5%	103.1%
A/V	49.2%	45.8%	44.2%	44.6%	52.7%	54.6%
Subject 4						
Mean AV	4.14	4.20	5.11	5.53	5.25	5.17
V	4.10	3.97	4.92	5.24	5.19	5.11
A	1.69	2.24	3.12	3.49	3.75	3.52
Std. dev. AV	.80	.69	.44	.40	.34	.50
V	.39	.73	.51	.42	.40	.41
A	.52	.40	.36	.36	.44	.35
AV/V	101.0%	105.8%	103.9%	105.5%	101.2%	101.2%
A/V	41.2%	56.4%	63.4%	66.6%	72.3%	68.9%

TABLE 4.- NONLINEAR REGRESSION COEFFICIENTS FOR EACH SUBJECT BY CONDITION

Subject	Condition	Asymptote	a	Standard deviation	b	Standard deviation
1	AV	5.77	1.960	0.157	0.127	0.012
	V	5.68	1.894	.125	.092	.008
	A	3.80	2.195	.111	.107	.007
2	AV	6.33	4.425	.201	.193	.010
	V	6.21	3.634	.188	.168	.010
	A	3.08	2.280	.110	.086	.005
3	AV	5.68	2.133	.101	.089	.005
	V	5.51	1.639	.102	.076	.006
	A	3.01	1.293	.095	.048	.006
4	AV	5.17	2.118	.210	.154	.019
	V	5.11	1.702	.161	.104	.012
	A	3.52	2.963	.134	.122	.007

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16. Abstract

The great demand for visual attention out-the-window suggests exploration of the use of auditory displays for selected cockpit instruments. In this experiment, auditory, visual, and combined auditory-visual compensatory displays of a vertical axis, critical tracking task were studied. The visual display encoded vertical error as the position of a dot on a 17.78-cm, center-marked CRT. The auditory display encoded vertical error as log frequency with a six-octave range; the center point at 1 kHz was marked by a 20-dB amplitude notch, one-third octave wide. Asymptotic performance on the critical tracking task was slightly but significantly better when using combined displays rather than the visual-only mode. At asymptote, the combined display was slightly, but significantly, better than the visual-only mode. The maximum controllable bandwidth using the auditory mode was only 60% of the maximum controllable bandwidth using the visual mode. Studies of other single axis auditory displays have produced enhancement of visual displays. They have shown that redundant cueing increased the rate of improvement of tracking performance, as well as the asymptotic performance level. This enhancement increases with the amount of redundant cueing used. In conclusion, this effect appears most prominent when the bandwidth of the forcing function is substantially less than the upper limit of controllability frequency.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Auditory display (frequency encoded; continuous) Manual control (vertical axis, critical-tracking task)	Unlimited Subject Category - 06

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