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Multi-Modal Information Processing for Visual Workload Relief

Michael W. Burke, Richard D. Gilson, and Richard J. Jagacinski

Human Performance Center and Aviation Psychology Laboratory

The Ohio State University

Columbus, Ohio

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ABSTRACT

Subjects simultaneously performed two single-dimensional compensatory tracking tasks, one with the left hand and one with the right hand. The tracking performed with the left hand was considered the primary task and was performed with a visual display or a quickened kinesthetic-tactual (KT) display. The right-handed tracking was considered the secondary-task and was carried out only with a visual display. Although the two primary task displays had afforded equivalent performance in a critical tracking task performed alone, in the dual-task situation the quickened KT primary display resulted in superior secondary visual task performance. Comparisons of various combinations of primary and secondary visual displays in integrated or separated formats indicated that the superiority of the quickened KT display was not simply due to the elimination of visual scanning. In an additional condition, a quickened signal obtained from an off-line KT display was used to drive a primary visual display. Performance was equivalent to previous dual visual task situations, indicating that quickening per se also was not the immediate cause of the observed KT superiority. Results are discussed in terms of S-R compatibility differences, competition for modality-dependent processing resources, task discriminability, and the role of sensory buffers in maintaining multi-task frames of reference under conditions of shifting attention.

INTRODUCTION

As man-machine systems have become more complex, faster, and more precise, the efficient monitoring and control of their operation has necessitated the presentation of more information to the system operator at a much higher rate than ever before. Unfortunately, the quantity of information is often greater than the operator can properly process, with resulting reductions in operational efficiency or, at worst, accidents with attendant possibilities of loss of life. The phenomenon of system failure precipitated by a high visual workload combined with high auditory task demands has probably been most actively researched in the context of aircraft control. However, the problem of visual overload is common to many systems. A great deal of research has been conducted, therefore, on reducing the input processing demands of command stimuli.

One technique available to systems designers for providing information overload relief is to use multi-modal presentation involving several sensory modalities as opposed to primarily within-modality presentation of all information sources (Howell & Briggs, 1959). The assumption underlying this approach is that presenting information for two tasks to two different modalities will yield better overall performance than if the information for controlling both tasks is presented to the same modality. This technique, however, is little understood in terms of predicting which task structures are amenable to such multi-modal treatment, and experimental investigations have given highly inconsistent results (Treisman & Davies, 1973).

Being without adequate theoretical support, multi-modal workload relief techniques require strict empirical verification of their intended facilitory effects, a fact of little comfort to a design engineer in the early stages of system development. Multi-modal presentation of information has tended in

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the past to be highly situation specific, and it is clear that an understanding of the basic processes involved in this phenomenon is needed before it can be generally utilized. With a properly developed theoretical base for its use, multi-modal workload relief techniques hold great promise for providing solutions to the problems of increasing information rates encountered in many areas of man-machine systems design.

Numerous alternatives to visual displays have been developed. There has been some success in developing effective auditory display configurations (Vinje & Pitkin, 1972; Vinje, 1972; Mirchandani, 1972) and there are some indications (but none conclusive) that such displays provide workload relief for the visual modality. However, there is still a major constraint in their widespread use; the auditory modality is uniquely suited for two critical system functions, warning and communication. It would be difficult to justify preempting these functions for presentation of control information. One viable alternative is the use of tactile displays. Some success has been achieved with displays utilizing the sense of touch, but generally their performance has been a poor second to the performance levels reached with traditional visual displays (Hill, 1970). Tactile displays have generally suffered from a major drawback --- difficulty in comfortably and effectively maintaining a fixed proximity between the stimulation source and the skin for adequate transfer of information. This problem has made most of these displays inconvenient to use and impractical in most applied situations.

One particularly promising method of tactile presentation capitalizes on both kinesthetic and tactual stimulation by means of the operator's manipulation of a servo-controlled slide embedded in a control handle (Fenton, 1966). Unlike other tactile-based displays, this kinesthetic-tactual (KT) display does not assume that the operator is a passive receiver of information, but explicitly assigns to the human an active role in generating information from the display. Active perception of an information source is usually more effective (Gibson, 1962, 1979).

With the KT display, the relationship between the position of the hand and fingers can be voluntarily adjusted to achieve a high degree of sensitivity. Extensive research (reviewed by Gilson, Dunn, & Sun, 1977) has shown the KT display to be an effective and practically implemented means of displaying information. Several studies have demonstrated its effectiveness in situations as diverse as automobile (Fenton & Montano, 1968), aircraft (Gilson & Fenton, 1974), and helicopter control (Gilson et al., 1977). Research reported in Jagacinski, Miller, and Gilson (1979) has demonstrated that use of the KT display with velocity quickening can result in performance equivalent to that of an unquickened visual display for a critical tracking task. Additional studies suggest that the use of this KT display can help alleviate the high visual workload associated with such difficult tasks as landing a fixed-wing aircraft (Gilson, 1976) or flying a helicopter in a hover or through an ILS approach (Gilson, Dunn, & Sun, 1977). Still, the factors causing the improvement are at present largely unknown. It is possible that the use of nonvisual displays may improve overall system performance largely by eliminating the peripheral scanning interruptions necessarily present in the visual modality. Alternatively, improvements in performance may be due to more central factors, such as an internal, cognitive scanning process. Switching between modalities may be somehow more efficient, less disruptive, or faster than switching between information sources within the same modality.

Such theoretical questions must be resolved in order to utilize multi-modal presentation of information for workload relief. Verification of this apparent visual workload relief capability and quantification of the improved secondary task performance capability was the subject of this investigation. Three major questions were considered: (1) Is secondary task visual workload significantly enhanced by using a primary quickened KT display rather than a primary visual display? (2) If so demonstrated, is the effect primarily due to the elimination of visual scanning? (3) Is the effect primarily due to velocity quickening of the KT display?

The measure of workload was derived from a critical tracking task (Jex, McDonnell, & Phatak, 1966), which requires subjects to stabilize a first-order unstable system whose time constant is made progressively smaller until the tracker loses control. The inverse of the "critical" time constant at which control is lost, λ_c, provides a measure of tracking capability. For visual tasks, λ_c is highly correlated with τ_e, the operator's effective time delay (Jex & Allen, 1972).

Within a dual-task framework, for results to be meaningful it is necessary to first equate primary single task performance on the visual and KT displays, so that one display does not have an initial advantage over the other. Based on the results of Jagacinski et al. (1979), a velocity-quickened KT display yielded approximately equivalent performance to an unquickened visual display. Second, in order to maintain primary task performance matching near its single task level and to prevent overemphasis of the secondary task, it was further decided to cross-adaptively couple the two tasks. Jex, Jewell, and Allen (1972) had earlier developed the necessary algorithms, parameter values, and automatic circuitry which were used in the present research.

Subjects performed a primary compensatory tracking task with their left hand, using information they received from either a visual or a velocity

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quickened KT display. Concurrently, subjects performed a secondary visual tracking task with their right hand. The dynamics of both the primary and secondary tasks consisted of first-order unstable (subcritical) tracking tasks. The time constant for the primary tracking task was fixed, while the time constant for the secondary task was coupled to the subjects' performance on the primary task. Cross-adaptive circuitry shortened the time constant of the secondary task until primary task performance just began to deteriorate from the level of performance obtained with minimal secondary loading. The resulting measure of secondary workload capability, λ_s, was the inverse of the shortest time constant that subjects could control on the secondary task while maintaining primary task performance near its minimally loaded level.

METHOD

Subjects

Twenty pretested and selected subjects were assigned to one of the five experimental conditions and received a monetary payment according to a set schedule and their performance.

Apparatus

Displays. The primary task was controlled either by a quickened KT display or one of four different visual displays. The KT display was built into the cylindrical handle of the control stick, and consisted of a servo-controlled solid rectangular section (1.25 cm x 2.4 cm x 4 cm long) sliding in and out of the handle. These positive and negative excursions from the flush surface of the control handle indicated the direction and magnitude of system error. The dynamic range of the slide was $\pm$ 1.0 cm from the handle surface, with this full response down 3 dB at 1.3 Hz. The phase lag for frequencies below 1 Hz could be approximated as a 0.12 s time delay, when the display was driven to maximal displacement (see Burke, 1979, for details). The "tactual-quickened (TQ) group" used this KT display with 50% velocity quickening as the primary task display. Another group of subjects, the "visual-quickened (VQ) group," received essentially equivalent display dynamics but as a visual signal, by first passing the velocity-quickened signal through an off-line KT display before driving the visual display. This visual control condition would thus have both the beneficial effect of quickening and the deleterious effect of servo-motor lag to approximately the same extent as the tactual display.

The primary task visual displays indicated system error by the vertical displacement of a green target from the center of a Tektronix Type 602 CRT display. Three different target sizes were used: a single integrated dot (2 mm diameter) for the "visual integrated (VI) group", a short horizontal line (1 x 8.5 mm) for the "visual short-line (VS) group", and a long horizontal line (1 mm x 8 cm) which nearly spanned the boundaries of the CRT screen for the "visual long-line (VL) group " (Figure 1). The subjects in the VQ group received the integrated dot visual display configuration.

Insert Figure 1 about here

The secondary task visual display used the same basic display configurations, but employed their vertically-oriented, horizontally-moving counterparts: the horizontal displacement of the single dot, a separate short vertical line, and a separate long vertical line. The TQ group's secondary visual display used the short vertical line. System error was depicted as a horizontal displacement with a dynamic range of $\pm$ 4.0 cm. For single tasks the center marker was 1 x 17 mm and for the dual tasks it was 2 x 2 mm. The display-to-viewpoint distance was 60 cm, subtending a visual angle of $\pm 3.8^{\circ}$. In that foveal viewing is typically regarded as $\pm 0.75^{\circ}$ of visual angle, some extra-foveal scanning would be expected for the visual display consisting of the two short lines, though not necessarily for the integral dot or the two long intersecting lines.

<u>Controls</u>. Compatible with the vertical primary display orientation, the primary task control stick moved in a vertical plane at the left side of the seated subject. The control stick was a 57 cm long unsprung isotonic lever arm, custom-built to simulate a helicopter collective control. Range of angular travel was $\pm 10^{\circ}$, with 20° above horizontal representing the neutral

control position.

The secondary task used a much smaller wrist controller (6 cm x 0.3 cm) with an angular left/right excursion of $\pm 20^{\circ}$ from its neutral position. Compatible with the secondary task's horizontal display orientation, the isotonic secondary control stick moved from side to side in a plane parallel with the subjects' seat back.

System Implementation. The system dynamics were simulated on an EAI PACE TR-48 analog computer with hybrid digital control. The analog computer drove the visual display CRT directly, and the KT display indirectly through a servo-amplifier interface. The actual position of the KT display's slide, regardless of the command signal applied, was given by a follower potentiometer attached to the drive motor. In addition to its function as feedback transducer for the servomotor, the follower signal served two other purposes. In the KT display condition, this signal of the slide's actual position was compared to where it should be (the command signal) in order to generate an indication of impeded movement. When the subject grasped the display too tightly, enough to override the servomotor, red warning lights were turned on in both the subject's cubicle and the experimenter's station. In another role, when the KT display was not touched by a subject but instead was used offline to simulate the KT dynamics for the VQ group, the analog computer drove the servomotor with a quickened signal, and the signal from the follower pot was amplified to drive a visual CRT display.

The critical tracking tasks consisted of a first-order unstable system and a means of progressively shortening its time constant (Jex, McDonnell, & Phatak, 1966). The unstable plant was controlled by the angular position of the appropriate control, while the system error was displayed as a displacement of its corresponding display. No forcing function was used since the subjects' inherent variability provided sufficient input to excite the unstable system. On each trial the initial level of instability was increased slowly at a constant rate of .05 rad/s^2 until it reached a "critical" level where the operator could no longer supply sufficient control to stabilize the system. Loss of control was defined as the displayed system error exceeding the previously specified display excursion limits. The critical level of instability, λ_c, was the dependent measure taken on each trial. The initial level of instability was preset by the experimenter at the start of each trial such that each trial lasted approximately 30 s.

In order to equate single-task performance with the visual and KT displays, it was necessary to quicken the KT display. The quickening ratio of error velocity ($\dot{\underline{e}}$) to error magnitude ($\underline{e}$) was 1:1. In order to make the total display ranges of the quickened and unquickened displays more comparable, the effective quickened display signal was ($\dot{\underline{e}}$ + $\underline{e}$)/2.

The circuitry used for the cross-adaptive dual-task paradigm followed the design of Jex, Jewell, and Allen (1972). The dynamics for both the primary and secondary tasks consisted of a first-order unstable system. The level of instability was fixed for the primary task on all dual-task trials. On selected trials, the level of instability on the secondary task was fixed at a nominally low value of .1 r/s, and the error on the primary task under this minimal loading was measured. On the remaining trials, cross-adaptive circuitry adjusted the instability of the secondary task until the primary task error exceeded its minimally loaded value by 25%.

Procedure

The experiment consisted of eleven sessions, one-hour per day, over a

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two and one-half week period. The experiment was divided into four phases: pretest, single-task training, dual-task performance, and post-test. All sessions consisted of three blocks of trials separated by 5 minute rest periods. For single-task sessions, each block consisted of 15 critical tracking trials of approximately 30 s duration each and a 10 s intertrial interval. The performance measure was the median of the 15 λ_c values for each block.

For the dual-task sessions, each block consisted of one minimally loaded trial and five cross-adaptive trials, all of 100 s duration. The performance measures taken were the block medians of primary task error and secondary task instability, λ_s, along with the minimally loaded error level.

<u>Pretest</u>. Five groups of approximately 10 subjects each were pretested in a single-task critical tracking paradigm using the secondary visual task with a short-line target. No performance feedback was given. Subjects were ranked on the basis of their median performance scores on the last two blocks. The four highest scoring subjects in each group were selected to continue on for the full experiment.

<u>Single-Task Training</u>. Days 2-6 consisted of familiarization and training on each of the two tasks separately. Days 2-5 consisted of training on each group's respective primary task display. Subjects received trial by trial feedback of their λ_c scores. All subjects then received one session of training (Day 6) on the visual secondary task with which they were already familiar from the pretest.

<u>Dual-task phase.</u> On Days 7-10, subjects controlled the primary and secondary tasks simultaneously. The first two sessions were primarily for

familiarization and training. Subjects were informed that they were to try to get as low an error score as they could on the visual or KT primary task, while only not losing control of the visual secondary task. The duration of the dual-task trials was 100 s, since the subjects were not to lose control of either task. On approximately 6% of these trials subjects did lose control, and these trials were repeated. Tight control of the primary task was also emphasized to the subjects by paying them on the basis of performance on Days 9 and 10 and making two-thirds of their performance payment be determined by their primary error. Only one-third of their payment was determined by their secondary task instability scores.

Post-test. In order to ascertain any shifts in the level of primary task performance due to further practice with it as a component of the dual-task paradigm, subjects were given a single-task post-test. Day 11 was identical in procedure to the primary-task critical tracking paradigm used on Day 5.

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RESULTS

Single-Task Performance

Means were calculated from the block medians of the four subjects serving in each of the five display conditions. Their mean performance for all blocks over all single-task sessions is shown in Figures 2 and 3. Separate analyses of variance were conducted on each of the four single-task phases shown.

Insert Figures 2 and 3 about here

A two-way analysis of variance was run on the pre-test data to examine for possible biasing effects in the assignment of subjects to experimental conditions; only the last two blocks of Day 1 were analyzed. The between-subject display-assignment variable indicated that there were no significant differences in the assignment of subjects to display conditions, $\underline{F}(4,15) = .51$, $\underline{p} > .1$. There was a significant main effect superiority for the last block, $\underline{F}(1,15) = 12.51$, $\underline{p} < .01$ but the effect accounted for only a small percentage of the variance ($\omega^2 = 8\%$); this suggests little practical change over these last two blocks. The display-assignment by blocks interaction was not significant, $\underline{F}(4,15) = .53$, $\underline{p} > .1$.

A similar mixed-design analysis of variance was conducted on the final day of primary task training, Day 5, using all three blocks. Performance in the five between-subject display conditions did not differ significantly from each other, $\underline{F}(4,15) = .49$, $\underline{p} > .1$. The within-subject block factor again showed a significant main effect, $\underline{F}(2,30) = 9.07$, $\underline{p} < .01$, but accounted for so little of the variance ($\omega^2 = 7\%$) as to be near asymptotic performance. Again, the display by block interaction was not significant, $\underline{F}(8,30) = 1.13$, $p > .1$.

An analysis of the visual secondary training session, Day 6 revealed no significant effect of display, $\underline{F}(4,15) = .24$, $\underline{p} > .1$, or of a display by block interaction, $\underline{F}(8,30) = .63$, $\underline{p} > .1$. However, there was a significant effect of blocks, $\underline{F}(2,30) = 22.80$, $\underline{p} < .01$, which accounted for a sufficiently high proportion of the variance ($\omega^2 = 29\%$) to conclude that performance had not asymptoted yet. The last two blocks of the two secondary task sessions, Days 1 and 6, were then compared and found to significantly differ from each other, $\underline{F}(1,15) = 88.16$, $\underline{p} < .01$; this factor accounted for a major portion of the variance ($\omega^2 = 62\%$). The display factor was not significant, $\underline{F}(4,15) = .44$, $\underline{p} > .1$ whereas the blocks did differ significantly from each other, $\underline{F}(1,15) = 9.02$, $\underline{p} < .01$. All interactions were not significant at the $\underline{p} > .1$ level or better.

An analysis of variance also compared the post-test phase, Day 11, with the final session of primary training, Day 5. There was no significant difference between Days 5 and 11, $\underline{F}(1,15) = .10$, $\underline{p} > .1$, and there were no significant differences among the display conditions used, $\underline{F}(4,15) = .49$, $\underline{p} > .1$. Likewise, all higher-order interactions were not significant at the $\underline{p} > .1$ level or better. The only significant difference found was in the block factor, $\underline{F}(2.30) = 9.76$, $\underline{p} < .01$, but this factor only accounted for a small amount of the variance ($\omega^2 = 8\%$).

Dual-Task Performance

Because stable, near-asymptotic performance was of more importance than acquisition, dual-task analyses were conducted only on the three blocks of of Day 10, the final session of dual-task performance (Figures 4 and 5). The statistical tests performed on the secondary task λ_s values were repeated

Insert Figures 4 and 5 about here

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for the primary-task error (e_p) scores. The overall analysis strategy was to analyze the four tightly clustered visual curves by themselves, and then to separately compare the KT display with the most nearly adjacent visual display (in this case, the VQ group). Comparing the KT display performance against the best performance among the visual display groups allowed the most conservative test of KT display superiority.

Analysis of the secondary-task λ_s scores of the four visual displays alone revealed a significant main effect of both blocks, $F(2,24) = 6.70$, $p<.01$, and display configuration, $F(3,12) = 4.44$, $p<.05$. The block factor accounted for 10% of the variance, while the display factor accounted for 27%. The interaction of the two factors was not significant, $F(6,24) = .8$, $p>.1$. A Dunn's Test (or Bonferroni t, with $\alpha_{FW} = .05$, 12 df) revealed no significant differences between adjacent visual display curves, but a significant difference between the lowest and highest performance curves (VQ and VS), and between the lowest and second highest performance curves, (VI and VS). The VQ display condition alone was then compared to performance with the quickened KT display. These two display conditions were found to be significantly different, $F(1,6) = 763.59$, $p<.01$, with this factor accounting for the majority of the variance ($\omega^2 = 72\%$). The block factor was also significant, $F(2,12) = 24.16$, $p<.01$, but only accounted for 4% of the variance. The display by block interaction was not significant, $F(2,12) = .29$, $p>.1$.

Comparisons conducted on the primary-task error data revealed no differences between the four visual conditions, $F(3,12) = .36$, $p>.1$. Comparison of the error scores of the TQ and VQ groups showed the error scores of the TQ group were significantly lower, $F(1,6) = 53.86$, $p<.01$, and this effect accounted for 51% of the variance. Block factors were not significant, nor were any interactions. The TQ group thus achieved significantly better secondary-task performance while also doing somewhat better on the primary task.

DISCUSSION

The major finding of the present study is that visual and quickened KT displays equated for performance on a single dimensional critical tracking task do not show equivalent time-sharing performance with a secondary visual task. The quickened KT display is markedly superior in the dual-task situation; the KT and visual displays produced about the same primary task error, but differed greatly in terms of secondary task capability. This result then answers the first question raised about the capacity of the quickened KT display to provide significant visual workload relief.

The next issue is the cause of the observed performance increase. Poulton (1966) among others demonstrated that when two simultaneous visual tracking tasks are displayed on separate units, and the displays are physically moved closer together, performance is improved as a result of the lessening of head and eye movements. Such visual scanning, then, is one possible source of dual-task decrement, and the elimination of this scanning decrement should produce higher performance. That a scanning factor is not the major cause of the observed KT display superiority is indicated by still-inferior performance of subjects using an integrated visual display format, which presented the two error signals as the combined horizontal and vertical movements of a single target and thereby eliminated the need for scanning. Thus, only a small fraction of the KT superiority is apparently due to the elimination of visual scanning, as indicated by the slightly improved performance with the integral dot display relative to tracking the two small separate lines.

Two final points should be noted concerning the applicability of these results to scanning in general. First, note that although the two small lines did not permit simultaneous foveal view of both displays, the scanning range was still quite small (being limited to the 8 cm x 8 cm display range

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on the single CRT). In normal cockpit environments, scanning over much wider ranges is commonly encountered, with the expectation that performance levels would be even worse. Pilot data from our laboratory indicates that larger visual time-sharing decrements may result when the primary and secondary tasks are displayed on even immediately adjacent CRT screens.

Secondly, since the two large lines spanned the entire display range on the oscilloscope screen, it would appear to be theoretically possible to simply follow their point of intersection, in much the same manner that one would follow the integral dot. Moreover, the large line display would be expected to be more compatible with the two-handed orthogonal control arrangement. The integral dot might have a greater tendency to be viewed as a vector sum of the horizontal and vertical errors rather than as orthogonal components, and hence one would predict this to be a less compatible control/ display arrangement. Contrary to these expectations, the large line display produced slightly worse performance than the integral dot (although this difference was not statistically significant). Subjective reports suggest that it is not an easy task to follow the intersection of the two-lines with continuous foveal view. Instead, there seems to be a type of preattentive "visual capture" occurring, where movement in one dimension seems to cause an involuntary shift of attention to that axis and to the detriment of the other axis.

If the difference between the quickened KT display and the visual displays is not simply due to the elimination of visual scanning, then perhaps there is some more central factor operative. Three possibilities are differences in inherent S-R compatibility between the visual and KT displays, the velocity-quickening used with the KT display, or factors specific to the use of two separate sensory modalities.

S-R compatibility is a ubiquitous behavioral phenomenon often implicated as the cause or confounding of many experimental results. It is an extremely robust effect, and is considered one of the most important factors determining human performance. Compatibility is thought to determine the complexity of the transformation (number of recodings) between a stimulus and its response, thereby determing available resource demands and so becoming an important factor in workload considerations (Fitts, 1964; Rogers, 1979). With respect to the present experimental results, it may be argued that the KT display's superiority is somehow due to its having a higher degree of S-R compatibility, hence reducing processing demands. The KT display may be thought to have a higher degree of SR compatibility because of its more intimate relationship between the source of stimulation, at the fingers and hand, and the responding member, the hand stimulated. Moving a display close to the responding limb does not always improve performance (Hill, 1970). However, adjusting the position of a limb on the basis of kinesthetic-tactual cues is a common daily activity. The present display design may afford a simple analog to this highly compatible activity.

There are several points which argue against a compatibility explanation in the present case. First, the visual displays can also be argued to have high degrees of compatibility, though it is unknown to what degree relative to the KT display. Secondly, the present results indicated that varying degrees of compatibility, at least among the visual display configurations, had little effect. Thirdly, for such a factor to be the cause of the observed KT superiority, one would need to explain why this processing advantage was not present in the single-task phase and yet operative in a dual-task situation. One final qualification is that an independent measure of compatibility is necessary before these arguments can be pursued in greater detail.

Another possible reason for the superior performance of the KT display is the velocity-quickening used to equate the two types of primary displays, since this quickening then becomes a confounding factor in interpreting the dual-task results. Therefore, a quickened integral-dot visual display was subjected to the same display dynamics as the KT display by passing a quickened signal through an offline KT mechanism before visual presentation to the subject. Results showed that visual tracking, when helped by quickening but also hampered by the same servo lag as the KT display, yielded approximately equivalent performance in the single-task situation but substantially lower secondary performance (as did the other visual displays) in the dual-task situation. The lead provided by the velocity quickening may simply be needed to overcome the mechanical lag in the display itself, or alternatively, to overcome an extra lag or longer effective time delay present in the KT perceptual system but not found in the visual system.

Perhaps the most likely cause of the visual workload relief capability of the KT display is its utilization of a different sensory modality. The observed superiority could be due to additional availability of processing resources. It may be as some attention theorists have speculated that each modality has its own reserve of processing capacity independent of and uninfluenced by the allocation policies of other modalities (Moray, 1967; Kantowitz & Knight, 1974). Treisman and Davies (1973) have argued that multi-modal presentation avoids structural interference between two tasks by making available additional stimulus processing mechanisms rather than additional freely allocatable capacity. Their experiments demonstrated a considerable improvement in the subjects' ability to divide their attention between two inputs when these were in different modalities (visual and auditory). In the present experiment the KT display may reduce visual workload by tapping an unused extra pool of capacity associated with the tactual modality.

In addition to perceptual analyzers, there are other modality-specific mechanisms which are candidates for structural bottlenecks to within-modality processing. It may take less time to switch attention and then become current on another task when the two tasks are in different modalities because of the presence of an extra sensory buffer. Switching attention between modalities, the operator could maintain the most recent state of the other task in such a buffer memory while attending to a different task. Given that the switching rate is not too slow and the signals not changing too fast, then the contents of the buffer would be a good estimate of the signal on the first task. Returning to that task could then be done more quickly and efficiently by simply updating the buffer's contents, an impossibility if the two tasks used the same modality and hence the same buffer. The existence of such buffer memories have been demonstrated in the visual modality (Baddeley, 1976), the auditory modality (Morton, 1970) and the tactual modality (Bliss, Crane, Mansfield, & Townsend, 1966).

Increased stimulus discriminability reduces processing time (Lindsay, Cuddy, & Tulving, 1965; Lindsay, Taylor & Forbes, 1968) and may have implications for multi-modal dual-task studies. More efficient switching between two tasks in different modalities may be due to reduced time delays stemming from increased task discriminability. One can conceive of a situation where capacity and structural resources are equivalent both within-and between-modalities, but where performance improves because task information somehow receives a modality-specific "tagging" (or qualitative difference) related to the channel structures it has passed through. The use of two different modalities may provide signals which serve as cues to reduce task confusion errors by keeping the two information sources distinct (Spieth, Curtis & Webster, 1954; Mudd, 1963; Shaffer, 1973).

The present research has demonstrated the usefulness of the KT display for relieving visual workload. Regardless of the eventual answers concerning the specific locus and process of multi-modal workload relief, it is interesting to note that equating two displays in terms of single critical task performance was not sufficient to produce equal dual-task performance. It has been possible to conclusively establish that peripheral scanning was not a major factor in the KT display's superiority, nor the velocity quickening per se provided the KT display. In addition, compatibility also does not appear to be a major factor, although the evidence for this conclusion is not strong. At this time, the most likely cause of the observed visual workload relief would seem to be the modality factor. Why using a different modality should improve performance was not directly tested, although several possible mechanisms were suggested. It is hoped that these findings will stimulate more research into the phenomenon of multi-modal workload relief.

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REFERENCES

BADDELEY, A. D., 1976, The Psychology of Memory. (New York: Basic).

BLISS, J. C., CRANE, H. D., MANSFIELD, P. K., AND TOWNSEND, J. T., 1966, The information available in brief tactile presentations. Perception and Psychophysics, 1, 273-283.

BURKE, M. W., 1979, An investigation of visual/tactual multi-modal information processing using dual cross-adaptive critical tasks. Master of Science Thesis, Department of Industrial and Systems Engineering, The Ohio State University. (Human Performance Center/Aviation Psychology Laboratory, Technical Report No. 2)

FENTON, R. E., 1966, An improved man-machine interface for the driver-vehicle system. IEEE Transactions on Human Factors in Electronics, HFE-7, 150-157.

FENTON, R. E., and MONTANO, W. B., 1968, An intervehicular spacing display for improved car-following performance. IEEE Transactions on Man-Machine Systems, MMS-9, 29-35.

FITTS, P. M., 1964, Perceptual-motor skill learning. In: Categories of Human Learning (Edited by A. W. Melton) (New York: Academic).

GIBSON, J. J., 1962, Observations on active touch. Psychological Review, 69, 477-491.

GIBSON, J. J., 1979, An ecological approach to visual perception. New York: Houghton-Mifflin.

GILSON, R. D., 1976, A tactual display aid for primary flight training. National Aeronautics and Space Administration Annual Report No. NAS2-8954.

GILSON, R. D., DUNN, R. S., and SUN, P., 1977, A kinesthetic-tactual display concept for helicopter-pilot workload reduction. Paper to the 33rd Annual National Forum of the American Helicopter Society, Washington, D. C.

GILSON, R. D., and FENTON, R. E., 1974, Kinesthetic-tactual information presentations -- Inflight studies. IEEE Transactions on Systems, Man, and Cybernetics, SMC-4, 81-90.

HILL, J. W., 1970, Describing function analysis of tracking performance using two tactile displays. IEEE Transactions on Man-Machine Systems, MMS-11, 92-101.

HOWELL, W. C., and BRIGGS, G. E., 1959, Information input and processing variables in man machine systems: A review of the literature. Technical Report NAVTRADEVCEN 508-1, U. S. Naval Training Device Center, Port Washington, New York.

JAGACINSKI, R. J., MILLER, D. P., and GILSON, R. D., 1979, A comparison of kinesthetic-tactual and visual displays via a critical tracking task. Human Factors, 21, 79-86.

JEX, H. R., and ALLEN, R. W., 1970, Research on a new human dynamic response test battery. Proceedings of the Annual Conference on Manual Control, 6, 743-777.

JEX, H. R., JEWELL,W. F., and ALLEN, R. W., 1972, Development of the dual-axis and cross-coupled critical tasks. Proceedings of the Annual Conference on Manual Control, 8, 529-552.

JEX, H. R., MCDONNELL,J. D., and PHATAK, A. V., 1966, A "critical" tracking task for manual control research. IEEE Transactions on Human Factors in Electronics, HFE-7, 138-145.

KANTOWITZ, B. H., and KNIGHT, J. L., 1974, Testing tapping timesharing. Journal of Experimental Psychology, 103, 331-336.

LINDSAY, P. H., CUDDY, L., and TULVING, E., 1965, Absolute judgments of simultaneously presented visual and auditory stimuli. Psychonomic Science, 2, 211-212.

LINDSAY, P. H., TAYLOR, M. M., and FORBES, S. M., 1968, Attention and multidimensional discrimination. Perception and Psychophysics, 4, 113-118.

MIRCHANDANI, P. B., 1972, An auditory display in a dual-axis tracking task. IEEE Transactions on Systems, Man, and Cybernetics, SMC-2, 375-380.

MORAY, N., 1967, Where is capacity limited? A survey and a model. Acta Psychologica, 27, 84-92.

MORTON, J., 1970, A functional model for memory. In: Models of Human Memory (Edited by D. A. Norman) (New York: Academic).

MUDD, S. A., 1963, Spatial stereotypes of four dimensions of pure tone. Journal of Experimental Psychology, 66, 347-352.

POULTON, E. C., 1966, Engineering psychology. Annual Review of Psychology, 17, 177-200.

ROGERS, S. P., 1979, Stimulus-response compatibility: Extra processing stages versus response competition. Proceedings of the Annual Meeting of the Human Factors Society, 23, 415-419.

SPIETH, W., CURTIS, J. F., and WEBSTER, J. C., 1954, Responding to one of two simultaneous messages. Journal of the Acoustical Society of America, 26, 391-396.

TREISMAN, A., and DAVIES, A., 1973, Divided attention to ear and eye. Attention and Performance, 4, 124-136.

VINJE, E. W., 1972, Flight simulation evaluation of audio IFR displays for V/STOL hover-control. Proceedings of the Annual Conference on Manual Control, 2, 375-380.

VINJE, E. W., and PITKIN, E. T., 1972, Human operator dynamics for aural compensatory tracking. IEEE Transactions on Systems, Man, and Cybernetics, SMC-2, 504-512.

FIGURE CAPTIONS

Figure 1 -- Alternative visual display configurations. Vertical movement is used for the primary task display, and horizontal movement is used for the secondary task display.

Figure 2 -- Mean group performances on a single critical tracking task with a quickened tactual display and three unquickened visual displays.

Figure 3 -- Mean group performances on a single critical tracking task with a quickened tactual display, an unquickened visual (VI) display (both repeated from Figure 2), and a quickened visual display having its signal passed through an off-line tactual display.

Figure 4 -- Mean group performances on a dual tracking task. The primary displays are the same as in Figure 2.

Figure 5 -- Mean group performances on a dual tracking task. The primary displays are the same as in Figure 3.

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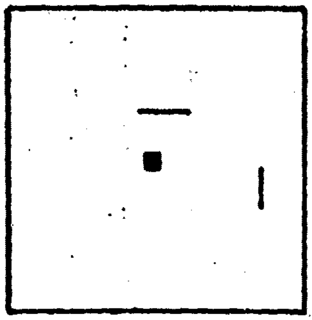
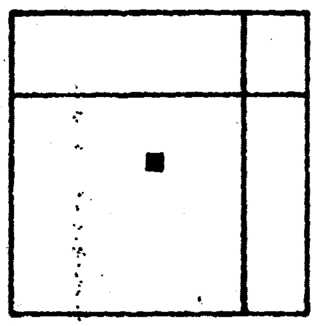
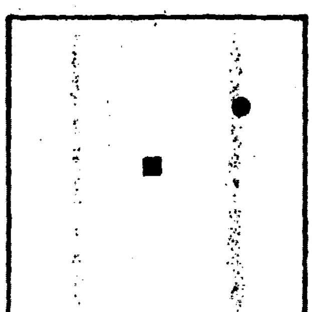
VISUAL DISPLAY CONFIGURATIONS



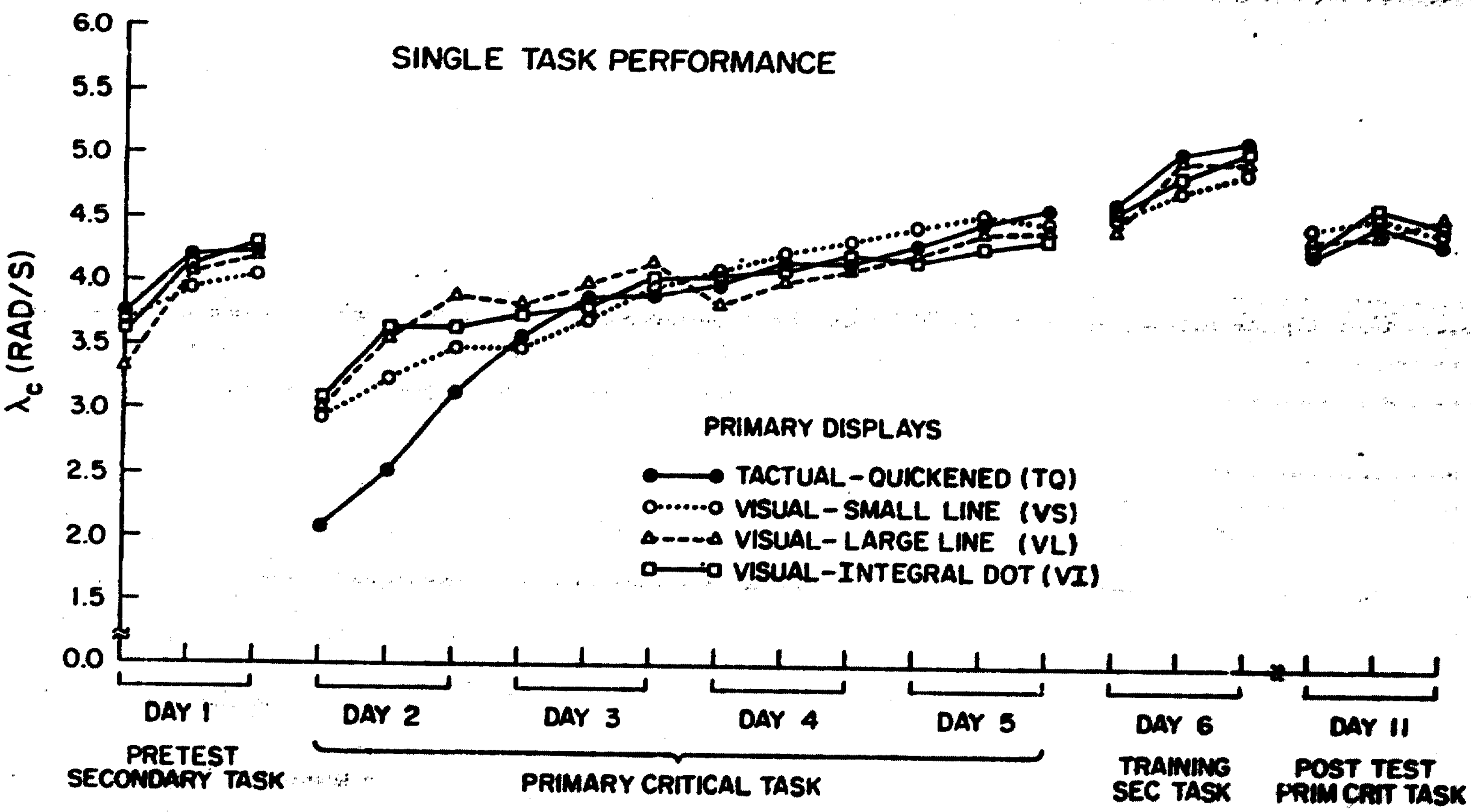
GROUP VS-SMALL LINE

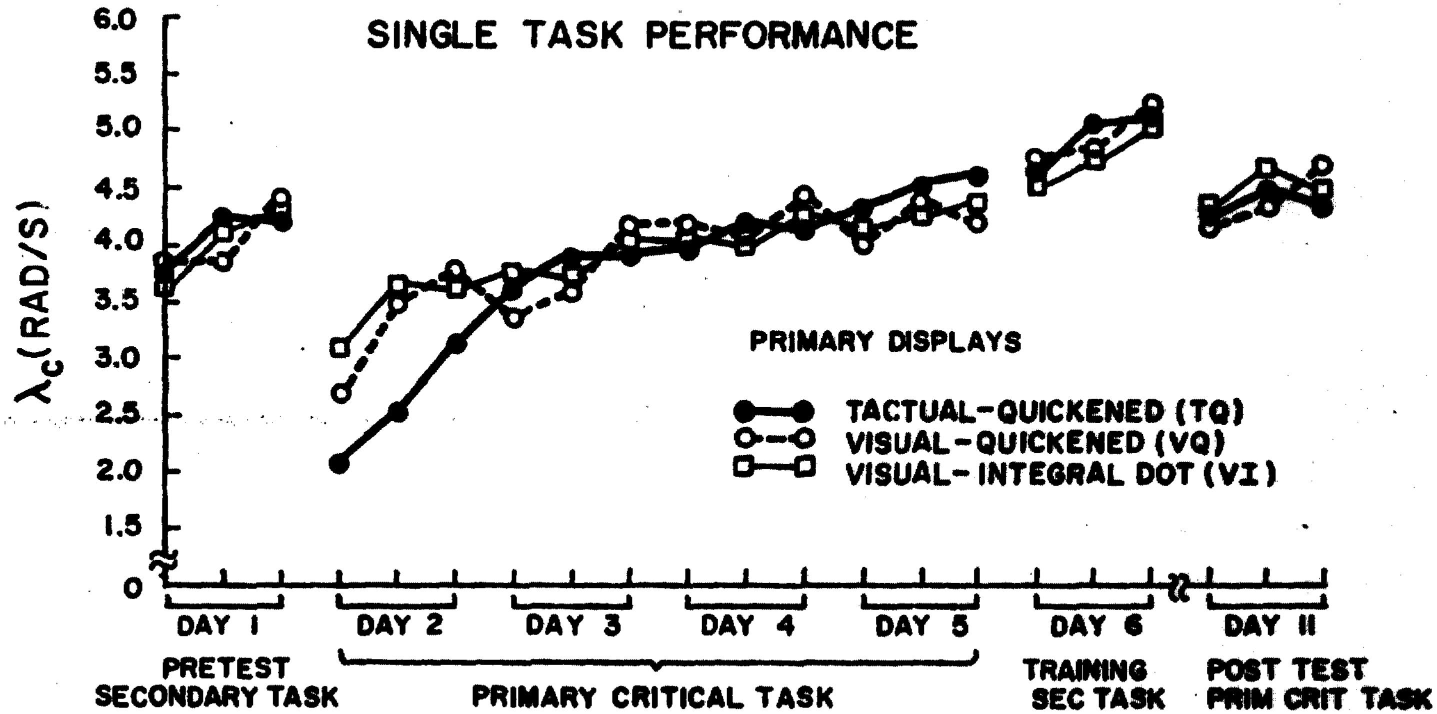


GROUP VL-LONG LINE



GROUP VI-INTEGRAL DOT


SINGLE TASK PERFORMANCE
λc (RAD/S)
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
0.0
PRIMARY DISPLAYS
TACTUAL - QUICKENED (TQ)
VISUAL - SMALL LINE (VS)
VISUAL - LARGE LINE (VL)
VISUAL - INTEGRAL DOT (VI)
DAY 1
DAY 2
DAY 3
DAY 4
DAY 5
DAY 6
DAY 11
PRETEST
SECONDARY TASK
PRIMARY CRITICAL TASK
TRAINING
SEC TASK
POST TEST
PRIM CRIT TASK



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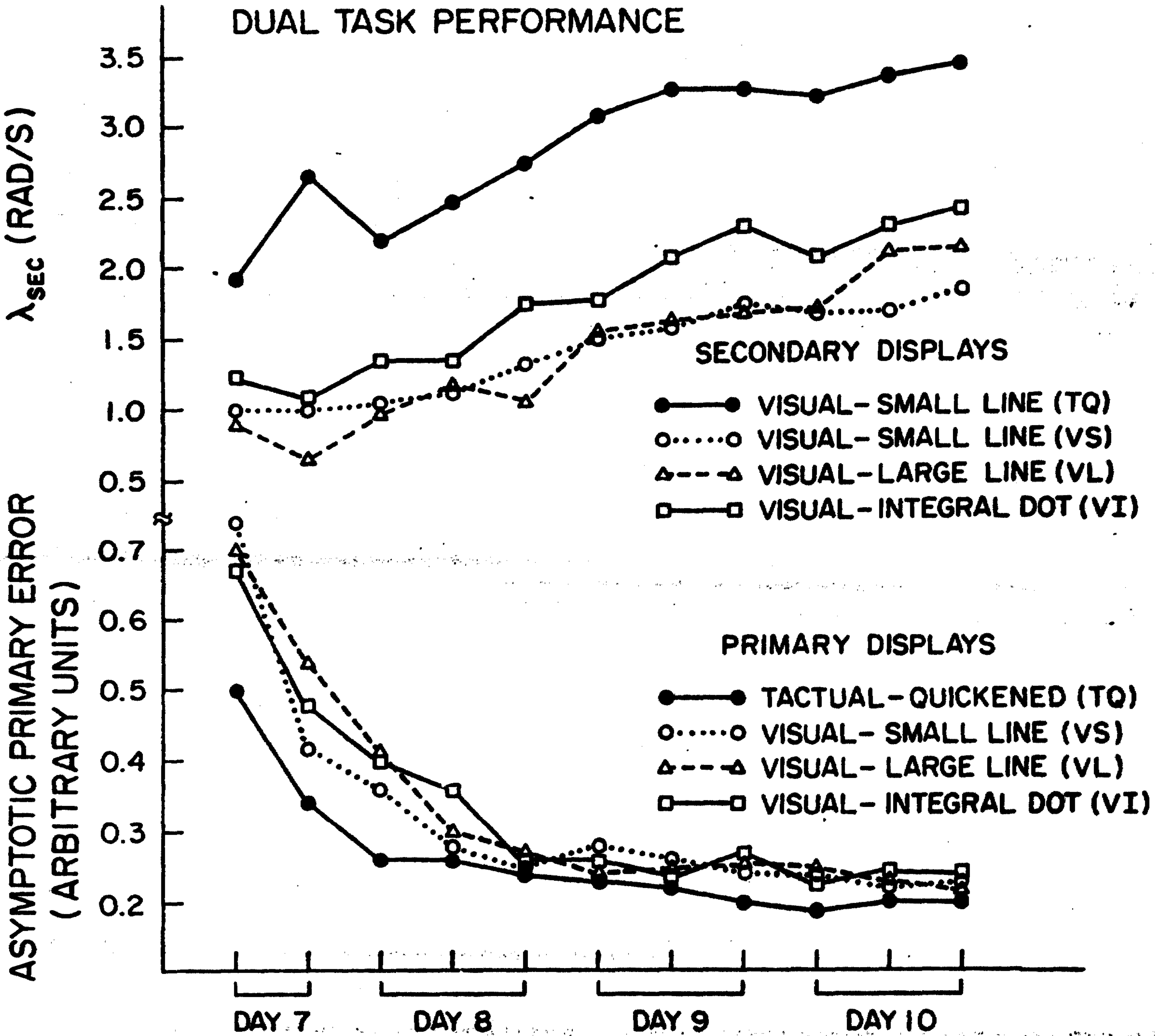
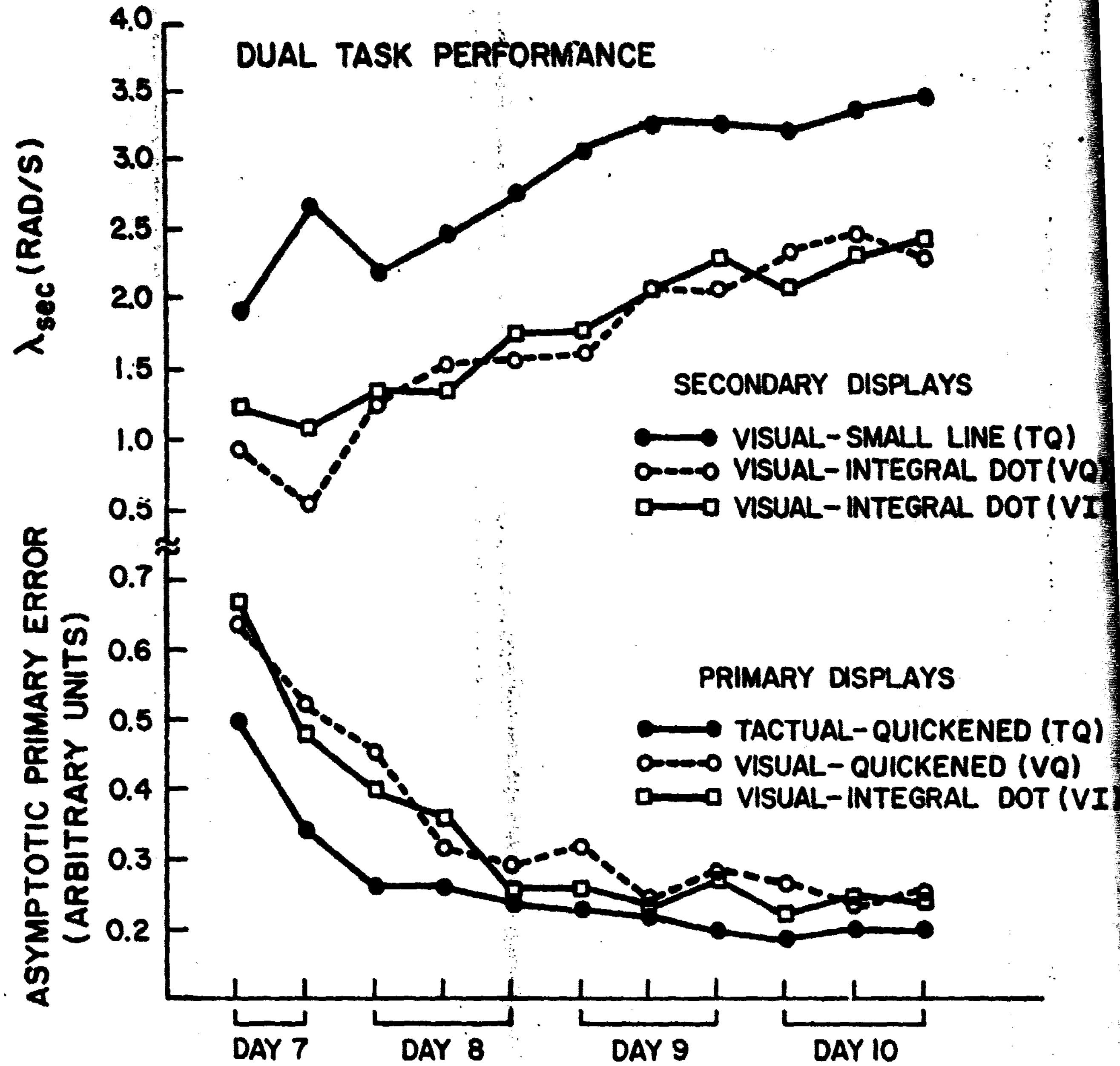

DUAL TASK PERFORMANCE
λSEC (RAD/S)
3.5
3.0
2.5
2.0
1.5
1.0
0.5
SECONDARY DISPLAYS
VISUAL- SMALL LINE (TQ)
VISUAL- SMALL LINE (VS)
VISUAL-LARGE LINE (VL)
VISUAL-INTEGRAL DOT (VI)
ASYMPTOTIC PRIMARY ERROR (ARBITRARY UNITS)
0.7
0.6
0.5
0.4
0.3
0.2
PRIMARY DISPLAYS
TACTUAL-QUICKENED (TQ)
VISUAL- SMALL LINE (VS)
VISUAL- LARGE LINE (VL)
VISUAL- INTEGRAL DOT (VI)
DAY 7
DAY 8
DAY 9
DAY 10


DUAL TASK PERFORMANCE
λ_{sec} (RAD/S)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
SECONDARY DISPLAYS
VISUAL-SMALL LINE (TQ)
VISUAL-INTEGRAL DOT (VQ)
VISUAL-INTEGRAL DOT (VI)
ASYMPTOTIC PRIMARY ERROR (ARBITRARY UNITS)
0.7
0.6
0.5
0.4
0.3
0.2
PRIMARY DISPLAYS
TACTUAL-QUICKENED (TQ)
VISUAL-QUICKENED (VQ)
VISUAL-INTEGRAL DOT (VI)
DAY 7
DAY 8
DAY 9
DAY 10

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