THE COGNITIVE DEMANDS OF SECOND ORDER MANUAL CONTROL: APPLICATIONS OF THE EVENT RELATED BRAIN POTENTIAL[1]

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ABSTRACT

Three experiments are described in which tracking difficulty is varied in the presence of a covert tone discrimination task. Event related brain potentials (ERPs) elicited by the tones are employed as an index of the resource demands of tracking. Experiments 1 & 2 varied tracking difficulty by the order of the control system dynamics in a teleoperator target acquisition task (experiment 1), and in random input compensatory tracking (experiment 2). The ERP measure reflected the control order variation, and this variable was thereby assumed to compete for perceptual/central processing resources. A fine-grained analysis of the results of Experiment 2 suggested that the primary demands of second order tracking involve the central processing operations of maintaining a more complex internal model of the dynamic system, rather than the perceptual demands of higher derivative perception. Experiment 3 varied tracking bandwidth in random input tracking, and the ERP was unaffected. Bandwidth was then inferred to compete for response-related processing resources that are independent of the ERP.

[1]Experiment 1 was supported by a subcontract from NASA-Jet Propulsion Laboratory (US NASA SBC CAL TECH 955610). Dr. John Hestenes was technical monitor. Experiments 2 and 3 were supported by a contract from the Air Force Office of Scientific Research Life Sciences Directorate (F49620-79-C-0233). Dr. Alfred Fregly was the technical monitor.

Two variables that are well established to influence the difficulty of manual control are the order of the controlled system, and the bandwidth of a disturbing noise function (McRuer & Jex, 1968). As shown in the data of figure 1, both variables influence tracking error, as well as the perceived difficulty of the task.[1] Furthermore, figure 1 suggests that for each variable, both subjective and performance measures increase linearly. An approximate level of bandwidth can be established that produces roughly equivalent difficulty ratings and performance to second order tracking (.55-.60 Hz).

A change in task parameters, such as bandwidth or system order, that attenuates performance and increases subjective effort must be assumed to consume a greater quantity of the operator's limited capacity processing resources. However, given recent experimental evidence that these resources do not reside within a single undifferentiated "reservoir" (Navon and Gopher, 1979, Wickens, 1980), but are instead multidimensional, defined by two processing stages (perceptual-central vs response) and two processing codes (spatial vs verbal), then the resource demands of a task must be a vector quantity. It is not, nowever, immediately clear how the vector of demand increase imposed by order and bandwidth is defined.

In the case of control order, the increased demand imposed by second order control could be perceptual, given the requirement to generate lead and respond to higher derivatives of the error signal. It could be central, given the more complex internal model defined by two state variables rather than one, or it could be response, given the "bang-bang" or double impulse control sometimes employed in the regulation of higher order systems. In the case of bandwidth, an increase in this parameter will influence the frequency with which information must be sampled (perception), and corrective responses must be selected (response). It is reasonable to assume that in both manipulations the increased load is imposed upon spatial processing more than upon verbal, given the fundimental spatial nature of the manual control task.

In order to assess the stage-defined locus of these variables, it is necessary to employ a workload measure that is selectively sensitive to early or late processing stages. Such a measure is provided by the late positive component of the event-related brain potential, or ERP. The ERP is a transient series of voltage oscillations recorded by electrodes from the surface of the scalp and elicited in response to discrete environmental or cognitive events. The late positive, or P300, component is a deflection in the ERP that appears to be particularly sensitive to the attention or processing resources allocated to the eliciting stimulus (Donchin, 1980). In previous investigations, we have shown that the P300, elicited by counted stimuli in a Bernoulli series, is particularly sensitive to the perceptual load imposed by a concurrent display monitoring task (Isreal, Wickens, Chesney, & Donchin, 1980), but is unaffected by the response load of a manual control task (Isreal, Chesney, Wickens, &

[1]The 1.5 order point is a condition in which the output of a first and second order system are combined with equal weighting.

Donchin, 1980). Assuming that P300 acts as a selective measure of perceptual/central processing load, the present series of experiments examines the sensitivity of this measure to increases in control order and in bandwidth, in order to infer the stage-defined locus of these manipulations.

Experiment 1: Teleoperator Simulation

Subjects in this experiment engaged in a target acquisition and capture task, depicted in figure 2. A target appeared at a random location and traversed the display in a linear path. The subjects' task was to manipulate the cursor, via the two axis control in such a way as to match the spatial velocity of the target (acquisition phase). Control dynamics could be set at either first or second order. Once acquisition was completed, the target began to tumble, and the subject then had to match the angular velocity as well by a left hand control (orientation phase). When error in all three dimensions was held below a certain criterion, a successful capture could be affected by depressing a "capture" button with the thumb of the left hand. As the task was performed, either the target or the cursor stimulus randomly intensified or "flashed." In the data to be reported, the subjects' task was to maintain a covert count of the number of times the target intensified during a trial. The P300 component of the ERPs generated by these intensifications served as the workload index.

Figure 3a indicates the P300 (the large downward deflection) elicited during the acquisition (top) and orientation (bottom) phase. Clearly the latter phase imposes greater workload (3 axes of control as opposed to two) and this is indicated by the diminished P300s elicited by the relevant counted targets. (The non-counted cursor flashes failed to differentiate workload in any condition.) Of particular interest to the current hypothesis is the diminished P300 during second, as opposed to first, order control in both phases. These results support the hypothesis that a major source of workload in the higher order control condition is the increased perceptual load imposed by the perceptual anticipation, or central processing load, imposed by internal model updating.

In a second experiment, when subjects were then provided extensive practice with both control dynamics of the target acquisition task, the difference in P300 between first and second order tracking was eliminated (although acquisition performance in the former continued to be superior). Our interpretation of these results (figure 3b) in light of the selective nature of P300 and the totally predictable linear trajectory of the target path, is that with extensive practice, subjects in second order tracking employ double-impulse control strategy to place the target on the right trajectory, and need not engage in further load inducing perceptual/anticipatory processing.

Experiment 2: Steady State Compensatory Tracking

Unlike experiment 1, subjects in experiment 2 engaged in three-minute trials of compensatory tracking of a random disturbance input with an upper cutoff frequency of 0.30 Hz. Again tracking order (first vs second) was the manipulated variable. A Bernoulli series of auditory tones, of high and low pitch occurring at an interval of 1.5 seconds were the stimuli employed to generate the ERPs. Figure 4 shows the averaged ERPs elicited by the counted auditory tones when the subject was not tracking at all (solid line), was tracking a first order system (dashed line) and was tracking a second order system (dotted line). In agreement with experiment 1, these results manifest the same attenuation of P300 with order ($p < .05$). In addition, they suggest the large differences in P300 between the condition of focussed attention and that when resources are diverted to tracking ($p < .01$).

Experiment 3: The Effect of Bandwidth

The same subjects that participated in experiment 2 were employed in an investigation of the bandwidth variable. In this study, employing only first order dynamics, a careful calibration was first performed to determine for each subject the level of bandwidth that would generate equivalent error to that observed in second order tracking. We assume, on the basis of the data from figure 1, that manipulations of order and bandwidth that generate equivalent changes in error, will also generate equivalent changes in subjective difficulty. Thus by the calibration process employed in experiment 3, we have made the bandwidth manipulation as equivalent as possible to the order manipulation of experiment 2.

The ERPs,generated and recorded exactly as in the previous experiments, are shown in figure 5. Again a marked decrease in P300 amplitude is observed between the control condition and "easy" tracking. However, no further attenuation is observed between low and high bandwidth tracking. In fact, there appears to be a slight increase in amplitude. These results represent a replication of the finding of Isreal, Chesney, Wickens, and Donchin (1980) in which they observed that P300 did not diminish as bandwidth was gradually increased from a low to high level. The results in the present case are convincing because of the comparability of the bandwidth with the order manipulation in terms of tracking error and subjective difficulty. Order attenuated P300, while bandwidth did not.

Discussion

The localization of demands of the tracking order manipulations at earlier processing stages is in agreement with another study of Wickens and Derrick (1981), in which the Sternberg Memory Search Task was employed as a selective workload index. Furthermore, this investigation failed to find any evidence for an interaction of control order with response-load variables of the Sternberg Task. Thus control order was not assumed to be response loading in their task. Discriminating between perceptual and central processing loci of second order control is somewhat difficult on the basis of the task interference data discussed above, since the multiple resources model postulated by Wickens (1980) assumes that both perceptual and central processing operations compete for common resources, and therefore will not differentially interfere with a secondary task.

To discriminate the perceptual from the central locus, the following more detailed analysis was thus undertaken. It was assumed that if the resource demands of second order tracking were directly attributable to the perception of higher error derivatives, then these demands should covary with the momentary state of the system. When error acceleration is high, demands should increase and P300s would be attenuated;when low,demands should decrease, and P300 enhanced. In contrast, if the demands were related to central processing, we assume that the more complex internal model of a second order system is activated at the beginning of the trial, and the resources required to monitor this activation are relatively continuous, and independent of momentary fluctuations in system state.

To contrast these hypotheses, P300s were selectively averaged according to the momentary state of the system at the time of stimulus presentation. "State" was defined along six dimensions (i.e., whether error position, velocity, or acceleration was above or below its median value, and whether stick position, velocity, or acceleration was above or below the median) In general, the results supported the central-processing hypothesis. With only minimal exceptions, all subjects seemed to show equivalent P300s at high and low ends of the averaging categories, no matter how these categories were defined (i.e., by e, $\dot{e}$, $\ddot{e}$, s, $\dot{s}$, or $\ddot{s}$). Interestingly, this equivalence was observed whether subjects were good or poor trackers. We are not surprised to observe the independence from the control stick variable, given the assumed independence of P300 from response variables. The independence from variation in perceptual (error) state suggests that the increased resource demands of second order control are relatively continuous, and therefore likely to be of central origin.

A second aspect of the results concerns the locus of the bandwidth manipulation. It is obvious that increasing the bandwidth does indeed increase the required frequency of perceptual sampling. However, as suggested by the data of Wickens and Derrick (1981), or Isreal, Chesney, Wickens & Donchin (1980), and experiment 3, this increase is not of sufficient magnitude to compete with a second task for resources. By process of elimination, the locus of bandwidth demands would seemingly be response related, although this hypothesis has yet to be explicitly tested. The failure of P300 to reflect bandwidth variation is important because it emphasizes the selective aspect of the ERP measurement and the multidimensionality of processing resources. Were P300 affect by any manipulation of task difficulty, then the present results would contribute little in the way of added knowledge. However, the selectivity observed suggests that different variations of manual control difficulty exert a qualitative as well a quantitative influence on the resources of the human operator.

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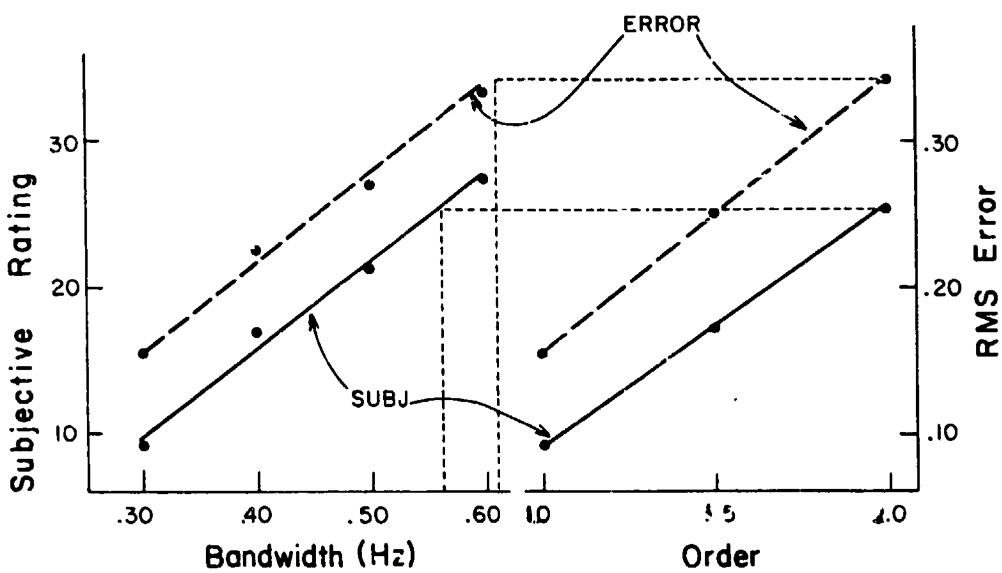


Figure 1.

Influence of bandwidth and control order on tracking error and subjective ratings of difficulty.

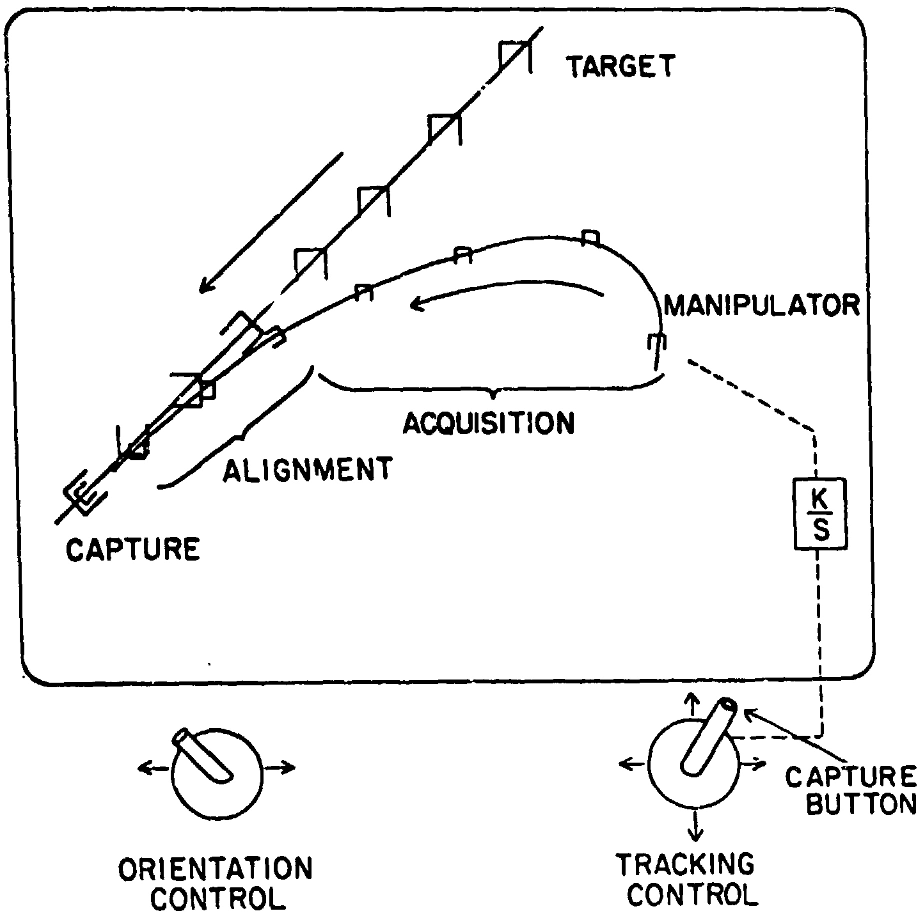


Figure 2.

Experimental paradigm for teleoperator target acquisition task.

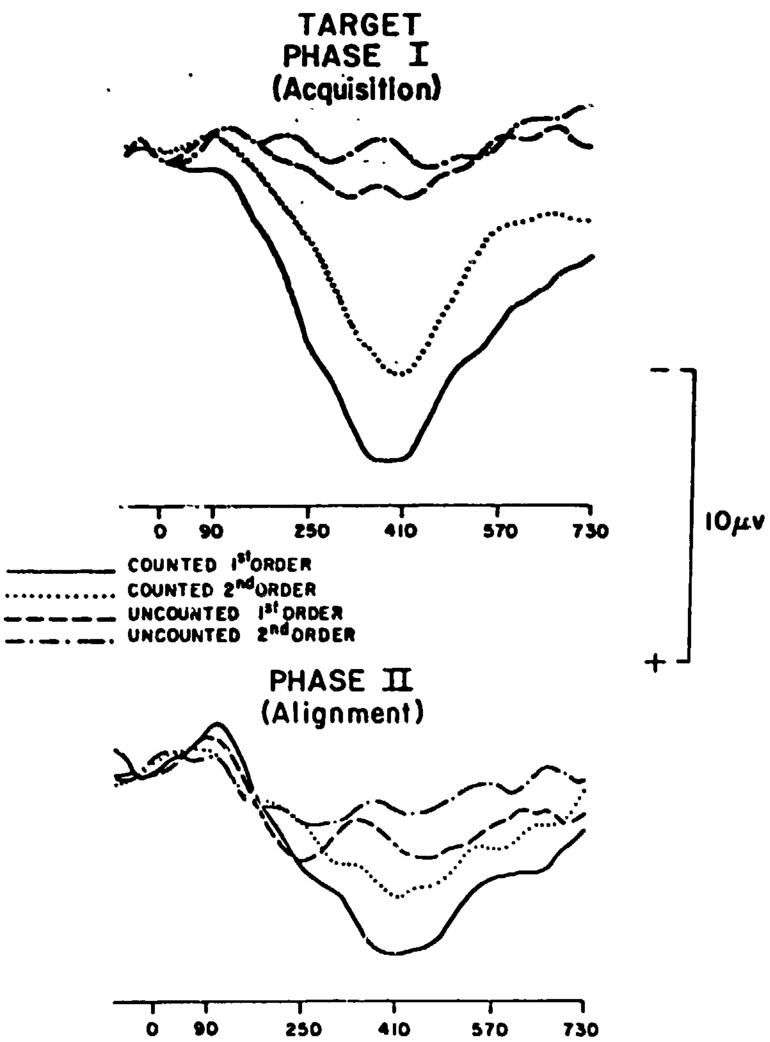


Figure 3(a)

(Experiment 1: Target Acquisition)
Effect of control order on the ERP.

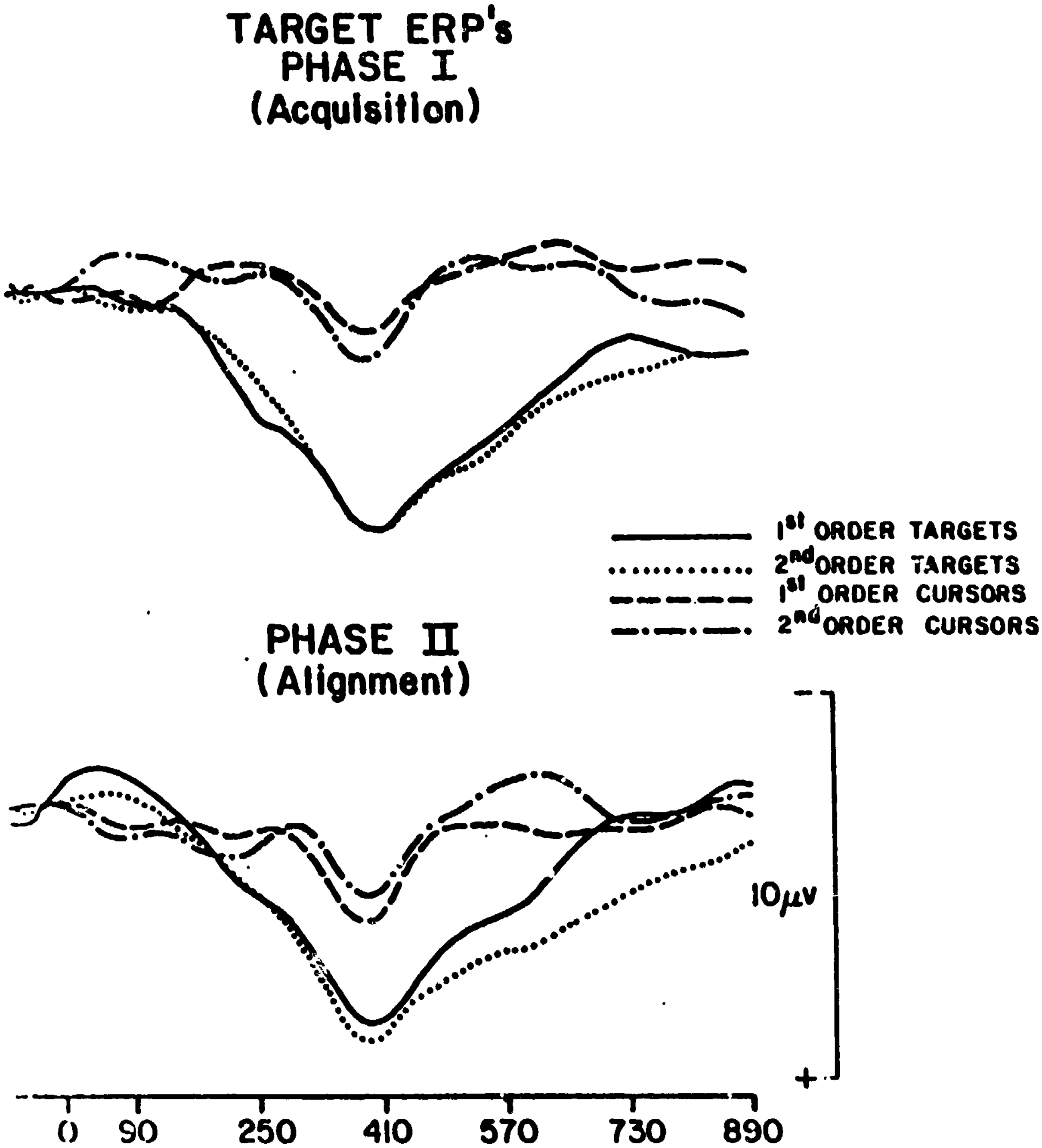
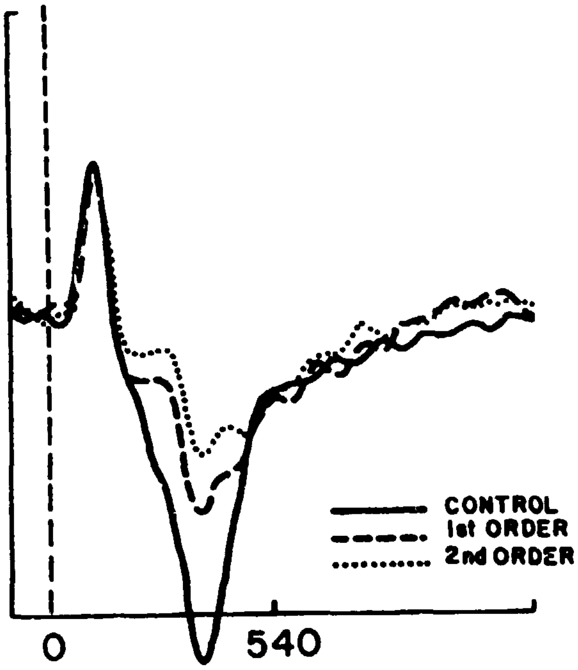


Figure 3(b)

(Experiment 1: Target Acquisition)
Highly practiced subjects (570
acquisition trials).



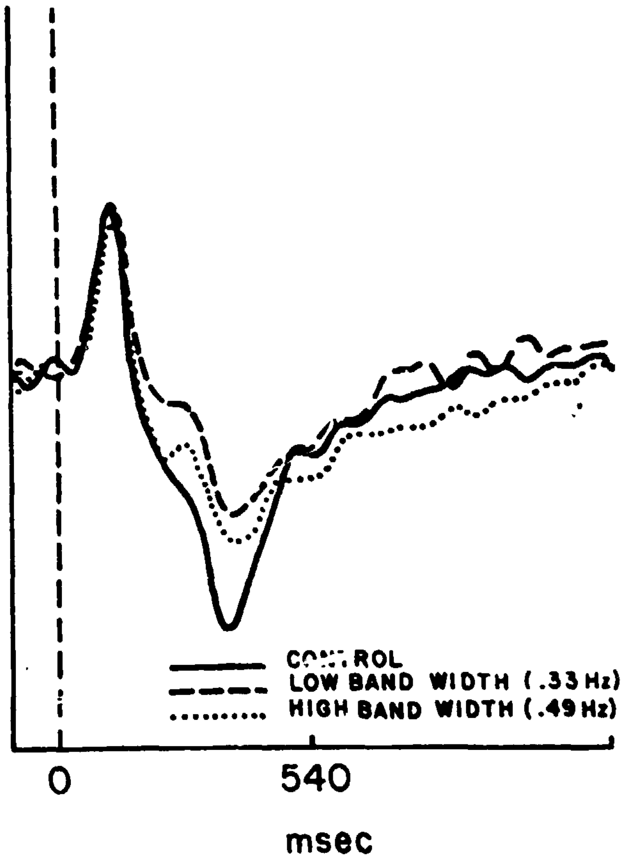


Figure 4.

Experiment 2: Random input tracking: Effect of control order on the ERP.

Figure 5.

Experiment 3: Random input tracking: Effect of bandwidth on the ERP.