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EVALUATION OF KINESTHETIC-TACTUAL DISPLAYS USING A CRITICAL TRACKING TASK[1]

by

Richard J. Jagacinski, Dwight P. Miller, Richard D. Gilson,
and Robert T. Ault

Departments of Psychology and Aviation
Human Performance Center
The Ohio State University
Columbus, Ohio

ABSTRACT

The present study sought to investigate the feasibility of applying the critical tracking task paradigm to the evaluation of kinesthetic-tactual displays. Four subjects attempted to control a first-order unstable system with a continuously decreasing time constant by using either visual or tactual unidimensional displays. Display aiding was introduced in both modalities in the form of velocity quickening. Visual tracking performance was better than tactual tracking, and velocity aiding improved the critical tracking scores for visual and tactual tracking about equally. The present results suggest that the critical task methodology holds considerable promise for evaluating kinesthetic-tactual displays.

INTRODUCTION

In an effort to alleviate the high levels of visual and auditory work load typically involved in aircraft control, a number of different tactual displays have been explored for presenting information to the skin. For example, stick shakers have served for a number of years as an effective means of alerting a pilot to a potentially dangerous situation.

More recently, techniques for providing control feedback by impressing stimulation onto the skin have been investigated, including matrices of air jets (Seeley & Bliss, 1966), arrays of vibrotactile elements (Triggs, Levison, & Sanneman, 1973), and arrays of electrocutaneous stimulators (Schori, 1970). Although these techniques provide a wide flexibility for patterns or codes, a close, invariant proximity between the stimulators and the skin is required for good tracking performance.

An alternative method is to allow the natural manipulations by the fingers of embossed display features, as with braille letters. Accordingly, a feedback control technique developed by Fenton (1966) employed essentially a variable height "braille dot" to indicate tracking error. The display consisted of a servo-controlled slide embedded in a control handle (see Figure 1). The slide protrudes fore and aft from the handle corresponding to unwanted positive and negative errors. The operator follows the slide in the direction in which it protrudes until the error is nullified and the slide returns to the flush position in the control handle. In essence, the display provides continuous information relative to single-axis compensatory tracking.

Experimental investigations of this display have included numerous multitask simulator studies conducted by Fenton and Gilson since 1966 (Fenton, 1966; Fenton & Montano, 1968; Gilson & Fenton, 1974) as well as actual automobile and aircraft control investigations. The full scale vehicular control studies have validated the tactual display as both a practical and effective supplement to tasks with high visual loading, i.e., close headway car following (Fenton, 1966) and aircraft ground reference and landing maneuvers (Gilson & Fenton, 1974; Gilson, 1976).

Up to now, given that visual displays are traditionally the primary source of control information, little work has been carried out to assess the utility of the tactual display as the sole source of control feedback. However, in order to study and optimize features inherent in the display itself, a sensitive, reliable, and valid single-task tracking measure is required for systematic parametric investigations.

The present study was undertaken to test the feasibility and reliability of a methodology developed by Jex, McDonnell, and Phatak (1966) with this tactual display as the sole source of information in a progressively more difficult single-task compensatory tracking situation. In addition, the validity and sensitivity of the methodology was tested by (a) comparing performance on the same task with a single-dimensional visual display and by (b) examining the visual and tactual displays with and without aiding information. The inclusion of the visual display provided a comparison of performance on the present tracking system with the previous work of Jex and others. Aiding was used as the primary intra-modality variable because previous work (Fenton, 1966) has shown it to have a strong influence on tracking performance.

The critical tracking task developed by Jex, McDonnell, and Phatak (1966) requires a subject to stabilize a first-order unstable system. The time constant of the unstable system is made progressively shorter until the subject finally loses control. The value of the time constant at the point where control is lost is a measure of the subject's tracking ability with the given display and control device. The inverse of this critical

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value is referred to as the critical root, λ_C, which has been shown to be a sensitive measure of performance (Jex & Allen, 1970). Other properties of this measure which recommend its use in display evaluations are low run-to-run variability and a strong correlation with subject's effective time delay in tracking with fixed values of λ less than λ_C.

In addition to testing the critical task with visual and tactual displays, the present experiment also tested these displays with and without aiding in the form of velocity quickening. Fenton (1966) and Hirsch (1973) have demonstrated the usefulness of providing aiding in tactual displays when they are used to supplement unaided visual displays. However, the usefulness of aiding in tactual displays used as a sole source of information remained to be investigated. The present experiment compared the relative usefulness of aiding for visual and tactual displays in an attempt to determine differences in information processing between the visual and tactual modalities and to compare the sensitivity and validity of the critical task methodology.

METHOD

Apparatus

The kinesthetic-tactual display consisted of a rectangular section of the cylindrical control handle which moved vertically through the handle to indicate the direction and magnitude of the system error (Figure 1). The rectangular section was 2.1 x 1.9 cm and the diameter of the handle was 6.2 cm. The frequency response of the display had an amplitude ratio which was down 3 dB at a frequency of 8 Hz when tested with input signals having a peak about 20% of maximum.

The visual display depicted system error as a 2 mm diameter green dot of light moving vertically on a Tektronix Type 602 CRT display. A 2 x 10 mm marker attached horizontally at the vertical center of the oscilloscope screen extending to the right of horizontal center served as the reference for zero error.

The control stick consisted of a lever arm, 40 cm long from display to pivot point. It moved through a vertical plane orthogonal to the planes of the chair seat and back, and range of angular travel was restricted to 30 degrees above horizontal with 15 degrees above horizontal representing the neutral control position. The lever was pivoted 38 cm above the floor, 8.5 cm from the left side of the chair seat and even with the chair back. Friction was maintained at a nominal level and the display handle was counterbalanced so that no force was necessary to maintain the angular position of the lever. The chair seat was 46 cm from the floor, positioned so that the operator's eyes were 24 in (61 cm) from the center of the visual display screen.

The simulation was performed on an Electronics Associates Incorporated PACE TR-48 analog computer. Logic for integrator control, comparator control, and trial event sequencing was supplied by BRS/LVE logic modules programmed through a patchboard.

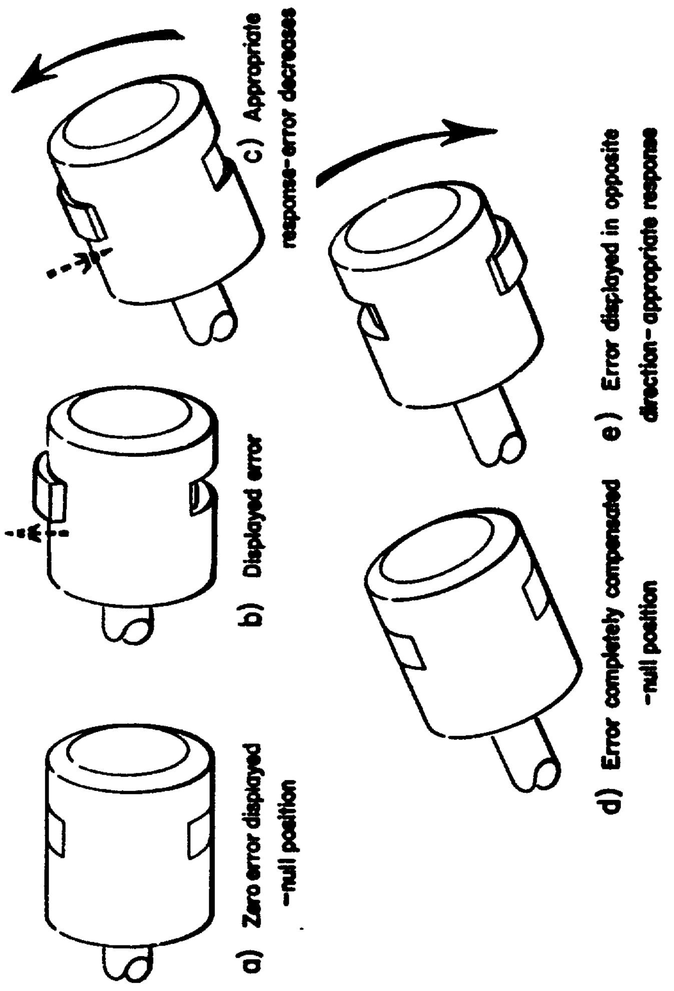

Figure 1. Control/display relationship for KT display.

A Sanborn Model 320 two channel strip chart recorder was used to monitor and record system error and control response. The subjects performed in an isolated 5 x 7 ft (2.1 x 1.5 m) room lit only by the CRT scale illuminator.

Control System Implementation

The first-order unstable system was controlled by the position of the control stick (Figure 2) which was operated in a manner similar to a helicopter collective. No forcing function was used because the operator's inherent variability or "remnant" in positioning the lever arm provided sufficient input to excite the controlled element. The system output, or error, was displayed as either a vertical displacement of a small round dot on a CRT (visual), or as a vertical displacement of a section of the control lever handle (kinesthetic-tactual). The critical task employed an autopaced instability function (Jex, McDonnell & Phatak, 1966) such that on each trial the initial instability was zero (λ_{IC}), but linearly increased rapidly over time as long as good control was maintained ($\dot{\lambda}_H$). When sufficient difficulty was encountered, the rate was reduced to .25 $\dot{\lambda}_H$ for the remainder of the trial ($\dot{\lambda}_L$). The error criterion for switching lambda rates, e_C, was specified as 10% of the maximum allowable error (e_{max}), filtered through a 1-second time constant. The two lambda rates ($\dot{\lambda}_H$ and $\dot{\lambda}_L$), which were used both in the visual and tactual display modes, were chosen so that a typical trial lasted between 30 and 75 seconds, just long enough to provide a reliable measure of critical instability. Loss of control was defined as the displayed system output going off scale (e_{max}) and the resulting dependent measure was the level of lambda attained at the trial's conclusion (λ_C). In the velocity aided conditions the aiding ratio of error velocity ($\dot{e}$) to error position (e) was 1:1. In order to make the total display ranges of aided and unaided displays comparable, the aided signal was scaled down by 50% so that the effective signal was $\frac{1}{2}(e + \dot{e})$. (See Table I for a detailed summary of system parameters.)

Subjects

Subjects were four students (two male and two female) at The Ohio State University who were randomly selected from the eight highest scoring subjects of 16 on a visual critical tracking pretest. The 16 subjects were paid $2.50 for the pretest. The four selected subjects were paid $2.50 per session for the first four subsequent sessions; the subject with the highest average score also received a $5.00 bonus. On the last four sessions, subjects were paid a base rate of $1.00 plus 1.67¢ x λ_C for each trial.

Procedure

Pretest: Sixteen subjects received 25 trials on a visual critical tracking task. Subjects heard 72 dBA white noise through a set of monaural headphones except when spoken to by the experimenter over an intercom. Before the first trial subjects centered the control stick with verbal feedback from the experimenter and were instructed to center it before each subsequent trial. There was no feedback after the beginning of the first trial. Each trial was preceeded by a ¼ second 400 Hz warning tone, a 3-second interval, and a ½-second start tone. At the start tone, a green

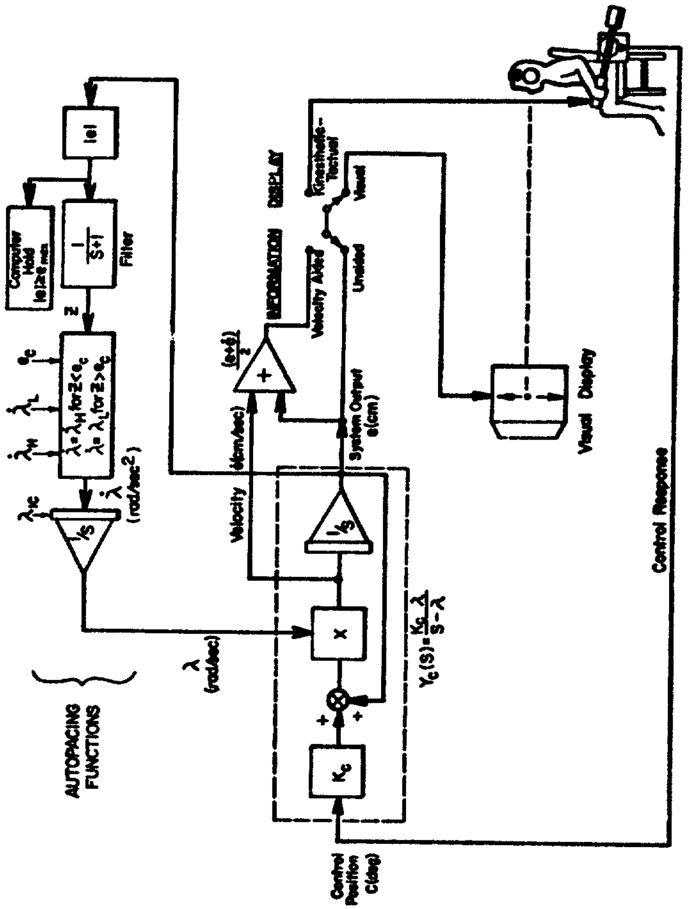

Figure 2. Control system implementation for visual and tactual critical tracking task.

Control System and Display Parameters	Units	Pretest	T	TA	V	VA
K_c - control-display sensitivity	cm/deg	4	04	.04	2	2
e_{max} - maximum allowable error	cm	±40	±4	±4	±2.0	±20
corresponding total degrees visual angle	degrees	75	NA	NA	3.75	375

Autopacing Parameters	Units	Pretest	T	TA	V	VA
λ_{IC} - initial value of unstable root	rad/sec	0	0	0	0	0
$\dot{\lambda}_H$ - initial (high) $\dot{\lambda}$ rate	rad/sec^2	2	15	15	15	15
$\dot{\lambda}_L$ - final (low) $\dot{\lambda}$ rate	rad/sec^2	05	0375	0375	0375	0375
e_c - error criterion for switching $\dot{\lambda}$	cm	4	04	04	.2	2
T_f - error criterion time constant	sec	10	1.0	10	10	10

Control Stick Parameters	Units	All Conditions
maximum deflection	degrees	±15 0
nominal required force	N	20

Tab' 1. Control systems parameters.

dot appeared at the center of the CRT display, moving vertically. Subjects were instructed to move the control stick opposite to the direction of the displayed error in order to keep the dot centered. When the displayed error reached ± 4.0 cm there was a 2-second tone which indicated the end of the trial and the dot disappeared from the screen. There was a 10-second interval between trials. The median value of λ_c for the last seven trials was used to select the top eight subjects.

Test: Four subjects were randomly selected from the top eight subjects and were each tested in the following display conditions on each day of the experiment:

1. visual unaided (V) - error displacement on CRT;
2. visual aided (VA) - error displacement + error velocity on CRT;
3. kinesthetic-tactual unaided (T) - error displacement in control handle;
4. kinesthetic-tactual aided (TA) - error displacement + error velocity in control handle.

Subjects received a block of 15 trials in each condition on each day with a 2-minute rest between blocks (60 trials per day). The four conditions were presented to the four subjects in a Latin square design with a different Latin square selected each day of the 8 days.

Subjects were instructed to move the control stick in the same direction as the displayed error (Figure 1) in the two tactual conditions. The direction of the displayed error was selected to be compatible with the direction of appropriate control response. The visual display was inoperative during all tactual display conditions. Subjects centered the control stick with verbal feedback and were told which condition they would be receiving before each block of trials. The beginning and end of each trial was signalled with the same tone sequence used in the pretest. Subjects were given no further feedback for the first 4 days. During the last 4 days, subjects were verbally informed of the value of λ_c they had just achieved during the intertrial interval.

RESULTS

Medians of 15-trial blocks were averaged across subjects and plotted over days for each of the four conditions in Figure 3. At no point during the 8 days did the ordinal relationship of display conditions change. The best tracking performance was attained in the VA condition, followed in order by conditions V, TA and T.

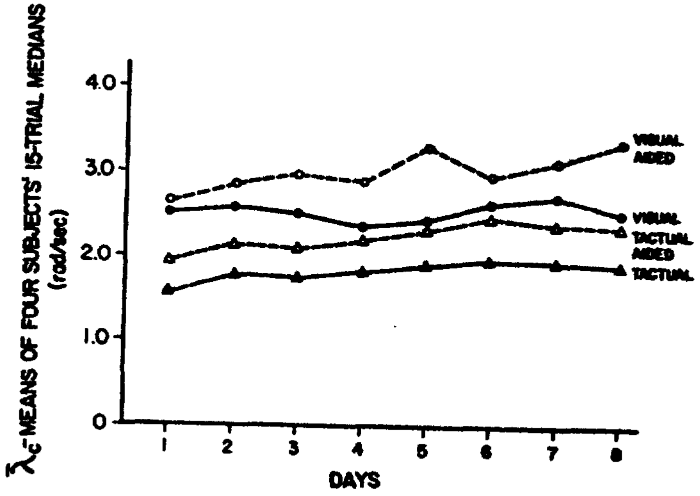

Figure 3. Average performance of four subjects over eight days of tracking.

A four-way (modality x aiding x subjects x days) analysis of variance for the last four days' performance yielded highly significant main effects for both modality, F(1,3)=39.2, $p < .01$ and velocity aiding, F(1,3)=44.9, $p < .01$. The visual modality was found to be superior to the tactual modality, and velocity aiding improved performance in both modalities. No interaction was found between modality and aiding, nor for any other factor combinations ($p > .65$). The additive nature of modality and aiding effects is displayed in Figure 4 which shows the mean and standard deviation for each condition averaged across subjects and days. The main effect of days was found to be non-significant ($p > .97$), indicating stable performance over the four days analyzed. Four two-way analyses of variance (subjects x days) were performed to recover variance estimates for each of the four conditions. The VA condition had a higher standard deviation (SD=.696 rad/sec) than the other conditions which ranged from .202 to .291 rad/sec.

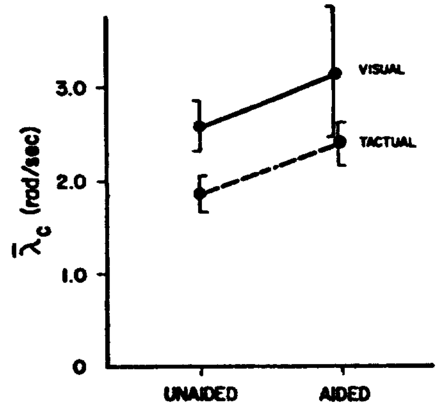

Figure 4. Means and standard deviations of λ_c in four conditions.

Sample time traces of two subjects' tracking behavior have been included to demonstrate qualitative aspects of their control responses (Figures 5 and 6). Each of the samples displays system output, e, (top) and control response, c, (bottom) as a function of time. The range of payments to subjects on Days 5 - 8 was from \$3.07 to \$3.78 per day.

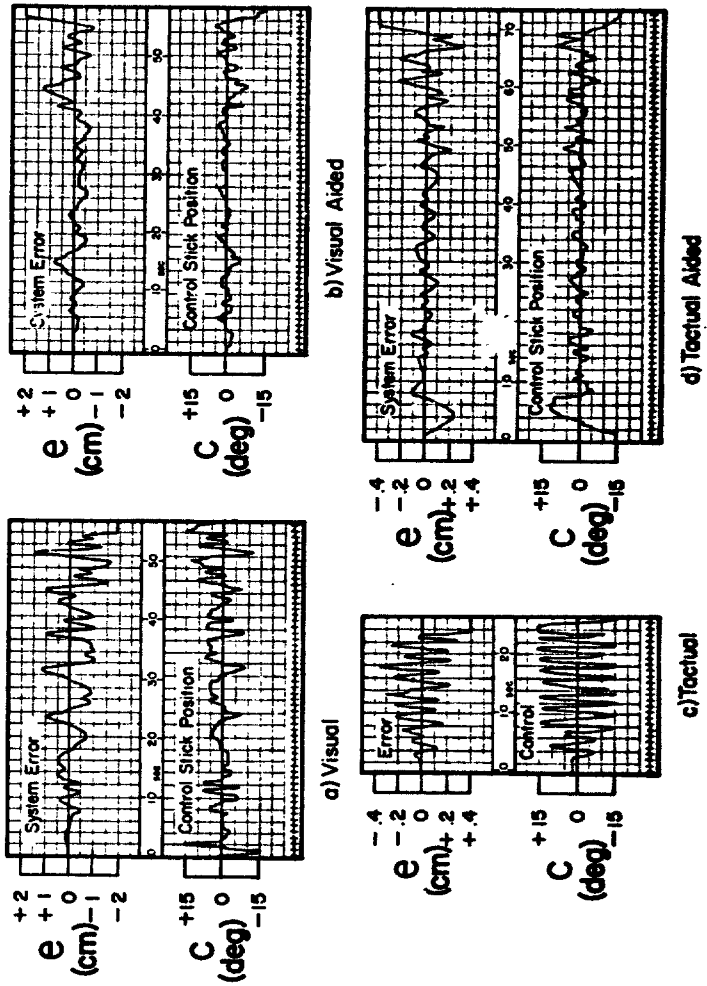

Figure 5. Time history of sample trials in each of four conditions: Subject 1, Day 8.

In questionnaires and interviews after the final sessions, two subjects indicated that using a loose grip was important in tactual tracking, while the others stressed anticipation of display movement. Three subjects thought the tactual S-R compatibility was optimal, while one would have liked the reverse relationship.

DISCUSSION

The results indicate that the critical task is both a feasible and reliable methodology for assessing tactual tracking with the above described tactual display. The feasibility is apparent in the fact that subjects performed this task with no particular difficulties despite the fact that the tactual display was novel and no pretraining trials were employed. Reliability of the methodology for tactual tracking is evident in: the smoothness of the plot of performance as a function of days in the experiment (Figure 3); the consistent ordinal relationship between testing conditions; and the relatively small standard deviation associated with the mean performance scores with the tactual display as compared to the visual display (Figure 4). Additionally, the lack of any significant effects of days in the analysis of variance carried out on the performance scores for Days 5 - 8 indicates that subjects had achieved asymptotic performance levels in all four display conditions tested.

That the critical tracking methodology is both as sensitive and valid a measure of tactual tracking as visual tracking is indicated by the approximately equal effects of aiding for the tactual and visual displays. This can be seen in Figure 4 and is indicated by the lack of a modality x aiding interaction in the analysis of variance. Given the considerable data base that has established the critical task as a useful measure for evaluating visual displays, the present results suggest that the same methodology is not only feasible, but a technique that holds considerable promise for evaluating tactual displays.

Although performance for the visual and tactual display conditions is surprisingly close, a direct comparison should be avoided for a number of reasons. First, neither the visual nor tactual displays used in the present study were intentionally optimized for display features. Second, although the subjects appear to have reached asymptotic levels of performance under the conditions of this experiment, a between-subjects design might yield different performance levels.[2] Finally, a direct comparison between tactual and visual values of λ_C should be avoided because of qualitative differences in control behaviors with the two displays.

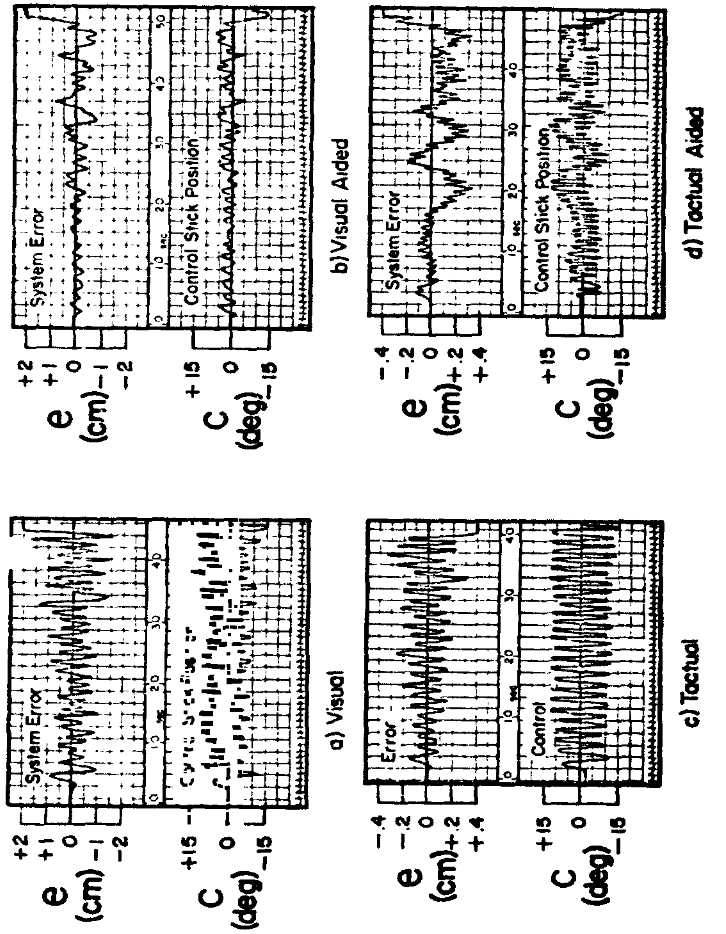

Figure 6. Time history of sample trials in each of four conditions: Subject 4, Day 8.

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[2] A pilot experiment was carried out in addition to the main experiment wherein two additional subjects were run and achieved much higher asymptotes (λ_C= 4.4) under the tactual-aided display condition only. Thus, the lower asymptotes for the subjects in the present experiment may have been the result of interference between conditions. However, these results must be treated as pilot data for the present.

For an interpretation of the experimental effects of display quickening with visual and tactual displays, it is necessary to discuss the theoretical significance of the critical value of lambda. As determined by Jex and Allen (1970), for first, second, and third order critical tracking tasks, the inverse of the human operator's effective time delay is linearly related to the critical value of lambda. The regression equation they obtained for four practiced pilots was $\tau_e^{-1} = 1.1 + 1.2\ \lambda_C$. For the first order critical task, subjects' behavior approximated simply a gain plus time delay. For the second order tasks, subjects additionally adopted lead equalization to cancel out the lag introduced by the integration. Accordingly, with an aided visual display and a first order critical task, one would expect the human operator to introduce lag equalization to cancel out the introduction of lead.

Moreover, compensatory tracking with K and K/s plants, respectively, parallel the equalization postulated for the aided and unaided visual displays with the first-order critical task. Given that McRuer, Graham, Krendel, and Reisener (1968) observed a time delay that was .03 sec shorter for the K plant, one would similarly expect the aided display also to exhibit a shorter time delay in the first-order critical tracking experiment. In fact, if one uses the Jex and Allen regression equation to translate the critical roots obtained in the present experiment into effective time delays, the values obtained for the aided and unaided visual displays are .203 sec and .238 sec, respectively. The aided display does exhibit a time delay that is shorter by .035 sec. The closeness of this value to the .03-sec difference observed by McRuer et al. (1968) for K and K/s tracking may be fortuitous considering various differences in control devices and subject populations; however, the direction of the difference is consistent with the postulated equalization. This analysis of course assumes proportional control strategies which were in fact exhibited in the visual display conditions as exemplified in Figures 5 and 6.

Although aiding increased the critical value of lambda about equally for the visual and tactual tracking conditions, there was a strong qualitative difference in the style of tracking performance. Namely, for the unaided tactual condition, subjects' behavior more closely resembled bang-bang rather than proportional control (Figure 5). Subject 4 (Figure 6) also followed this pattern, but differed from the other three subjects in that he additionally superimposed a small amplitude, rapid oscillation or "dither" over a smoother, slower control pattern evident in the tactual aided condition. This behavior may represent an attempt to overcome deadband or other nonlinear effects associated with the tactual display. It is noted, however, that the degree of control amplitude modulation in the visual condition was relatively minimal for this subject.

Subjects typically go to non-linear behavior when they have difficulty producing the equalization necessary for stable linear control (e.g., see Hall, 1963). In the present task, this generalization suggests that subjects were unable to adopt the necessary gain plus time delay configuration for proportional control with the tactual unaided display, although they were apparently able to adopt lag equalization for the aided tactual display for which proportional control was generally exhibited.

These results suggest that in using the tactual display, subjects may always exhibit a lag if they are using proportional control. A lag would be appropriate for proportional control of the aided, but not the unaided display. If there is an unwanted lag in the tactual unaided tracking, it is important to demonstrate that the lag is not associated with the electromechanical construction of the tactual display. By implication the lag can then be attributed to the human subject's use of the information from the display. A Fourier analysis of the tactual tracking is presently underway to test this hypothesis.

A second point of interest with regard to the tactual tracking data is that theoretically, a linear relationship can exist between λ_C and a parameter analogous to effective time delay when the subjects exhibit a bang-bang control pattern. If the subject's control can be approximated as a regular alternation between two control values with the time between switches equal to T_e, then a phase-plane analysis reveals that the critical value of lambda will be proportional to T_e^{-1}. The proportionality constant will depend on the control value (movement amplitude x system gain) and the error criterion used to terminate the critical task trials. Jex, McDonnell, and Phatak (1966) derived a similar prediction assuming a linear control strategy in which the subject approximated a gain and time delay, τ_e. For the linear control strategy the proportionality constant between λ_C and τ_e^{-1} was unity, rather than a function of control amplitude and the error criterion.

In summary, the present results suggest that the critical task methodology will be an effective tool for evaluating tactual displays. Furthermore, the qualitative differences found between tactual and visual tracking may lead to a better understanding of the information-processing differences between these modalities.

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