Spring 1996

Evaluation of a Display with Both Quickened and Status Information for Control of a Second Order System

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EVALUATION OF A DISPLAY WITH
BOTH QUICKENED AND STATUS INFORMATION
FOR CONTROL OF A SECOND ORDER SYSTEM

by

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A Thesis Submitted to the
Aeronautical Science Department
in Partial Fulfillment of the Requirements for the Degree of
Master of Aeronautical Science

Embry-Riddle Aeronautical University
Daytona Beach, Florida
Spring 1996

AN EVALUATION OF THE EFFECTIVENESS OF A DISPLAY
WITH BOTH QUICKENED AND STATUS INFORMATION
FOR CONTROL OF A SLUGGISH SYSTEM

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This thesis was prepared under the direction of the candidate's thesis committee chairman, Dr. John A. Wise, and has been approved by the members of his thesis committee. It was submitted to the Department of Aeronautical Science and was accepted in partial fulfillment of the requirements for the degree of Master of Aeronautical Science

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ACKNOWLEDGMENTS

The author wishes to thank the thesis chairman, John A. Wise for his critical feedback and assistance during the course of this study. Significant thanks are owed to John Deaton for his long hours spent contributing to the authors understanding of experimental design and statistical analysis of data. Many thanks are given to Daniel J. Garland for his critical assessment of the final study.

I would like to thank the Engineering and Physical Sciences Research Council, and the Fulbright Commission, both institutions from the United Kingdom, for their support during my studies and thesis work.

I would also like to extend my appreciation to the pilots from ERAU, whose abilities and enthusiasm made this study possible.

ABSTRACT

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Title: Evaluation of a Display with Both Quickened and Status For Control of a Second Order System

Institution: Embry-Riddle Aeronautical University

Degree: Master of Aeronautical Science

Year: 1996

Quickened displays have a severe limitation in that they do not give any indication of status information, and therefore no indication of actual error. It was hypothesized in this study that a display with both quickened and status information would enable the operator to make more effective control responses than either a status alone display, or a quickened alone display.

A horizontal axis pursuit tracking task was developed and controlled by eighteen participants with three display types: (1) a status alone display; (2) a quickened alone display; and (3) a status and quickened combined display.

The primary hypothesis was only partly accepted. The results indicated that after two minutes tracking time the combined and quickened displays give the best performance, with worse performance from the status display. After ten minutes tracking time the combined display was the best, followed by the status display and the quickened display.

The study concluded that the use of a combined display did yield superior performance for the tracking task devised. The effectiveness of the combined display relative to the quickened display or the status display was, however, a function of practice time.

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Introduction

An important dichotomy in the display of information relevant to flight control can be drawn between status displays, which tell the pilot the current state of the aircraft, and command displays, which tell the pilot how he or she should control the aircraft. In the cockpit, status displays are those which occupy the traditional instrument panel that provide status information relating to the altitude, velocity, rate of climb, heading, and so on. One drawback of the status display is that extra cognitive computations are often required to translate a knowledge of the current state of the aircraft into a decision as to what control action should be made to change that state according to the desired flight path (Stokes & Wickens, 1988). The objective of the command display is to make these predictive calculations directly and thus provide the pilot with information stating exactly what control actions are required.

Command displays become more important as aircraft size increases. The high inertia of modern large bodied transport aircraft means that a control input delivered at one time will not effectively alter the flight path until a few seconds later. Effective control must be achieved by responding to the predicted error rather than to the current error. An optimum source of error prediction is the rate of change and acceleration of the current error. However, acceleration in particular is not a variable that the human eye is well equipped to perceive, nor one that the brain can easily compute (Sekuler & Blake, 1994). There are two techniques, prediction and quickening, that have been developed as command displays to help overcome these perceptual and cognitive limitations.

The predictor display assists the pilot in the anticipation task by showing information about the predicted future of the variable under control. It does this by extrapolating present conditions into the future on an accelerated time scale, or through a real time computation for some fixed time into the future. The predictor display can show where the vehicle will be at a certain time in the future.

The quickened display is another method of prediction, but has fundamental differences from the true predictor display. Instead of predicting position for a certain time into the future, the quickened display simply gives a presentation of the velocity or acceleration of the vehicle. In providing information about velocity or acceleration, the control system order is effectively reduced, and the quickened display is easier to control.

To illustrate the advantage of using a quickened display, consider the manual control of a second order system. A second order system is one in which the operator's input is integrated twice to give the system output. Put in simple terms, this means that if the operator moves the control stick, the system will start moving, and it will continue moving until another control input is made in the opposite direction to cancel that movement. The rolling motion of an aircraft can be represented as a second order control system, since a control stick deflection will start the aircraft rolling, and it will continue to roll until the stick is returned to its central, neutral position. In order to return the aircraft to its wings level attitude, two further stick movements will have to be made, one to start the aircraft rolling, and one to stop it rolling once the wings are level again. This illustrates the dynamics of a second order control system.

A quickened display works by giving a presentation of the system velocity and/or acceleration. Again, returning to the aircraft example above, if the aircraft is made to roll with a stick input, the quickened information would describe how quickly the aircraft is rolling (velocity) or how fast it is accelerating in roll (acceleration). Providing the pilot with information about how quickly the aircraft is rolling should make it easier to arrive at the desired bank angle. Without the quickened information the pilot must predict, based upon bank angle alone, when to stop the rolling motion. In practice, the pilot predicts by noting the rate of change of bank angle, which is exactly the information a quickened display provides.

In providing information about higher derivatives (e.g., the roll velocity or acceleration), the order of the system is decreased because the velocity information only requires one time integration of the operator's input, and so the second order system effectively becomes a first order system. The lower the order of control, the more system performance will be enhanced (Knight, 1987). Reducing the effective order of control reduces both the subjective workload and the number of control movements that the operator must make.

Instead of displaying status information (angle of bank), the quickened display gives rate of change of status information (roll velocity), or acceleration of status information (roll acceleration). Put simply, in order to anticipate a desired roll angle, the pilot will need to obtain information about how quickly the aircraft is rolling, and use this to estimate when to commence control action and stop the aircraft roll. The quickened display provides a direct indication of roll rate, or roll acceleration, and so gives the pilot a better cue for anticipation.

The quickened display is preferred for head-up-display implementation because it only requires one symbol to be displayed (the quickened symbol replaces the status symbol), and so minimizes clutter in what is a very restricted display space (Huff & Kessler, 1990). More complex systems, such as ship heading control, may benefit greatly from quickened displays.

The greatest disadvantage of a quickened display, however, is that the operator may think it is the same as a status display, since the display still responds to control actions, just as status displays do.

The pilot of an aircraft may face a situation where a sudden control action is necessary to avoid an obstacle, such as the top of a mountain or another aircraft. If a quickened display is being used, the pilot may think for an instant that sufficient control action has been taken as the quickened display marker moves to the desired position. However, the quickened display marker may have reached the desired position well before the output of the control system does, especially if a large lag component is present in the system, such as found in large aircraft characteristics.

The quickened display does not leave the pilot with a true indication of the exact current status of the system, so a possible improvement may be to include status information along with quickened information in the same display. The operator could then use both sources of information to effectively control the system, and at the same time be constantly aware of system status.

Statement of the Problem

The purpose of this study is to determine the effectiveness of a display with both quickened and status information available to the operator, for control of a continuous manual control task.

Review of the Related Literature

The human ability to predict motion.

It is commonplace in engineering literature to state that control systems function to reduce the difference between their input and output, or the difference between the desired and actual values of the controlled variable. This is not true of the human control process nor of human operated control systems. Because of the operators ability to think, to extrapolate forward in time, the manual control process is oriented around the future (Kelley, 1968). This can be stated as a basic characteristic of manual control. Manual control systems function to reduce the difference between what an operator wants to happen to a controlled variable and what he or she thinks is going to happen unless a change is instituted.

What the operator wants to happen reflects the operator's planning of the desired future state. What the operator thinks is going to happen represents the prediction process, the extrapolation into the future of the state of the controlled variable in the operator's dynamic internal model of the environment.

Prediction thus plays a key role in the process of manual control. The freedom of conscious processes from present time, the ability to envision the future, forms a major part of manual control skill. Since the operator controls a complex system by reducing the discrepancy between what is desired of the system output, and what is predicted if no change is instituted, the ability to predict is crucial to success.

Predictions of more than one kind play a role in manual control. Control action taken by the human operator is shaped by the difference between the desired state of the controlled variable and that predicted if no control action is taken. Also involved is a prediction of what will happen if a particular action is taken. Control thus employs not only a prediction of the result of no control, but the results of various possible control actions. The operator plans or programs an action or sequence of actions in control, based on a prediction of what the result of the action or sequence will be.

The selection by the operator of the desired value of the controlled variable, the operator's plan, is limited by the prediction process. The operator plans the future system output by selecting, from the possibilities that are perceived, that which is considered more desirable. In continuous control, what is possible is often bounded by what would happen if the operator moved a control to either extreme of a range of operation. The operator then selects the desired output or plans the course within what is believed to be the possible range.

The primary difference between the experienced operator of a complex control system and the novice is in the ability to predict. When a novice is given displays that enable an accurate prediction of system output, he or she performs like a skilled operator, without the need for training (Kelley, 1968). The principal reason for the long learning time required to train aircraft pilots, helmsmen, and other operators of complex control systems is the time it takes to learn to predict system performance under various conditions. The ability to predict system performance is, in major respects, the same as the ability to control the system.

If displays were available that could predict or assist in the prediction of future output state, then the human processing resources necessary to predict future state would not be required. It is no wonder then, that predictive information, if displayed appropriately, can be very effective in manual control systems. There are two types of displays that can be used as command instruments, predictive displays and quickened displays.

Predictive displays.

The predictive display offers the pilot one or more symbols depicting the future state of the aircraft, inferred from certain assumptions concerning the current state of the aircraft, and the pilots future control activity (Gallagher, Hunt, & Williges, 1977).

The predictor instrument provides the operator of a manual control system with a display showing information about the predicted future of the variable under control. It does this by means of a computer algorithm which extrapolates present conditions into the future. The predictive information is generated by an analog model of the system to be controlled, operating on an accelerated time scale. The model receives signals from sensing instruments responsive to existing conditions in the real system. These signals form the initial conditions with which the computer begins each cycle of accelerated time.

The computer continuously updates the prediction given new information as the system progresses in time.

Figure 1 is a block diagram of a predictor instrument as it may be employed in a manual control loop. The controlled element could be an aircraft, ship, nuclear reactor, or any complex control system that requires manual control. Sensing instruments provide the initial conditions for calculation of future position. Calculation is accomplished by computer, based on a fast time model of the controlled element. The predictive signal from the computer is used to generate and display the future state of the system. Within the diagram of Figure 1, note the 'programmer' block. The programmer is a simple device that represents the assumed control action of the operator during the prediction period. The future embraces a range of possible values of the variable controlled, and these are primarily dependent on the control action of the operator, so one control action must be selected and programmed. The most common assumption is that the operator will return the control to a null position, through some appropriate lag, or after some delay.

Another means of generating a true predictive display is the point prediction technique, which generates a prediction for some fixed period in the future with a real time computation (Dunlap and Associates, 1960). It is very similar to the fast time prediction technique, except that positions are predicted continuously in real time, rather than cyclically in fast time, and results in a display of discrete predicted points rather than of a continuous path. Point predictions are simpler to calculate, but are less convenient when complex equations are involved.

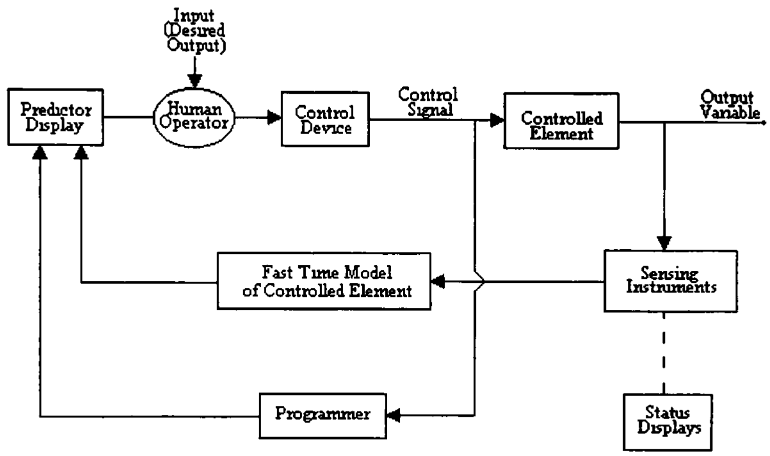


Figure 1. Block Diagram of a Predictor Display in a Manual Control Loop.

Quickened displays.

The quickened display is fundamentally different to the predictor display in that it does not predict the future status of the variable under control, but instead gives an immediate presentation of the anticipated results of the controllers actions (Jensen, 1981). It does this by simply providing a direct presentation of the current velocity or acceleration of the system. This technique is accomplished by adding the higher derivatives of the error (velocity and acceleration) directly on to the current error position with some relative weighting.

Using the quickened display, the pilot tracks or nullifies an error symbol that moves ahead of the actual state of the variable. From the pilots point of view, a system of lower order (fewer time integrations) is being tracked.

As system order is increased above first order, both error and subjective workload increase dramatically. Control systems of second order and higher are unequivocally worse than either zero or first order systems (Kelley, 1968). So, the purpose of display quickening is to reduce the effective control order, and so decrease subjective workload and error.

The reason for the decrement in performance for higher order systems is that to control any higher order system effectively, it is vital to anticipate its future state from its present state. This means that the operator must be able to perceive higher error derivatives, a process known as generating lead. Human operators do not perform this function well (Wickens, 1992). Also, when controlling higher order systems, the operators pure time delay, or reaction time, is longer, which contributes an additional penalty to performance (McRuer & Jex, 1967).

Quickened displays add low order of control components to the display of the controlled system movements. The apparent responsiveness of the operators control movements improves, and stimulus - response compatibility is enhanced with a quickened display (Knight, 1987). Stimulus - response compatibility refers to the 'directness' of the relationship between the operators control movement and the effect on the system as seen by the operator. It is beneficial to have high stimulus - response compatibility because it reduces the need for complex information transformations by the operator.

The quickened display looks exactly the same as a status display in that only one symbol (or cursor) is shown. Unlike a status display however, the quickened symbol does not directly display the system status, and so does not indicate the true system error. Instead it displays the quickened error, or the true error with higher derivatives of the system status (velocity, acceleration) added on.

Figure 2 is a block diagram of a quickened display as it may be employed in a manual control loop. Sensing instruments determine the actual status of the output variable. The status variable information is then differentiated to provide a quickened display of information.

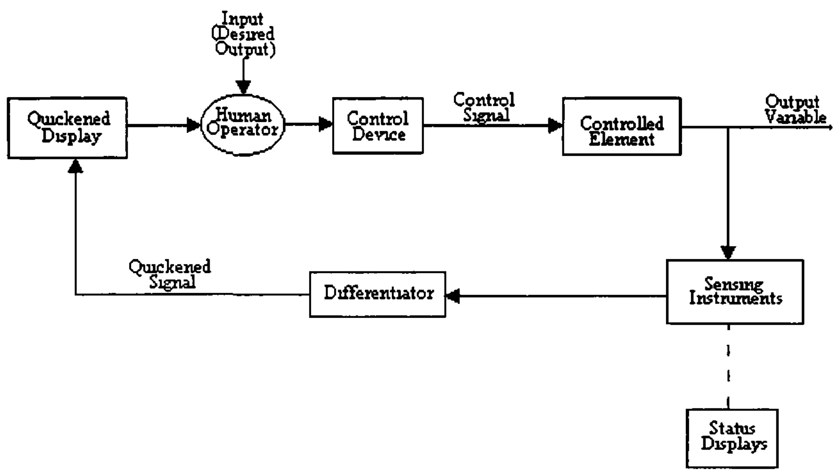


Figure 2. Block Diagram of a Quickened Display in a Manual Control Loop.

Weinstein, Ercoline, McKenzie, Foster Bitton, and Gillingham (1993) demonstrated the use of a quickened climb / dive marker for a head up display. The use of a quickened marker does not add another symbol to the display, and so it helps to avoid clutter on the HUD and is preferable to the predictor display.

The principle of display quickening forms the basis of the flight director display, where various higher order derivative terms, such as glideslope deviation and vertical velocity, are combined to produce a command target signal for the pilot to match (Weir, Klein, & McRuer, 1971). It is important to realize that the command does not represent the true zero error flight path, but instead represents a signal which, if used as the basis for control, will provide guidance along the desired flight path. Quickening reduces the order of tracking control, and so results in a reduction of display error. However, it does not necessarily reduce system error.

The greatest disadvantage of a quickened display is that the operator may think it is the same as a status display (Bernotat & Widlock, 1966). This can happen because the quickened display gives the correct status information whenever it is at rest. It is only when the quickened display is moving that it is misleading. Yet the display still responds to the operators control actions, just as status displays do. It is easy to think that a quickened display is a status display.

The quickened display does not leave the pilot with a true indication of the exact state of the system, so a possible improvement may be to provide status information along with the quickened information. The principle criticism of command (quickened) displays is that they focus the operators attention on the innermost loop of the control process, control position, when they should be thinking in terms of system output and other longer range outer loop processes (Elkind, 1956). The advantages of displaying both the actual situation and a predicted situation to a human operator in a control loop have already been proven (Jensen, 1981; Roscoe, Corl, & Jensen, 1981). With both status and quickened information available, the operator will have status information to be able to plan and to predict based on the actual system status, and the quickened information to realize a precomputed response.

The feedback control loop.

A study of interest to any research involving manual control is by Jagacinski (1977). In his review of feedback control theory, the author explains the concepts of open loop, closed loop, sluggish and oscillatory behavior, and negative and positive feedback. Feedback control theory is a well established engineering field, and very useful for investigating the role of feedback in guiding dynamic manual control. Since the principle of predictive and quickened displays is to modify the feedback available to the operator, it will be used as a tool in this study.

The elements of a simple status display that could be used for a tracking task in the vertical axis are shown in Figure 3. The target symbol moves in a random fashion, and it is the task of the operator to track the target symbol by moving the status symbol. The status symbol is moved by manipulating some kind of control, such as a joystick.

The control engineering block diagram for this tracking task is shown in Figure 4. It is worth outlining the fundamentals of this block diagram, since it is a useful notation to use in investigation of any feedback control system.

The diagram starts on the far left hand side with the disturbance signal input, θ_d. This input represents the target position at any given time, and so describes the random

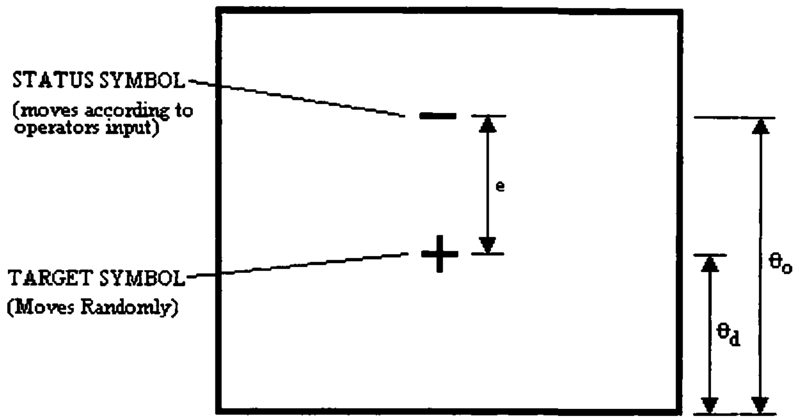


Figure 3. Pursuit Tracking Display with Status Information.

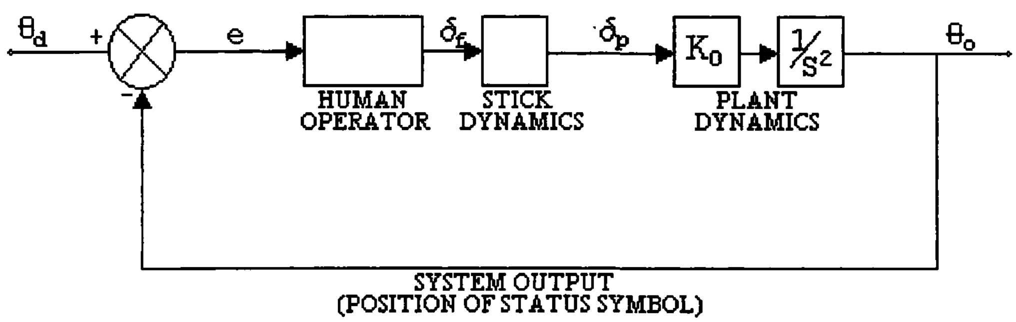


Figure 4. Block Diagram of a Control Loop with Status Feedback.

movement of the target. It is the aim of the operator to track this input target signal as closely as possible with the status symbol. At the far right of the diagram is the system output, θ_o, which describes the position of the status symbol at any given time. The status symbol is moved by the operator, through movement of a control stick, and the difference between the position of the status symbol and the target at any given time is the error, e.

The system output, or position of the status symbol, is the signal that is used as feedback by the operator to minimize the error. In the block diagram, this feedback channel runs from the system output back to the system input, where it is subtracted from the input signal to form the error signal. The error signal is the difference between the system input and the system output, and the operator acts on the error to control the system. Put simply, the operator looks at the difference between the system output and the target position to determine what control actions are needed to minimize the error.

The input to the left hand side of the human operator block is the control error, e. The human operator responds to this control error signal with movement of the hand to exert a force on the control stick, and give the output signal δ_f. This force is translated into an electrical signal, δ_p, through the next block, the stick dynamics. The stick dynamic response is the relationship between input force and the electrical signal it produces when that force is applied.

The electrical signal now passes through the plant dynamics. The plant dynamic behavior describes the relationship between stick input signal and system output. The plant dynamics shown are second order, which is evident from the notation K_o/s^2. The power of the 's' term in the denominator of this function (called the plant transfer function) indicates the order of the plant dynamics. A second order system requires one control input to start it moving, and another, opposite input to stop it, and usually requires constant control responses from the operator. It is not an easy system to control.

The feedback variable in Figure 4 is position of the status symbol. This is referred to as the status feedback signal, and a display that shows position of the status symbol is a status display. The difference in position between the status symbol and the target is the true error in a status display.

Figure 5 now introduces the quickened display, and the elements of the display that the operator will view. Note that, to the operator, this display looks identical to the status display in Figure 3 because only one symbol is shown. The difference, however, is that this symbol no longer represents the status position and true error. Instead it shows the quickened position and the quickened error, e'. This means that the operator no longer has available any true indication of system error, since a status symbol is not present. This highlights the disadvantage of a quickened display upon which this study is based.

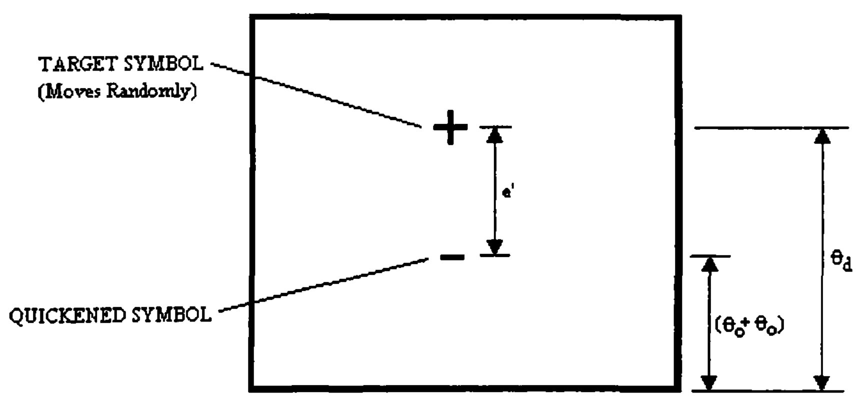


Figure 5. Pursuit tracking display with quickened information.

The engineering block diagram of the quickened display is shown in Figure 6. Note that everything is the same as for the status display, except that the feedback variables have changed. The feedback variable is now $\theta_o + K_q\dot{\theta}_o$, or the system output position plus the system output velocity (with some gain, K_q). The plant dynamics have been divided up from K/s^2 to a single K term, and two 1/s terms, but the overall system transfer function is still K/s^2. The K term is a gain, and each 1/s term is an integration of the signal. Therefore, by picking off the system output before the last stage integrator, output velocity is the obtained signal.

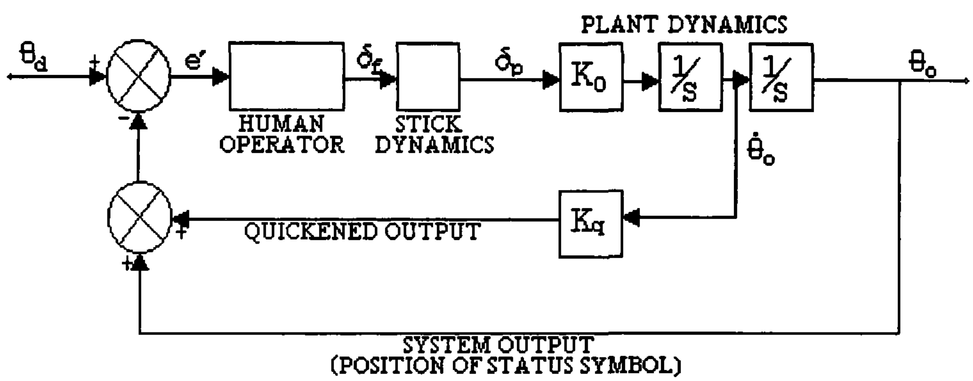


Figure 6. Block Diagram of a Control Loop with Quickened Feedback.

The difference between the quickened symbol and the target symbol no longer equates to true error, since the quickened symbol no longer displays true status position. The quickened symbol now displays the status position with an indication of the status velocity added on. However, because the system is being controlled with reference to the derivative of the output position, a system of lower order is effectively being controlled, and should therefore be easier to control (Ziegler, 1968).

Figure 7 is the third display type, the combined display that presents both status and quickened information. Two symbols are now available to the operator, the status symbol which is exactly the same as the status symbol in Figure 3, and the quickened symbol of Figure 5. In combining both types of information in one display, it is suggested that the disadvantage of a purely quickened display may be overcome.

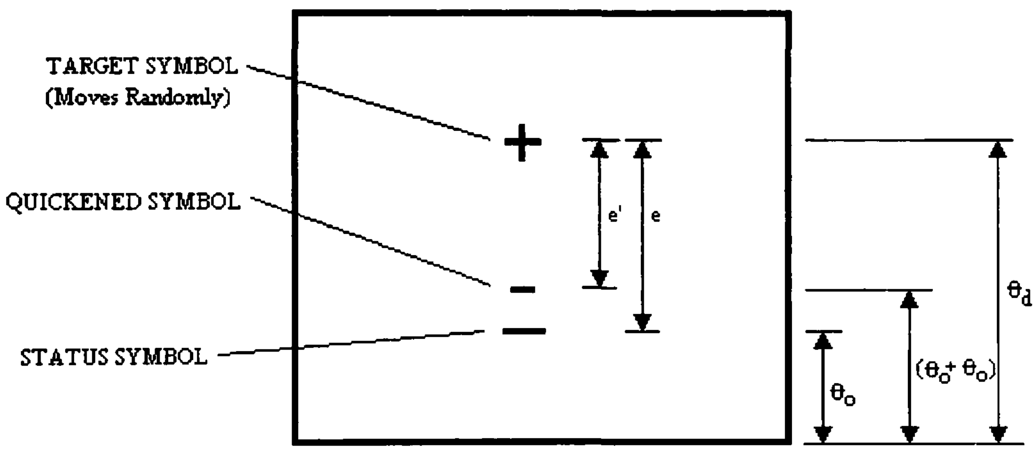


Figure 7. Pursuit Tracking Display with Status and Quickened Information.

Figure 8 is the block diagram that represents the system with status and quickened information as feedback. It is a combination of both the status alone system and the quickened alone system. The principles are exactly the same as the two separate displays above, except that the operator now has two error signals to act on, the status error signal, e, and the quickened error signal, e'.

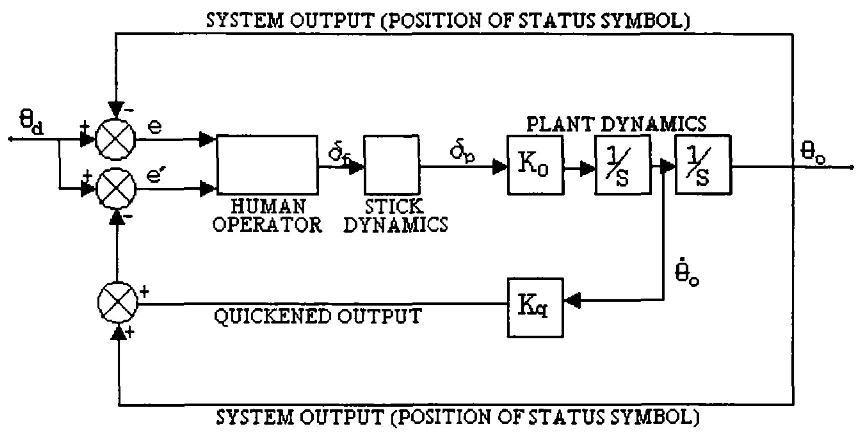


Figure 8. Block Diagram for a Control Loop with Status and Quickened Information.

Of particular interest to the human factors engineer are the mathematical models that have been developed to describe human behavior in tracking tasks, such as McRuer's crossover model (McRuer & Krendel, 1957). By describing the human operator in terms of a mathematical model, the dynamic behavior of the human can be investigated just like any other mechanical or electrical device. The applications of such pilot modeling are, as you may expect, extremely limited, although attempts have been made to develop very complex models. Garg (1988) used a mathematical model, the Optimal Control Model, to try and correlate actual human performance with model predictions in a task involving quickened displays. Though not perfect, the agreement between experimental and analytical results was very good.

Previous studies.

Garg and Schmidt (1988) completed a simulation study of the effects of control and display augmentation on human performance in a closed loop continuous tracking task. Three pilot participants were used to control eight different systems with differing amounts of display and control augmentation. The plant dynamic transfer function was K/s^2, which is difficult to control in that it requires the human to generate a significant amount of lead. The system block diagram is shown in Figure 9.

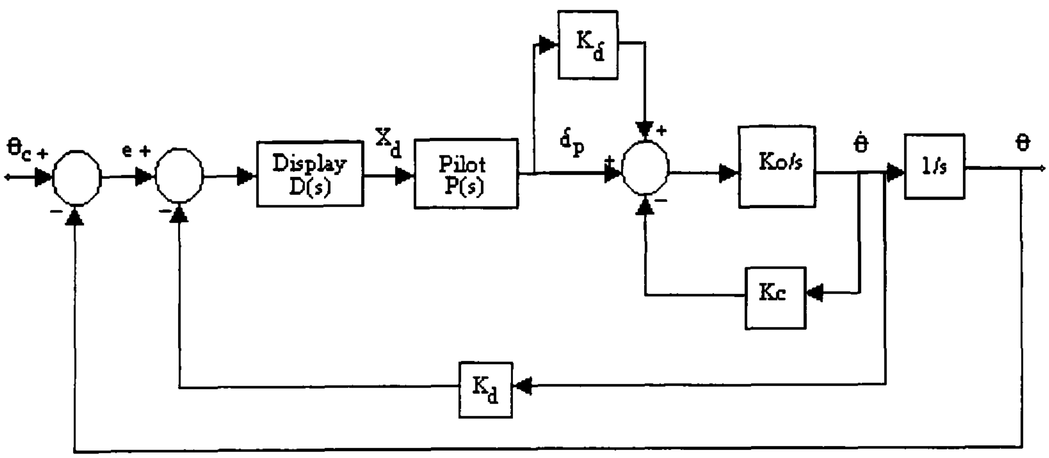


Figure 9. System Block Diagram (from Garg and Schmidt, 1988).

With reference to Figure 9, control augmentation was through manipulation of the feedback gain K_c, and the feed forward gain K_d. Display augmentation was through manipulating the display gain, K_d from the feedback of the first stage integrator. In this way, various different levels of velocity quickening gain could be applied to the display.

The eight different systems could thus be described by the gain settings K_d, K_c, and $K_{d'}$. K_o was constant for each system. The gain settings were chosen according to analytical evaluation from a previous study, and the detailed reasons for those choices are discussed in Garg (1988). Briefly, they were chosen as predicted by computer models to give best performance in tracking (RMS. error) and workload (RMS. manual control input) and combinations thereof.

The experimental results showed that display quickening could be used to improve tracking performance, but only limited improvement in actual tracking performance could be obtained. Making the level of display augmentation very high (i.e., a high value of K_d) actually resulted in deterioration of tracking performance.

The study was also performed for the case when the quickened display is presented along with the true error (current status) information. These results indicated that tracking performance improves further when the status information is available, again for reasonable levels of display quickening. Very high levels of display quickening, however, resulted in deterioration of tracking performance, possibly because of the confusion caused by two bars moving 'randomly' at the same time.

The research by Garg and Schmidt (1988) highlights the requirement that display augmentation must be carefully designed. Specific schemes for display augmentation depend upon the information being displayed, the control task, and the physical characteristics of the vehicle being controlled (Weinstein et al., 1993). In the design of flight directors, for example, which use display quickening as a basis for their algorithm, the design is first analytically evaluated using closed loop pilot modeling techniques, and then subjectively evaluated through man-in-the-loop simulations prior to implementation.

Garg and Schmidt (1987) present an analytical technique to aid in the design of pilot-optimal quickened displays, called the cooperative synthesis technique. The technique designs display qualities in order to be "in harmony with the pilots abilities and limitations in order to be acceptable to him as an aid in accomplishing the task". Display laws are synthesized for the K/s^2 plant, and the methodology is applied to a high order dynamic system in a multi control task scenario for a modern fighter aircraft.

Various prediction and quickening display algorithms are evaluated by Jensen (1981) in a flight simulator task involving curved landing approaches. He developed several algorithms that combined the principles of both compensatory tracking with quickening, and pursuit tracking with prediction, into one predictive type display. Research comparing compensatory and pursuit tracking display types has consistently shown the pursuit presentation to be superior (Jaeger, Agarwal, & Gottlieb, 1980), although pursuit type displays do suffer from field of view problems (since both indices, the desired position and the actual position, move in a pursuit type display, and only one symbol, the desired position, moves in a compensatory display). Combining pursuit and compensatory presentations on the same display has indicated that with even a small proportion of pursuit on a display is highly beneficial (Senders & Cruzen, 1952), and so this was the principle behind combining both types of presentation and augmentation in one display.

Results from Jensen (1981) indicate that intermediate levels of prediction and quickening provided best vertical control in the experiment. The application of quickening provides the pilot with a better indication of the imminent results of control movements, whilst the application of prediction presents a complete picture of actual system status, not available with an entirely quickened display. Prediction quickening algorithms of increasing order were also seen to significantly reduce control responses, which corresponds with the assumption that increasing complexity of prediction can relieve operator workload in predicting the motion of a system. The author states that quickening does not appear to be the final answer in flight displays, but its consideration seems warranted.

Statement of the Hypothesis

Performance on a continuous tracking task will be better with a display showing both status and quickened information than it will be with a display of quickened information alone, or a display of status information alone.

Method

Participants

This study is to investigate the effectiveness of combining quickened information and status information on a single display, for control of a manual tracking task. Such displays have possible applications in the aircraft cockpit, ship control, and any other manual control systems that involve complex dynamic behavior. The population for which the results can be generalized should, therefore, be persons likely to be given the task of controlling such systems.

The sample of the population from which participants have been chosen are pilots, holding at least an FAA private pilot license, and for convenience, currently studying at Embry Riddle Aeronautical University. Pilots differ from 'ordinary' people in being trained to perform tracking tasks with control systems of second and higher order, and an advantage of using pilots is that they usually require less practice to master a tracking task of high order (Poulton, 1974).

The participants were all volunteers and between the age of 19 and 29. The FAA private pilot license requires that all pilots hold at least a third class medical certificate, which stipulates: (a) distant visual acuity should be 20/50 or better in each eye separately, or 20/30 or better if corrective lenses are worn; (b) no serious pathology of the eye, and; (c) the ability to distinguish aviation red, aviation green, and white (US DOT Regulations, 1995). The sample size was 18 (13 males and 5 females).

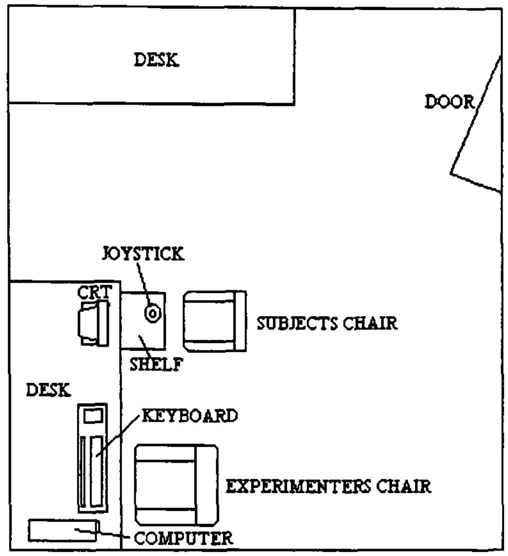
Instrument

Software compatible with an IBM PC was used to develop the tracking task, and provide the three different display conditions. The software package was the Manual Control Laboratory, version 1.0, which is produced by Engineering Solutions Inc. ®. Software was installed on a 486 IBM PC, with a processor speed of 66 MHz. Data were automatically recorded on a data file during each experimental trial. The control (plant), and disturbance dynamics were held constant throughout each trial. The joystick was manufactured by Dexxa, model number 963000-00. The joystick was spring centered, and friction was low.

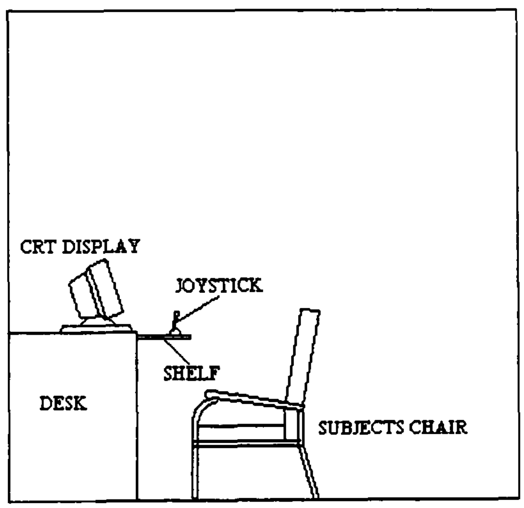
Design

The study is based on an experimental mixed design. Each participant was tested in the same quiet room with good lighting and at a comfortable temperature. The task was presented on a 28.5 cm by 21 cm color monitor placed at a viewing distance of approximately 65 cm. A joystick was used to manipulate the controlled element. The experimental setup is shown in Figure 10.

The task was a one axis (horizontal) pursuit tracking task. The vertical axis was disregarded because the direction of control - response was in conflict with pilots expectations of an aircraft response. During the pilot study, this resulted in several control reversals, and so the vertical axis was disabled for the experiment. The plant dynamics represent a second order system with system transfer function K_o/s^2. The three display types are shown in Figure 11.



Plan View



Side View

Figure 10. Experimental Setup.

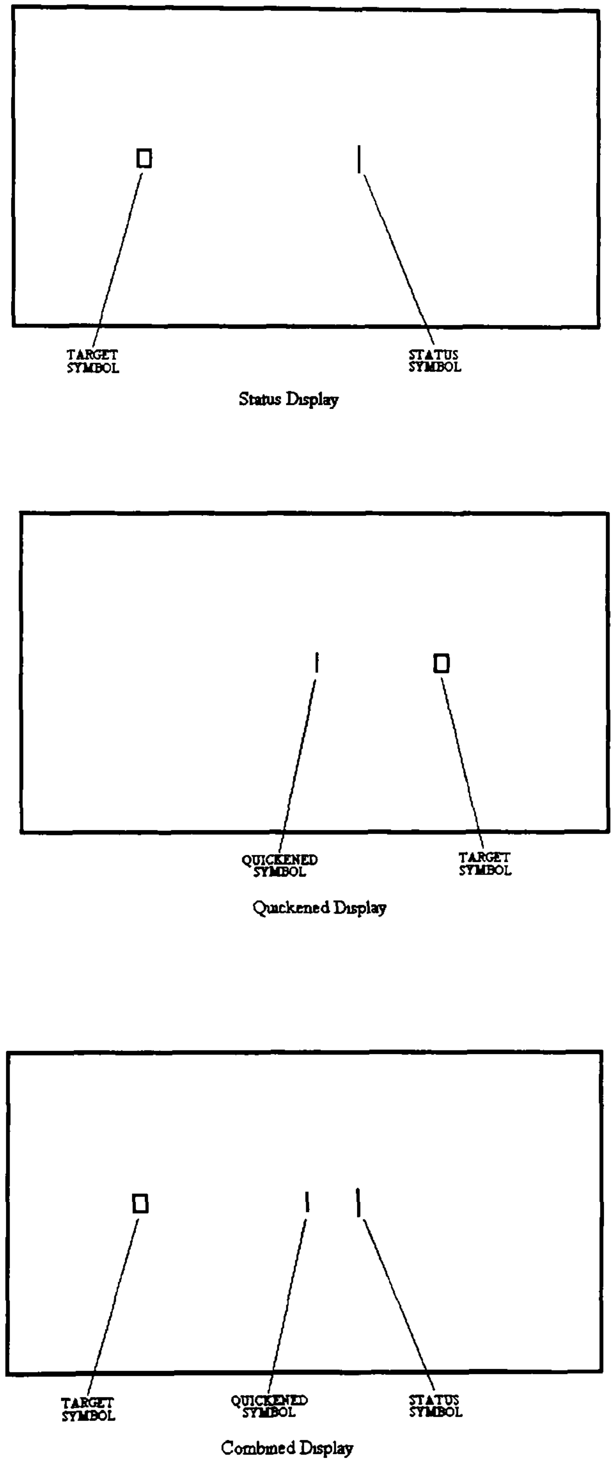


Figure 11. Experimental Display Types.

The open loop gain applied to the system, K_o, was set to a value of 0.6 in the software setup menu. A gain of 0.6 provides a system response that is slow, or sluggish, in the task of tracking the defined disturbance signal but not too sluggish as to be totally ineffective. In other words, the open loop gain selected gives a system that is relatively difficult to control, but not so difficult as to be rendered useless.

Quickened feedback was through the first stage integrator only, and so represented a velocity feedback path. The gain applied to the feedback from the first stage integrator (or the quickened gain, K_q) was set at 0.5 in the software setup menu. Too low a quickening gain gives a quickened output that is very similar to the status output, and therefore does not change performance significantly. The response of the quickened symbol is much the same as the status symbol, and so with a sluggish status symbol, the quickened symbol is also sluggish, and the error remains high. Too high a gain produces a quickened output that is much faster to respond, but the quickened symbol now leads the true status symbol by a large distance. When the quickened symbol is positioned directly over the target, the actual error may still be very high. A compromise between these two extremes is required, and a quickened gain setting of 0.5 was thought to be acceptable. This provides a quickened symbol that is responsive, but not so responsive as to lead the status symbol unacceptably.

Both the open loop gain K_o, and the quickened gain K_q were held constant across all participants and all display conditions.

The disturbance dynamic behavior simulated a random signal, actually achieved through summing three separate sine waves of differing frequency. Using the software disturbance setup menu, the three frequencies were 1.0 rad/sec, 0.8 rad/sec, and 0.5 rad/sec. Each frequency was assigned the same relative amplitude of 1.0, and a disturbance overall amplitude of 0.95. A random signal was simulated to eliminate the possibility of participants learning the system behavior.

The target was represented as a box, 5 mm x 5 mm (target size 0.05 in the software menu). The status symbol was a vertical green line, 9 mm in length, and the quickened symbol was a vertical yellow line, 7 mm in length.

A pilot study was conducted to evaluate task difficulty and amount of practice to be given. To determine the amount of practice that had to be given, each participant completed eight trials on the status display, and performance was recorded. It was assumed that the status display would be the slowest of all three displays to learn, because past research shows it to be most difficult to control (Kelley, 1968). When participants RMS. error scores fell within a score of +/- 0.04 for each subsequent trial on the same display type., it was assumed that learning effects were small. Using trial lengths of two minutes, it was found that four trials were needed to provide enough practice. Therefore, five trials were completed by each participant in each display condition for the experimental data (a total tracking time of ten minutes for each display). Data were recorded on all five trials to examine the effects of practice on performance.

For the actual experiment, with trial lengths of two minutes, and each participant completing fifteen trials (five trials in each of three display types), the total experimental session lasted about 45 minutes for each participant. Any period greater than this began to induce fatigue (much of the time is spent tracking and devoting attention to the task), and so the experimental session was thought to be sufficiently long, but not too long.

To eliminate any possible practice effects between display types, and effects due to fatigue, the order of trials was counterbalanced. With three display types, there are six possible orders of presentation, and so three participants were randomly allocated to each order.

The independent variable was display type. With the status only display, participants have to simply control the system with the status symbol. With the quickened display, participants have to control the system using the quickened symbol only. The status plus quickened display combines the first two and provides the quickened symbol along with the status symbol.

The dependent variable chosen as a measure of performance was RMS. (root mean square) status error. The units of RMS. error are measured in one half screen heights, where one screen height is 21 cm.

Procedure

Participants were given a written instruction sheet (Appendix A), to become fully aware of the task and understand the basic principle behind display quickening. Before commencing the trials, the experimenter read through the instruction sheet with each participant. If any doubts or questions remained after instructions had been read and each display had been briefly demonstrated, they were answered by the experimenter, but care was taken not to indicate any bias toward any of the display types.

Once familiar with the task, participants were asked to complete the control task for five trials with each of the three display types as described. For the status only display, participants were instructed to "minimize the error between the target and the green line as best as is possible". The green line was the status symbol. For the quickened only display, participants were instructed to "minimize the error between the target and the yellow line as best as is possible". The yellow line was the quickened symbol. For the status plus quickened display, participants were instructed to "minimize the error between the target and the green line as best as is possible. It may help to use the yellow line in your control strategy". With such an instruction, the actual plant being controlled by the participant is always K_o/s^2.

The order of trials was randomly assigned to each participant, and participants completed five trials for each display type from which data were recorded. Each trial lasted for 120 seconds, and a rest period of 45 seconds was given between trials.

Each participant was required to sign a consent form prior to data collection (Appendix B).

Results

Data were analyzed with a 3 x 5 x 6 mixed design analysis of variance. The within participants factors were display type (three levels) and trial number (five levels). The between participants factor was presentation order (6 levels). Outcome data are presented in Appendix C.

Main Effect of Display Type

The mean RMS. error scores for the status display, quickened display, and combined display when averaged across trial number and order of presentation were 0.256, 0.231, and 0.205 respectively. There was a significant main effect for display type as indicated by the mixed design ANOVA, $F(2,24) = 3.74$, $p = 0.039$. The RMS. error score was significantly influenced by display type when averaged across trial number and order of presentation. An eta square of 0.24 indicates that 24% of the variability in RMS. error scores was related to display type.

It was hypothesized that the combined display would give lower RMS. error scores than either the quickened display or the status display. The combined display RMS. error mean was significantly lower than the status display RMS. error mean when tested as a planned comparison, $F(1,12) = 15.11$, $p = 0.002$, one tailed. However, the RMS. error mean score for the combined display was not significantly lower than the RMS. error mean for the quickened display, $F(1,12) = 2.52$, $p = 0.138$, one tailed. Thus, scores than the status display, but no significant difference between the combined and quickened displays.

From examination of the means graphed in Figure 12, it appears that, in addition to the previous findings, the RMS. error mean with the quickened display is lower than RMS. error score with the status display. This apparent difference was evaluated with a Tukey HSD post hoc procedure, HSD(24,3) = 0.047, p = 0.05. Performance at tracking with the quickened display (0.231) was not significantly different than with the status display (0.256), when averaged across trial number and order of presentation.

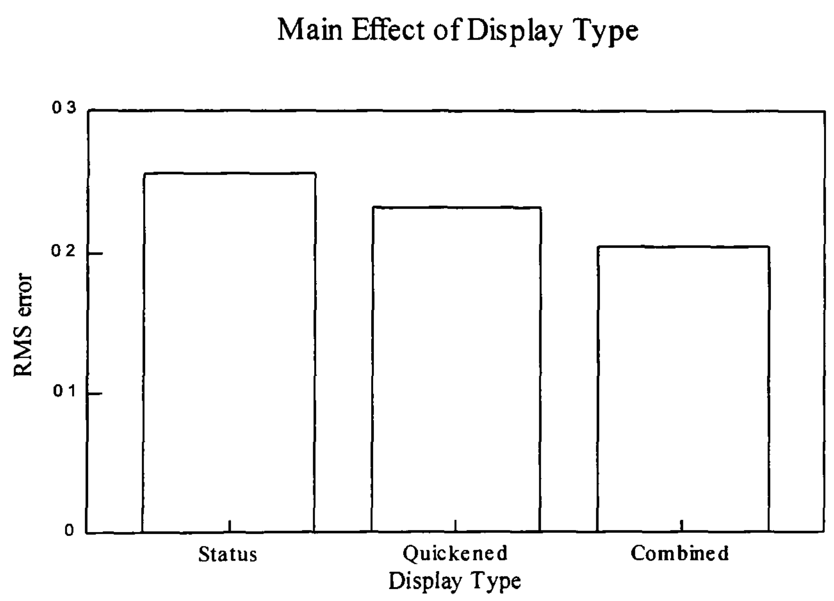


Figure 12. Display Type Mean Error Scores when Averaged Across Trial Number and Order of Presentation.

Main Effect of Trial Number

The mean RMS. error scores for trial number 1, 2, 3, 4, and 5, when averaged across display type and order of presentation were 0.3190, 0.2596, 0.2147, 0.1858, and 0.1749 respectively. There was a significant main effect for trial number as indicated by the mixed design ANOVA, $F(4,48) = 85.09$, $p = 0.000$. When averaged across display type and order of presentation, mean RMS. error score was significantly influenced by trial number, or practice time. An eta square of 0.88 indicates that 88% of the variability in RMS. error score was due to trial number.

From examination of the means graphed in Figure 13, it appears that there is a decrease in RMS. error score for each consecutive trial number. The apparent differences were evaluated with a Tukey HSD post hoc test, $HSD(48,5) = 0.026$, $p = 0.05$. There was

Main Effect of Trial Number

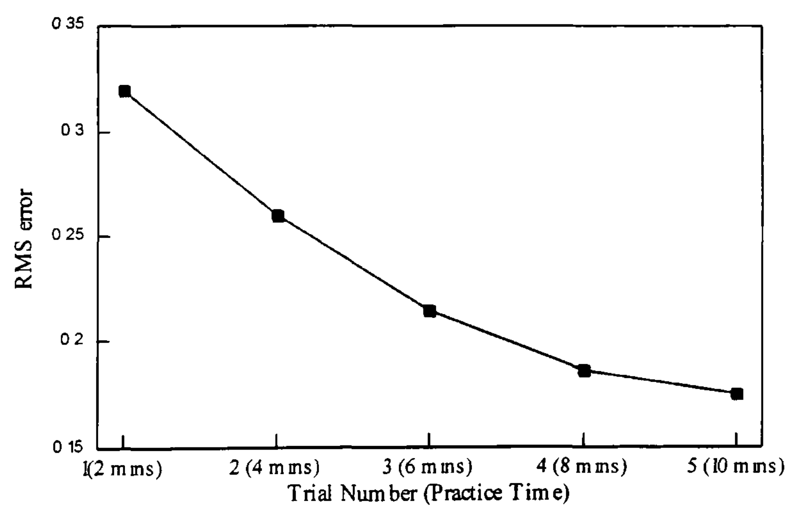


Figure 13. Trial Number Mean Error Scores when Averaged Across Display Type and Order of Presentation.

a significant decrease in RMS. error score for each consecutive trial, until trial number four. There was no significant difference in RMS. error between trial number four (0.186) and trial number five (0.175) when averaged across display type and presentation order.

Display Trial Interaction

The mean RMS. error scores for the status, quickened, and combined displays for trial numbers 1, 2, 3, 4, and 5 when averaged across order of presentation are given in Table 1. The pattern of means for display type and trial number do show a significant interaction effect, $F(8,96) = 9.14$, $p = 0.000$. The relative performance of the different display types depends upon the trial number, or amount of practice. An eta square of 0.43 indicates that 43% of the variability in RMS. error scores was due to this interaction effect. The interaction means are graphed in Figure 14.

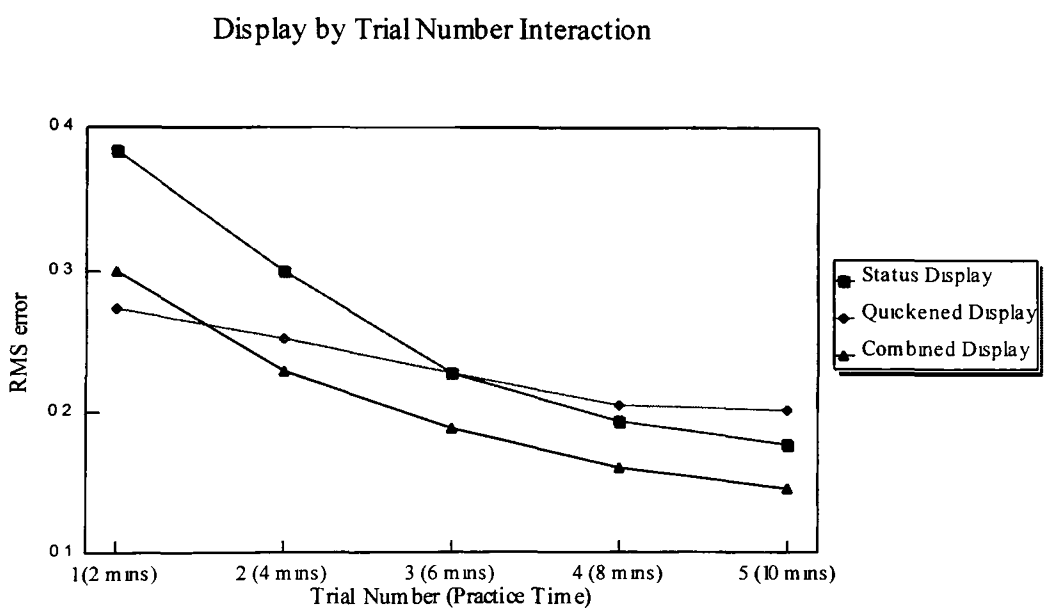
Table 1

Trial Number and Display Type Means when Averaged Across Presentation Order

Order	Status	Quickened	Combined
1	0.385	0.273	0.3
2	0.298	0.251	0.229
3	0.228	0.228	0.189
4	0.194	0.204	0.16
5	0.177	0.202	0.146

It was hypothesized that the combined display would give lower RMS. error scores than either the status display or the quickened display, and that this relationship would hold across all trials. In order to summarize the effects of learning, each display was compared after the first trial (two minutes practice), and after the fifth trial (ten minutes practice).

After two minutes practice time, the combined display RMS. error mean was significantly lower than the status display RMS. error mean when tested as a planned comparison, $F(1,12) = 9.99$, $p = 0.008$, one tailed. The combined display error mean



<u>Figure 14.</u> Mean Error Scores for Each Display Type and Trial Number when Averaged Across Order of Presentation.

(0.299) was not, however, less than the quickened display mean (0.273). Therefore, after two minutes practice, the hypothesis was only partly supported with the combined display giving lower RMS. error scores than the status display, but not giving lower RMS. error scores than the quickened display.

After ten minutes practice time, the combined display RMS. error mean was significantly lower than the status display mean when tested as a planned comparison $F(1,12) = 6.35$, $p = 0.027$, one tailed. The combined display mean was also significantly lower than the quickened display mean as a planned comparison $F(1,12) = 29.39$, $p = 0.000$, one tailed. Therefore, after ten minutes practice, the hypothesis was fully accepted, in that the combined display gave better performance than either the status or the quickened display.

With reference to Figure 14, it appears that, in addition to the planned comparison findings above, for the first trial there is no difference between performance with the quickened and combined displays. It also appears that the quickened display gives a lower RMS. error mean than the status display. After the first trial, all three displays appear to give lower RMS. error means with each consecutive trial, until trial number four. The difference in RMS. error means between trial number four and five, for each display type, appears to be small. For the fifth trial, in addition to the planned comparison findings, it appears that the status display gives a lower RMS. error mean than the quickened display.

These further apparent differences were evaluated with a Tukey HSD post hoc procedure, $HSD(96,15) = 0.046$, $p = 0.05$. For the first trial, there is no significant difference between performance with the combined display (0.299) and performance with the quickened display (0.273). Also, the quickened display does have a significantly lower RMS. error mean than the status display (0.385).

For the status display, there was a significant decrease in RMS. error means between trial 1 (0.385) and trial 2 (0.298), and between trial 2 and trial 3 (0.228). After trial 3, there was no significant decrease in RMS. error between subsequent trials for the status display. For the quickened display, there was a significant decrease in RMS. error between trial 1 (0.273) and trial 2 (0.251). After trial 2, there were no further significant decreases in RMS. error between consecutive trials. For the combined display, there was also a significant decrease in RMS. error between trial 1 (0.299) and trial 2 (0.229). Again, after the second trial, there were no further significant decreases in RMS. error between subsequent trials.

Finally, for the fifth trial, there was no significant difference between RMS. error mean with the status display (0.177) and with the quickened display (0.202).

Other Effects

The mean RMS. error scores for presentation order 1, 2, 3, 4, 5, and 6, when averaged across display type and trial number were 3.126, 2.775, 3.819, 4.415, 3.146, and 3.763 respectively. These means did not differ significantly, $F(5,12) = 0.51$, $p = 0.767$. There was no significant difference in RMS. error scores for the six orders of presentation when averaged across display type and trial number.

The mean RMS. error scores for presentation orders 1, 2, 3, 4, 5, and 6 for status, quickened and combined display types, when averaged across trial number, are given in Table 2. This pattern of means does not show a significant interaction effect, F(10,24) = 0.37, p = 0.948. The performance of each display type, when averaged across trial number, did not depend upon order of presentation.

Table 2

Presentation Order and Display Type Means when Averaged Across Trial Number

Order	Status	Quickened	Combined
1	0.237	0.225	0.163
2	0.196	0.2	0.159
3	0.287	0.236	0.241
4	0.278	0.273	0.277
5	0.245	0.217	0.167
6	0.296	0.237	0.22

The mean RMS. error scores for trial numbers 1, 2, 3, 4, and 5 for presentation orders 1, 2, 3, 4, 5, and 6, when averaged across display type are given in Table 3. The pattern of means for trial number and presentation order do not show a significant interaction effect, F(20,48) = 0.82, p = 0.676. The relative effect of trial number, when averaged across display type, did not depend upon order of presentation.

The pattern of means for the three way interaction of display type, trial number, and order of display do not show a significant interaction effect, F(40,96) = 0.666, p = 0.925.

Table 3

Presentation Order and Trial Number Means when Averaged Across Display Type

Order/Trial	1	2	3	4	5
1	2.798	2.075	1.74	1.431	1.334
2	2.454	1.831	1.479	1.281	1.281
3	2.89	2.64	2.223	1.962	1.742
4	3.509	2.815	2.309	1.91	1.891
5	2.78	2.142	1.599	1.491	1.426
6	2.799	2.516	2.245	1.96	1.768

Summary of Results

When averaged across trial number (practice time) and order of presentation, the mean RMS. error score was lower for the combined display than for the status display, but there was no difference between the status and quickened displays, or between the quickened and combined displays.

When averaged across display type and order of presentation, there was a significant decrease in RMS. error for each progressive trial number until the fourth trial. There was no significant difference in RMS. error between the fourth and fifth trials.

When averaged across display type and trial number, RMS. error scores were not dependent upon order of presentation.

There was a significant interaction effect between display type and trial number. For the first trial, the RMS. error scores for the combined display were lower than for the status display, but there was no difference in scores between the combined display and the quickened display. Also, RMS. error scores for the quickened display were lower than for the status display.

All three of the displays showed a significant decrease in RMS. error between the first and second trials. After the second trial, only the status display showed a further significant decrease between consecutive trials, and this was between the second and third trials only.

For the fifth trial, RMS. error scores for the combined display were still lower than those for the status display. The combined display scores were also lower than the quickened display scores, but there was no difference in performance between the status and quickened displays.

Conclusions

The hypothesis stated that the combined display of quickened and status information would give better performance than a quickened alone display or a status alone display. The hypothesis has been partly accepted.

From analysis of the main effect of display type, it was found that the combined display was better than the status display, but did not differ in performance from the quickened display. The reason for the hypothesis not being fully accepted is due to the significant interaction effect with trial number, or amount of practice given. It was expected that the relationship between display would not change with practice, but the significant interaction effect demonstrates that this was not the case.

Analysis of the interaction effect shows that, after two minutes practice, the quickened display shows the best performance, along with the combined display. The quickened error score is lower than the combined error score suggesting that, if anything, the quickened display may be slightly better (though the actual difference is not significant). The status display gives the worst performance after two minutes practice.

This result shows that, after only two minutes practice, the quickened display is better than the status display for tracking the random moving target. This result is supported by past research that has compared status and quickened displays (Garg & Schmidt, 1988). In addition, the combined display gives performance very similar to that of the quickened display, and so we may conclude that any display augmentation, whether presented along with the status information or not, is beneficial after only two minutes practice.

After ten minutes practice, the relative performance of each display has changed. The combined display now gives the best performance, followed by the status display, with the quickened display giving the worst performance of all. The hypothesis is confirmed in full after ten minutes practice. Garg and Schmidt (1988) also found the combined display to be superior to the quickened display, but only if the level of quickening was reasonable. If the level (gain) of quickening was set too high, actual tracking error deteriorated because of the confusion caused by the incompatibility between the status information and the quickened signal.

It is interesting to note that, after ten minutes practice, the quickened display gives a higher mean error score than the status display (although the difference is not significant). It was expected that the quickened display would be better than the status display across all trials. There are two possibilities suggested for this loss in effectiveness of the quickened display as practice time increases.

The first explanation is that the control task was too easy to control. The task was designed so as to represent a sluggish second order system, which should be relatively hard to control manually. If the design is not difficult enough, then participants could learn to control the status display quite effectively, even after ten minutes. The advantages of display augmentation will be reduced as the control task becomes easier, until the point is reached where zero error can be achieved without augmentation. How is augmentation going to assist in a control task that has zero error performance without augmentation?

In fact, if the control task is made too easy, display quickening will reduce the effectiveness of control. The operator controls the task with reference to the quickened cursor, but is unaware of the true status error. The quickened cursor always leads the status cursor (when it is in motion) and so the status cursor will never be exactly on target if the quickened cursor is on target. The error will never be zero, because the error is measured from the position of the status cursor, which would never be on target. This is the main criticism of display quickening without status information. The quickened cursor will always give a certain error, even if it is maintained dead center on target throughout the trial. This observation was also made by Garg and Schmidt (1988) who stated that "only limited improvement could be obtained with the purely quickened display augmentation".

The second explanation for worse performance with the quickened display over the status display is that the quickened display gain K_q was not well selected. In this study, the gain was selected through subjective evaluation. The design methodology is presented in the method section, but it is important to have a feedback gain that is not too high, nor too low. If the gain is not well selected, the augmentation will not be successful. Nevertheless, if the task is very difficult or unfamiliar to participants, then even a poorly selected quickening gain may help in performance, but the advantage of poorly designed augmentation will quickly become apparent. This may explain why the quickened display is successful after two minutes, but is no better than the status display after ten minutes.

Though we have little supporting evidence, the need to design the quickened display to some design criteria is of obvious importance. In any commercial application of display quickening, a quantitative technique would need to be adopted, rather than the subjective technique used in this study, to optimize the gain or level of quickening. Such a technique was developed by Garg and Schmidt (1987) but its application was unsuitable in this study.

The combined display with both status and quickened information available was superior to the status display across all trials. This suggests that providing the additional quickened information is a useful cue in anticipating control actions.

An issue of concern for any display with more than one moving symbol is that it may lead to operator confusion. Participants were asked to comment on this issue, but few expressed any concern. The display used in this study was, however, very simple in design and did not have any of the distractions of a typical flight display. If such a display were adopted for, say, an ILS indicator, then confusion may become an issue.

The quickened display was beneficial after the first trial, but lost its effectiveness as practice time increased. This suggests that a quickened display may be useful for applications where operators have little experience with the task. If the status information is not included in the quickened display, then a purely quickened display was observed to give only limited improvement. After ten minutes practice, participants were at least as good at using the status alone display as they were using the quickened alone display.

From analysis of the main effect of trial number, an overall practice effect, averaged across display type and order of presentation, emerges (Figure 13). It was of concern in this study that tracking performance should be evaluated at least until practice effects are almost eliminated. Through a pilot study it was determined that at least eight minutes tracking time were required to achieve this. It was assumed that the status display would be the slowest to learn. Details of the pilot study are presented in the method section.

The main effect of trial number shows us that there is a significant practice effect (reduction in mean RMS. error score) between each consecutive trial, except the fourth and fifth trials. There is no significant difference between the mean error scores for the last two trials, and this gives supporting evidence that the learning curve is reaching its asymptotic level. It would be wise to examine the mean error scores for a longer practice time before determining that the asymptotic level has been reached, but this process is limited by practical considerations, such as fatigue of participants.

In addition to the main effect of trial number, the interaction effect of trial number and display type shows a similar practice effect for each separate display. Each display shows a significant practice effect between the first and second trials. Beyond the second trial, only the status display shows a further significant decrease between subsequent trials, and this is between the second and third trials. This adds support to the assumption that the status display is the slowest of all the displays to learn.

The main effect of presentation order was tested to examine whether order of presentation affects RMS. error scores. It was hoped that there would not be a significant effect, since an order effect would confound the results, and make interpretations problematic. There was no significant main effect of presentation order.

Neither was there an interaction effect of presentation order with display type. The relative performance of each display type was not influenced by the order in which the three display were presented to participants. It was important to include this interaction because it is possible that practice effects with one display type may transfer to another display type. However, the control dynamics of the status and quickened displays are quite different (that is why display quickening can be successful) and this probably helped in controlling the learning transfer effect.

The value of a combined display with both status and quickened information has been clearly demonstrated in this study. Although the research hypothesis was only partly accepted, the combined display produced better performance than the status display across all trials. As practice time increased, the benefits of a purely quickened display were reduced, but the combined display continued to give better performance.

So, having concluded that a combined display can be an effective augmentation tool, what are its practical applications? It has long been realized that purely quickened displays can assist operators in controlling complex dynamic systems, and so why not develop combined displays for the same applications?

Combined displays may be helpful in training operators of complex systems, just as quickened displays have been used (Dooley & Newton, 1965). Combined displays could be used as an adaptive training aid to make operators familiar with the control of a system, using a simulator, before operation of the 'real time' system that may not have the advantage of display augmentation. Separate studies would first need to demonstrate the use of adaptive training using this technique, but it is a possible application.

Any task that requires control of very slow and sluggish systems, with pure time delays or large lag components may benefit from combined displays, such as control of ship heading and speed, or for control of large transport category aircraft. The latter application may lend itself more to display augmentation in the future as aircraft size tends to become larger, aircraft speeds increase, and control demands become more complex.

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APPENDIX A

PARTICIPANT INSTRUCTION SHEET

Instructions

The following experiment has the aim of evaluating three different display types for tracking a random moving target. Two of the displays use a display technique called 'quickening'.

Quickening can be best explained by looking at the following display :

The display has two lines, one green and the other yellow, that are both controlled by the joystick. Notice that if the joystick is moved, the yellow line moves quicker and ahead of the green line. The moving box is the target.

In the first display, only the green line is available for control. The aim of the exercise is to keep the green line as close as possible to the target box.

---------------------- Practice with the first display ---------------------

In the second display, only the yellow line is available for control. The aim is to keep the yellow line as close as possible to the target box.

----------------------- Practice with the second display --------------------

In the third display, both the green and yellow lines are available. The aim now is to keep the green line as close as possible to the target box. You may find it useful to use the yellow line to help in your control strategy.

---------------------- Practice with the third display -------------------

APPENDIX B

PARTICIPANT CONSENT FORM

CONSENT FORM

Project: The Effectiveness of a Quickened Plus Status Display

I agree to participate in a one day study on performance differences between three different display types in the control of a random tracking task. I will be asked to complete several control tasks using each display type.

During the experiment I will be asked to track a random moving target by manipulating a joystick. If for any reason this task begins to feel unpleasant, I will be permitted to stop upon my own request. I also understand that I am free to discontinue participation in this study at any time. If I elect to discontinue participating, I understand that all forms I have completed will be destroyed.

I certify that I do not have epilepsy, nor am I taking medication or drugs.

I understand that no risks or discomforts are expected, and that all information concerning my participation in this study will be kept confidential. Any published reports will present only statistical data, or individual data without personal identification.

A preliminary description of the project has been given to me in person. I understand that I am free to ask questions about the procedures to be used, and at the end of the session, I will be fully informed as to the purpose of the research project. I also understand that the experiment is expected to have no direct benefit to me personally but that the results will be used to further scientific knowledge about the effects on performance of different display types.

If you have any questions or comments, please discuss them with those involved in the study, and/or Dr. J. A. Wise, Center for Aviation/Aerospace Research, (904) 226 6385.

Name (print) ________________________

Signature ___________________________ Date ______________

APPENDIX C

OUTCOME DATA

ORDER 1 (S,Q,C)

Participant	trial #	STATUS RMS. error	QUICKENED RMS. error	COMBINED RMS. error
1	1	0.568	0.407	0.405
	2	0.461	0.32	0.2
	3	0.318	0.278	0.214
	4	0.257	0.242	0.138
	5	0.219	0.223	0.129
2	1	0.187	0.203	0.193
	2	0.188	0.197	0.135
	3	0.136	0.182	0.116
	4	0.088	0.168	0.085
	5	0.094	0.174	0.083
3	1	0.409	0.223	0.203
	2	0.225	0.187	0.162
	3	0.139	0.195	0.162
	4	0.143	0.189	0.121
	5	0.116	0.182	0.104

ORDER 2 (Q,S,C)

Participant	trial #	STATUS RMS. error	QUICKENED RMS. error	COMBINED RMS. error
4	1	0.311	0.175	0.188
	2	0.183	0.23	0.224
	3	0.146	0.219	0.193
	4	0.135	0.196	0.167
	5	0.141	0.175	0.141
5	1	0.347	0.18	0.42
	2	0.269	0.204	0.196
	3	0.208	0.216	0.115
	4	0.162	0.174	0.099
	5	0.173	0.18	0.104
6	1	0.365	0.293	0.175
	2	0.197	0.208	0.12
	3	0.112	0.185	0.085
	4	0.089	0.189	0.07
	5	0.099	0.177	0.091

ORDER 3 (C,S,Q)

Participant	trial #	STATUS RMS. error	QUICKENED RMS. error	COMBINED RMS. error
7	1	0.572	0.363	0.635
	2	0.604	0.382	0.518
	3	0.564	0.327	0.443
	4	0.503	0.305	0.397
	5	0.438	0.312	0.315
8	1	0.248	0.214	0.204
	2	0.209	0.213	0.156
	3	0.146	0.185	0.124
	4	0.133	0.172	0.074
	5	0.077	0.17	0.071
9	1	0.272	0.211	0.171
	2	0.189	0.206	0.163
	3	0.119	0.173	0.142
	4	0.109	0.161	0.108
	5	0.115	0.143	0.101

ORDER 4 (Q,C,S)

Participant	trial #	STATUS RMS. error	QUICKENED RMS. error	COMBINED RMS. error
10	1	0.562	0.328	0.47
	2	0.469	0.309	0.413
	3	0.283	0.313	0.364
	4	0.246	0.218	0.265
	5	0.257	0.22	0.293
11	1	0.278	0.283	0.445
	2	0.236	0.319	0.204
	3	0.164	0.225	0.171
	4	0.169	0.207	0.164
	5	0.149	0.201	0.154
12	1	0.386	0.401	0.356
	2	0.301	0.309	0.255
	3	0.279	0.31	0.2
	4	0.208	0.22	0.213
	5	0.188	0.24	0.189

ORDER 5 (C,Q,S)

Participant	trial #	STATUS RMS. error	QUICKENED RMS. error	COMBINED RMS. error
13	1	0.348	0.389	0.212
	2	0.232	0.285	0.136
	3	0.171	0.251	0.157
	4	0.155	0.237	0.148
	5	0.166	0.236	0.133
14	1	0.633	0.245	0.358
	2	0.449	0.239	0.286
	3	0.275	0.165	0.22
	4	0.241	0.166	0.185
	5	0.262	0.173	0.16
15	1	0.257	0.219	0.119
	2	0.174	0.178	0.163
	3	0.141	0.147	0.072
	4	0.097	0.171	0.091
	5	0.075	0.152	0.069

ORDER 6 (S,C,Q)

Participant	trial #	STATUS RMS. error	QUICKENED RMS. error	COMBINED RMS. error
16	1	0.271	0.306	0.25
	2	0.197	0.296	0.221
	3	0.192	0.298	0.245
	4	0.164	0.22	0.225
	5	0.149	0.248	0.196
17	1	0.297	0.231	0.232
	2	0.275	0.233	0.185
	3	0.271	0.219	0.135
	4	0.234	0.227	0.117
	5	0.192	0.192	0.104
18	1	0.614	0.235	0.363
	2	0.514	0.208	0.387
	3	0.431	0.219	0.235
	4	0.351	0.205	0.217
	5	0.284	0.219	0.184