The Relationship between Attention to Preview and Action during Roadway Tracking

DISSERTATION

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Abstract

Cognitive aspects of driving on a winding roadway were investigated using a model comprised of a driver, a vehicle, and a roadway. The model contained a feedback loop for maintaining lane position and feedforward that utilized anticipatory roadway information available in preview (Donges, 1978; McRuer, Allen, Weir, & Klein, 1977). Perturbation techniques assessed both feedback control and feedforward attention.

Subjects' attentional allocation to preview was determined by analyzing the Fourier spectrum of their steering movements as they attempted to center a cursor on a winding roadway. This technique provided a distribution of signal-to-noise ratios indicating where and how much attention subjects allocated to different preview locations. We used this measure to test predictions of an optimal control model (Miller, 1976) that attention for a rate control system would be concentrated on preview regions closer to the vehicle and decrease to almost no attention to regions further away.

Experiment 1 demonstrated that the measurement technique could adequately capture how subjects allocated attention. We compared how the spatiotemporal shape and the relative magnitude of subjects' attentional distribution changed when they had restricted or fuller view of the upcoming roadway. We found subjects performed better with fuller view, and that they distributed their attention in a manner that was qualitatively consistent with Miller's (1976) predictions. Comparisons between different regions of restricted preview found subjects could shift their attention equally well to near or far preview regions. Experiment 2 manipulated subjects' tracking style by putting them in an error minimizing or an effort minimizing mode. We examined their attentional allocation with restricted preview and failed to find support for a generalization of Miller's (1976) model for fuller view, which predicted subjects would allocate less attention to preview when they prioritized minimizing their effort. In contrast feedback control was affected, which indicated that feedback and feedforward control may be two independent aspects of tracking control. Experiment 3 tested whether subjects' attentional distributions changed in response to the dynamics of the vehicle being controlled. Previous researchers have found that higher derivative control systems require more anticipatory information (e.g., McRuer & Jex, 1967; Miller 1976). Subjects tracked the oncoming roadway with both a rate and a sluggish lag control dynamic. We failed to find a difference in the feedforward attentional allocation between these two system dynamics, but did find a difference in feedback control. However, combining results from these experiments with those of Jagacinski, Hammond, and Rizzi (2017), who used a position control, we determined that attention is adaptive to control dynamics and susceptible to task-relevant distractions.

Overall, these results suggest that feedforward attention and feedback control contributed independently to tracking. Feedback control was more sensitively adjusted by subjects than feedforward attention. We showed that attention can be assessed from movement patterns, and that action has a strong influence on how attention is engaged during different driving conditions.

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Publications

Jagacinski, R. J., Hammond, G. M., & Rizzi, E. (2017). Measuring memory and attention to preview in motion. *Human Factors*, *59*, 796 – 810.

Jagacinski, R. J., Rizzi, E., Kim, T. H., Lavender, S. A., Speller, L. F., & Klapp, S. T. (2016). Parallel streams versus integrated timing in multilimb pattern generation: A test of Korte's Third Law. *Journal of Experimental Psychology: Human Perception and Performance*, *42*, 1703-1715.

Fields of Study

Major Field: Psychology

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Driving is a complex task that many people successfully perform on a daily basis. One of the more difficult aspects of this skill is knowing which parts of the upcoming road the driver should attend to negotiate incoming turns. More challenging still is how a driver accomplishes this when their view of the road is partially or fully obscured, such as driving at night or in a fog. Characterizing how attention plays a vital role in drivers' steering movements can provide insight to the cognitive mechanisms that make it possible for humans to adapt to the various circumstances in vehicular control.

Dynamic models for steering control describe the process as a combination of the controller (i.e., driver) and the plant (i.e., vehicle) in order to understand the overall response of the system (driver + vehicle) (Figure 1). The typical system model requires two components to achieve adequate control (e.g., Donges, 1978, McRuer, Allen, Weir, & Klein, 1977). One is a feedback loop that maintains the vehicle in the center of the roadway by nulling lateral position error. This error is generated when the vehicle drifts from the center of its lane. The second aspect of the process is a feedforward component that responds to future roadway. This information allows the system to anticipate upcoming steering movements (Sheridan, 1966; Wierwille, Gagné, & Knight, 1967). The question we wish to investigate is which parts of the upcoming roadway are most informative to the task, and how does attention allocation by the controller play a role in effective feedforward control? We also investigate how various task manipulations affect both feedforward and feedback control.

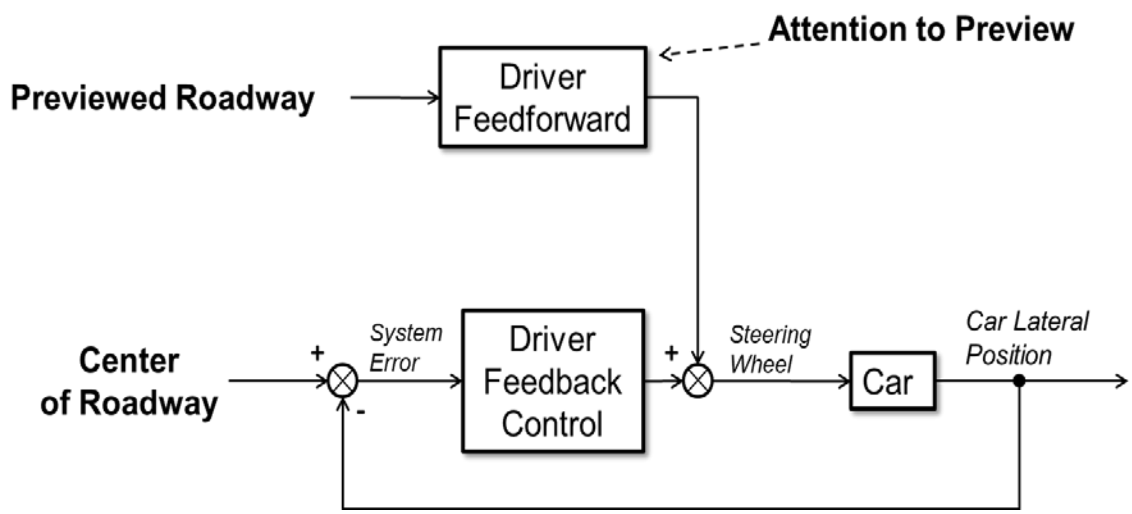


Figure 1. A typical control model of driving describing the overall system (driver + vehicle) as both on error nulling feedback loop that responds to lateral position error and anticipatory feedforward control that responds to upcoming previewed roadway.

Attention and Driving

Previous researchers have theorized about what aspects of the preview drivers might attend. One of the main debates is whether drivers should focus on a single discrete future roadway location, multiple discrete future locations, or distribute their attention across multiple regions (Jagacinski, Hammond, & Rizzi, 2017). Some researchers have used classical control theory to argue for a single point of attentional allocation for feedforward control. One such model proposes that drivers may focus their attention one reaction time into the future so that when the driver finally responds, their vehicle's movements would perfectly coincide with the arrival of the roadway (Hess, 1987). Land and Horwood (1995), however, conducted a series of studies in which they tested how various future regions in the roadway affected car driving performance. Land and Horwood tested subjects in driving conditions with full view, a single discrete location, and two discrete locations of the roadway display in a simulated driving task. Their results demonstrated that driving performance with two discrete locations is indistinguishable from driving with full view. Driver performance in the single discrete location condition was always worse than the other two conditions unless the vehicle was moving very slowly. When the single visible part of the road was closest to the vehicle's front, they described driver performance as being unstable and jerky, whereas when the single visible region was further from the vehicle, performance was smoother, but lane keeping performance suffered (Land & Horwood, 1995). They argued that drivers only require two regions of previewed roadway for successful driving. One location informs the feedback loop by focusing on more immediate previewed roadway. This information is used by the system to nullify lane drifting. The second region of attention was found to be further ahead on the road. The information from this region was used for the feedforward control aspect of driving.

Land and Horwood’s (1995) results agree with a previous model from Donges (1978) that suggested drivers require two attentional locations for adequate performance. Their study estimated that the anticipatory region was approximately 0.85 s into the future. Interestingly, this time frame into the future was always the same regardless of how fast the vehicle was going. This result may suggest that this region may be specified based on the time it takes the human-plus-vehicle system to process information entering the feedforward control loop.

It is relevant to note that in Land and Horwood’s study subjects were still able to control the vehicle when their preview was limited to a single discrete location near the vehicle. A situation like this might be similar to driving in fog where preview information is limited. Under these circumstances the driver can switch control away from the feedforward aspect of the task and perform it entirely using feedback control, though performance may not be as good as when more preview information is available. The authors noted that performance for the single discrete condition was still comparable to full view performance if the vehicle was moving slowly. This means that if error nulling does not need to occur rapidly, drivers could accomplish the task of steering their vehicle without preview information.

In contrast to Land and Horwood (1995), Miller (1976) and Sharp (2005) used optimal control theory to make similar predictions about how a driver's attention would be allocated to preview. They theorized that attention would not be limited to one or two locations, but rather distributed across various regions in the previewed roadway. The distribution of attention might not weight all regions equally, but rather emphasize some regions more than others. The weighting of these regions would depend on the dynamic characteristics of the vehicle being controlled, and on a tradeoff of the driver's emphasis on minimizing mean-squared lateral position error and mean-squared control movement. Lateral position error is a measurement of task accuracy, while mean-squared control movement is a measure of effort. The present experiment used a measurement technique capable of distinguishing the two hypotheses about attention allocation while driving.

Attention and Action

Attention in this task was investigated in the context of action. Studies have shown that the two may be explicitly linked and that investigating either in the absence of the other may misrepresent the true nature of both (Pratt, Taylor, & Gozli, 2015). The task one is doing strongly influences what one must attend to, and similarly attention in a task will shape the way an action is executed.

For example, in a study by Welsh and Pratt (2008) subjects had to find a target in a display based on whether they knew the target would onset or offset from the display. During their trial a distractor was set to be the opposite of the target stimulus, e.g., if the target was an offset stimulus, the distractor would be an onset stimulus. Subjects identified the target by either performing a simple key-press action or a point-and-reach response. The study found that for simple key-press responses attention was sensitive to distractors that were both onset or offset stimuli. However, if subjects performed a point-and-reach response only onset stimuli captured attention during the action. Therefore, the act of reaching was only sensitive to information that was present during the reach, and attention was only influenced by stimuli that were relevant to that action (Welsh & Pratt, 2008; Pratt, Talyor, & Gozli, 2015).

Driving on a roadway can be viewed as an on ongoing action process in which the attention–action loop might be constantly engaged with the stimuli in the environment. For example, many studies have suggested that attention – as measured by gaze allocation – influences steering movements. Specifically, drivers have a tendency to steer in the direction of where they are looking even if it is away from the path they are trying to maintain (Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Cooper, Medeiros-Ward, & Strayer, 2013; Strayer, 2016). This tight coupling between gaze – which some researchers utilize as a measure of attention – and steering is an example of the interdependence between attention and action.

Another way to think about this relationship is that attention to the roadway depends on the required actions the driver will take. If the driver is maintaining the vehicle on a straight roadway, this would require little attentional effort and therefore, not as much anticipatory information to accomplish it. In fact, some studies have found that lane keeping under high cognitive load is accomplished more successfully than when under low cognitive load (Cooper, Medieros-Ward, & Strayer 2013). Results from these studies have been interpreted as evidence that during driving there is a hierarchical control system in which some aspects of the driving task are automated (e.g., lane keeping), requiring minimal attention and active control, while other parts require more attention to achieve (e.g., driving on a very winding road) (Medeiros-Ward, Cooper, & Strayer, 2014; Strayer 2016). Medeiros-Ward et al. (2014) noted that the automated component of driving functioned in familiar and predictable environments, whereas the attention-requiring component was activated in unfamiliar or unpredictable situations. If a driver attempted to apply too much control to the automated aspects of their driving, they may actually become more variable in their performance (Medeiros-Ward, Cooper, & Strayer, 2014).

The demands of the driving environment influence whether a driver can engage in either automated or attention-demanding processes. For example, if drivers need to negotiate an upcoming turn, they shift their gaze to the upcoming road bend 1 s to 3 s prior to entering it and tend to focus their eyes on the road edge near a tangent point of the roadway (Land & Lee, 1994; Land, 1998). This is presumably an engagement of a directed process which requires the driver to allocate attention to the appropriate visual region for successful control. In contrast less demanding lane keeping has been considered by most researchers an automated process requiring minimal attentional control, presumably freeing-up attentional resources that the driver can use for other relevant tasks (Kahneman 2011; Strayer, 2016).

These studies, among many others, serve as evidence that when studying attention during driving behavior it should be done in the context of action. The action the driver is performing of either managing a simple roadway or negotiating snaking turns influences which stimuli in the environment become relevant to the task, which stimuli are attended or ignored, and how attention is allocated to both roadway and control aspects of driving.

Feedback Control during Driving

Dynamic models of driving include a feedback loop in their description of the behavior. The feedback loop responds to the error signal that is generated when the vehicle drifts out of the target position the driver is trying to maintain, typically the center of a roadway or lane (Figure 1). Feedback loops operates on the error signal, therefore, if no error signal is generated the feedback loop has nothing to do. The effectiveness of the feedforward control can therefore influence the need of feedback control in a system that includes both.

McRuer and Jex (1967) described this feedback system including the person and the vehicle as being composed of an integrator, a gain (K), and a time delay (τ). If we consider the roadway as a complex combination of sinusoidal inputs, the gain is the bandwidth of frequencies belonging to the roadway at which the human is effective correcting errors. The gain also determines how quickly the system corrects those errors. Theoretically, if the gain were infinitely high the system would respond instantaneously to error (Jagacinski & Flach, 2003). However, when a system includes a time delay, as it does in McRuer and Jex’s model, gains that are too high can cause oscillatory behavior that could result in system instability. This is because time delays in these models represent the processing time for translating error into appropriate corrective movements. This means in a tracking system with a time delay, steering responses to the roadway input signal might not temporally align with the actual input. Therefore, if the system is overly responsive to errors it may actually produce worse performance by overcompensating for small deviations in the input signal. Different combinations of gains and time delays determine how effectively the system will operate (e.g, Jagacinski & Flach, 2003).

Because the feedback system responds to error, it is sensitive to any aspect of the driving environment that could increase the error in system. It can even be influenced by the performance goals of the driver. For example, D.C. Miller (1965) found a trained subject tracking a moving target with a joystick could change his behavior to meet specified error and effort performance criteria. These changes in tracking influenced the gains they utilized in their feedback loop. It is important to investigate what other aspects of the driving environment influence the feedback loop, and whether these influences affect the feedback control system independently from feedforward control.

In the following series of experiments we investigate both feedback and feedforward aspects of control during tracking. We attempt to distinguish how each of these control systems is influence by characteristics of the task environment, the controller, and dynamics.

Chapter 2: Experiment 1A - Effect of the Amount of Previewed Roadway on Attentional Allocation

Our goal in this experiment was to investigate drivers' attentional allocation to the roadway in a simplified simulated environment. Previous studies have looked at attention in driving using measurements such as eye-tracking (Land & Lee, 1994; Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Cooper, Medieros-Ward, & Strayer 2013). However, as Land (1998) notes, it is possible for drivers to direct their attention to areas in the periphery of their vision without actually directing their gaze to it. Therefore, in our study we introduced a measurement technique that used participants' steering movements to determine how attention was directed in the feedforward component of their driving (Johnson & Phatak, 1990).

We used this method to test Miller's (1976) predictions that attention to a previewed roadway would be distributed across multiple close preview regions rather than the full range of preview available. This prediction would still require that subjects attend multiple sources of roadway information simultaneously. Experiments on attention have found both failures and successes of the attentional system monitoring multiple sources of perceptual information. For example, one study found that when subjects were asked to visually track moving objects in a display, the number of objects they could track depended on the speed of the moving objects and the spacing between the target and non-target objects (Alvarez & Franconeri, 2007). This study suggested that task demands tapped into an attentional resource pool that determined how many objects could be successfully tracked. Harder tasks demanded more attentional resource, which limited the number of moving targets that could be tracked simultaneously. Kahneman (1973) described this as a capacity limit on attention which is adjusted by how much effort an individual must exert to complete a task. The more demanding the task, the more attentional effort is required. However, this attentional resource is limited. Processing highly demanding perceptual stimuli would leave little attentional resources for processing any additional stimuli in parallel. Dividing attention would be possible in tasks that are not very demanding (Kahneman, 1973, p. 148).

If subjects do distribute their attention when full preview is available, could subjects attend to preview as successfully if we restricted the amount of preview available? Dividing attention to multiple sources of information is typically considered the more difficult task (Kahneman, 1973), so in addition to investigating attention to relatively full roadway preview, we compared differences between attention and performance in full and restricted preview conditions.

Hypotheses

Our main goal in this study was to be able to characterize cognitive aspects of human performance on a tracking/driving task through participants' behavioral response.

Specifically, could we determine the shape of their attentional allocation on a previewed roadway from their steering movements? The following hypotheses were tested:

(1) We predicted our measurement technique would be sensitive enough to capture differences in how participants attended to the roadway in this task.

(2) We expected our measurement technique would be able to capture differences in attentional signal in response to changes to the roadway preview. We tested the effects of a restricted slit view versus full view of the roadway preview up to 1.0 s. We predicted that when participants were restricted to focus their attention to a single spatial region in the display, they would allocate more attention to that region than if attention had been divided across multiple preview regions. We hypothesized that dividing attention would distribute subjects' attentional capacity across the preview regions being attended, whereas the slit view condition would concentrate attention in one area (Kahneman, 1973). Furthermore, we predicted higher maximum attention in the restricted preview region than if subjects' attention was distributed among various preview regions.

(3) We tested whether differences in attentional distributions had any functional effect on participants' performances in the task. Some researchers have argued that adequate performance may only require attention to one or two discrete locations in the visual display (Hess, 1987; Land, 1998), while other researchers have used optimal control theory to calculate a weighted distribution of attention across near preview regions (Miller, 1976; Sharp,

2005). We predicted that participants would show better performance when their attention was spatially distributed on a full roadway display.

(4) The progression-regression hypothesis (Fitts, Bahrick, Briggs, & Noble, 1959; Fuchs, 1962) predicts that as individuals become more skilled at a task they attune to higher derivatives of the signal essential to their task performance, e.g., velocity and acceleration characteristics of the input signal. Velocity error in our tracking task can be thought of as a measure of how well participants match the slope of the roadway, and acceleration error relates to how well participants match the curvature of the roadway.

We investigated whether participants were attuned to these higher derivatives of the input signal in our tracking task, and whether distributed attention or focused attention to a specific region would result in better performance. We predicted that participants would benefit from distributed attentional allocation on a full display because it would be easier to perceive roadway slope and curvature information in this context than if focusing on a single restricted preview region of the display.

Method

Participants

Eight university students between the ages of 18 and 25 volunteered as part of an introductory psychology course research experience. To assess their eligibility for the study, they completed a short questionnaire and demonstrate 20/25 corrected vision on a basic eye exam. Informed consent was obtained from all participants.

Apparatus

Participants sat at a desk with a Measurement System 525 joystick constrained to a single axis. They used the joystick to manipulate the rate of lateral movement of a circular cursor on a computer display. They tried to maintain the cursor directly below a cross that indicated the center of a winding roadway. The roadway consisted of two curving lines whose lateral movement was determined by the sum of 10 sine waves. This made the roadway appear unpredictable to participants. Preview of the upcoming roadway was available to participants at 0.05 s, 0.10 s, 0.20 s, 0.30 s… to 1.00 s into the future. The sensitivity of the rate control system was set such that 2.5° of joystick rotation corresponded to 1° per second of visual angle cursor displacement.

Participants sat 26 inches (66 cm) away from the display. The vertical extent of the display was approximately 3.1° of visual angle viewed from that distance while the horizontal range of the roadway center was approximately 4.8° to the right and left (see Jagacinski, Hammond, & Rizzi, 2017). Participants could attend to all parts of the visual display without shifting their eye gaze. The display was updated at 100 Hz.

Procedure

The experiment consisted of two one-hour sessions on two separate days. Day 1 was used to familiarize participants with the procedure and to practice using the joystick system. Day 2 measurements were used for data analysis.

A day's sessions consisted of four blocks of four trials each. One type of block was a Full View control condition in which the entire roadway display was visible to participants. Participants also experienced a Slit condition, in which parts of the roadway display were hidden by gray bars whose heights were specified and whose widths covered the entire display. The two bars were placed on the display such that they formed a slit where participants could see a specific region of the roadway between 0.53 s and 0.67 s into the future. The remaining two blocks were nearly identical to the Full View and Slit block except the 10 previewed positions of the roadway display from 0.1 s to 1.0 s were each perturbed by a unique frequency sinewave (Perturbation conditions). These perturbations served as frequency labels used to determine where participants were attending on the visual roadway display. The attentional measure is discussed in detail in the next section. The four types of blocks are shown in Figure 2.

The four blocks were counterbalanced so that on Day 2 a participant would either do both Slit conditions or both Full View conditions first. Whether they would perform the control condition or the perturbation conditions first was also counterbalanced across subjects. This resulted in four unique orders of the four blocks. On Day 1, the training day, participants always did the Full View conditions before the Slit conditions to familiarize themselves with the task better. However, whether they did the control or perturbation condition first was counterbalanced on Day 1, and matched the ordering they received on Day 2.

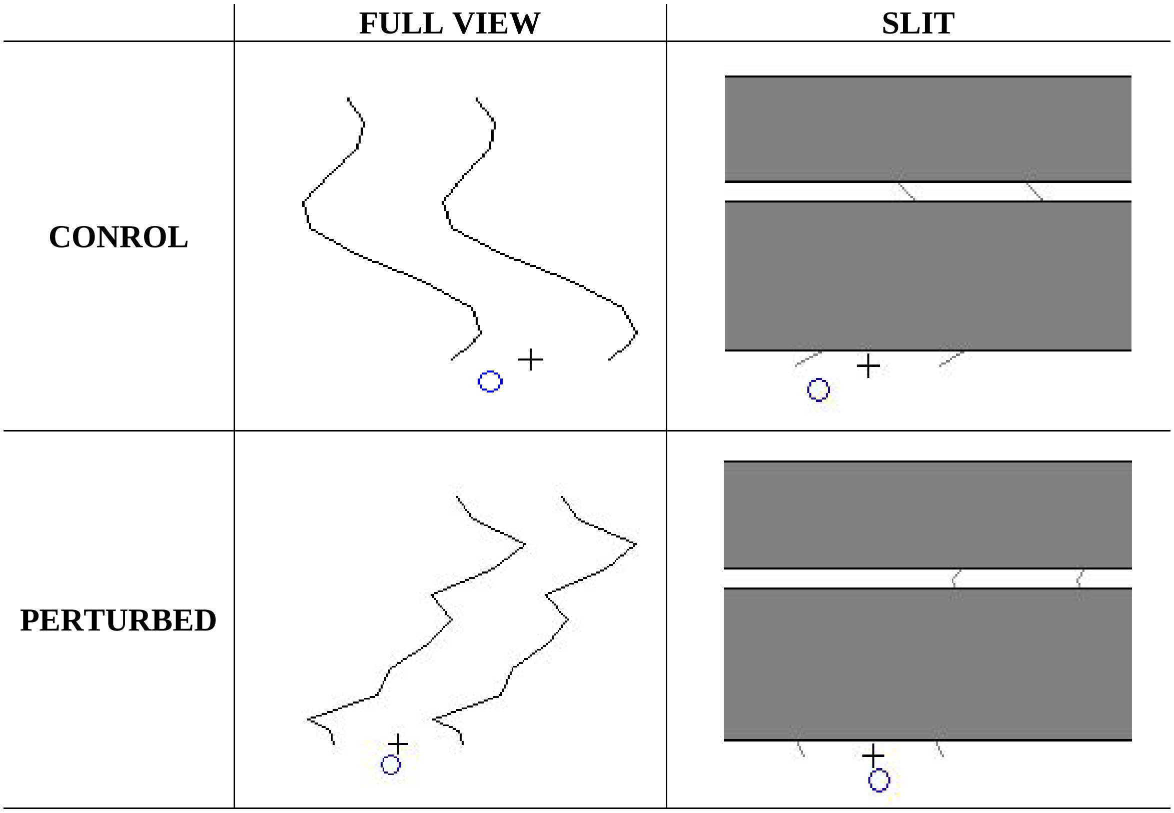


Figure 2. The four quadrants show the four conditions that participants saw during the experiment. The circular cursor was controlled by participants' joystick movements; the cross indicated the center of the roadway display. The Full View column is what the full roadway display looked like to participants. In the Slit column, gray bars were used to obscure the roadway except for a specific region that remained visible through a slit between the bars. The perturbation manipulation is shown in the bottom row. It creates the appearance of "elbows" at 10 specific future roadway positions; the elbow is present though not as obvious when the slit is over the road. The center of the slit corresponds to 0.6 s into the future.

Each trial lasted 174 s, but the first 10 s were treated as warm-up and not analyzed. In each block participants were told to maintain a circular cursor directly below a cross which indicated the center of a roadway. A block consisted of 4 trials with a 20 second break between each trial. Once a block was completed they were given feedback on their performance as the median root-mean-squared error score for that block. To keep subjects motivated they were informed that the best performing subject would be rewarded a $20 bonus at the conclusion of the study. After each block, participants were then given a 2 minute break before starting the next block.

The road's movement was determined by summing 10 sine waves whose frequencies ranged from 0.3 to 10.1 rad/s. The first six sine waves from 0.3 to 3.0 rad/s had amplitudes that were five times that of the remaining four sine waves used to specify the road. The overall lateral movement of the roadway had an approximate bandwidth of 3 rad/s, which was more challenging than a typical roadway.

Measuring Attention

Participants' distribution of attention was measured across a one-second span of oncoming roadway preview. Ten positions separated by 0.1 s into the future roadway were each perturbed by a unique sinewave in the Perturbation conditions. In essence, each future position of the road oscillated with a unique frequency. Frequencies used at each of the ten locations did not correspond to any of the sinewaves used to generate the road's lateral movement, so they functioned as observation noise that was unrelated to the actual movement of the road. We call these "frequency labels" because we could examine these frequencies in a Fourier analysis of our participants' steering performance to determine which of the ten regions on the roadway they attended. We assessed this attentional allocation by calculating a ratio between the amplitudes of these frequency labels during the Perturbation conditions and control conditions.

Presumably, during control conditions the Fourier amplitudes should be low at the labeling frequencies, simply reflecting perceptual-motor noise. This perceptual-motor noise is known as remnant, and it is uncorrelated with the roadway input frequencies. Remnant instead resembles *white noise* that randomly occurs throughout the frequency spectrum (Allen & Jex, 1972; Jagacinski & Flach, 2003, p. 223); the remnant amplitude is typically lower than the amplitudes of the input signals participants track. By measuring the frequency labels' remnant amplitude we established a baseline for its presence in participants' steering movements. Each frequency labels' amplitude baseline was compared to their amplitude during the Perturbation condition. If a participant was attending to a particular region of the display, the frequency label assigned to that region should show a larger amplitude signal relative to the baseline noise level (remnant) that it had in the control condition. We then took a ratio of the amplitude of the frequency label during a Perturbation block to that same frequency label during a control block (baseline) to create a ratio that reflected the degree to which each preview region was being attended.

The use of perturbations to understand controller behavior has been used before in simulated helicopter piloting (Johnson & Phatak, 1990). In our task, the perturbations allow us to specify attention as a signal-to-noise ratio in subjects' steering movements (see Levison, 1979). The signal in this measure is the amplitude of a frequency label during a Perturbation block versus the noise, which is that same frequency label's remnant amplitude.

Results

Attentional Distribution

If a participant was attending to a particular region in the display then we expected that region, denoted by how many second into the future it is, to have a signal-to-noise ratio above 2. This value represented a reasonable benchmark for identifying attentional signal because there is a low probability of noise reaching this value (see *Prevalence of Noise* in later section). The amount of attention allocated to a particular region of the preview can be quantitatively indexed by the magnitude of the signal-to-noise ratio for that region. Figure 3 clearly shows the location of the slit (0.6 s into the future) is the only region with a signal-to-noise ratio above 2 in the Slit condition. This result provides evidence that our measurement system can quantify attention allocation.

The first question we wanted to investigate was whether attentional allocation was different between Full View and Slit conditions. We conducted a 2 x 10 (Condition: Full View, Slit; Preview Positions: 0.1 s to 1.0 s into the future) analysis of variance on the signal-to-noise ratios. The analysis found a main effect of condition in which we measured more attentional signal during Full View conditions rather than Slit conditions, [$F(1, 7) = 24.537$, $p < 0.01$; $\bar{x}_{Full\,View} = 1.753$, $\bar{x}_{Slit} = 1.281$]. This implies that during slit conditions subjects did not simply shift their whole attentional capacity into the slit region; they attended less to the display when the slit was present. We also found an interaction [$F(9, 63) = 4.312$, $p < 0.01$] verifying that subjects were attending to roadway preview visible in the slit more so during Slit conditions versus Full View conditions.

Figure 3 shows how qualitatively different attentional allocation was in Full View conditions when compared to Slit conditions. If Full View represents what subjects typically attend to when the entire roadway preview is visible, then Figure 3 demonstrates that the Slit condition was able to force subjects to attend elsewhere. We wanted to conduct a matched pairs *t*-test to assess whether the amount of attention allocated to the 0.6 s into the future preview region was statistically different for Full View versus Slit conditions. However, we encountered two issues that complicated this analysis. Presumably, the maximum region of attention for the Slit condition would be at 0.6 s into the future, but this was not always the case. One subject's signal-to-noise maximum was at 0.5 s into the future, and another's was 0.7 s into the future, though this subject also showed comparably high signal-to-noise at 0.6 s. This suggests that subjects could pick up information about the roadway at these neighboring locations by observing the portions of the roadway lines that connected the 0.5 s and 0.6 s preview points and the 0.6 and 0.7 s preview points. The width of the slit permitted view of 1/3 of the length of the lines connecting these points. This fact does not call into question whether subjects were attending the 0.6 second region. Instead it suggests subjects attending to that position might do so by looking at the upper or lower edge of the slit rather than the exact center.

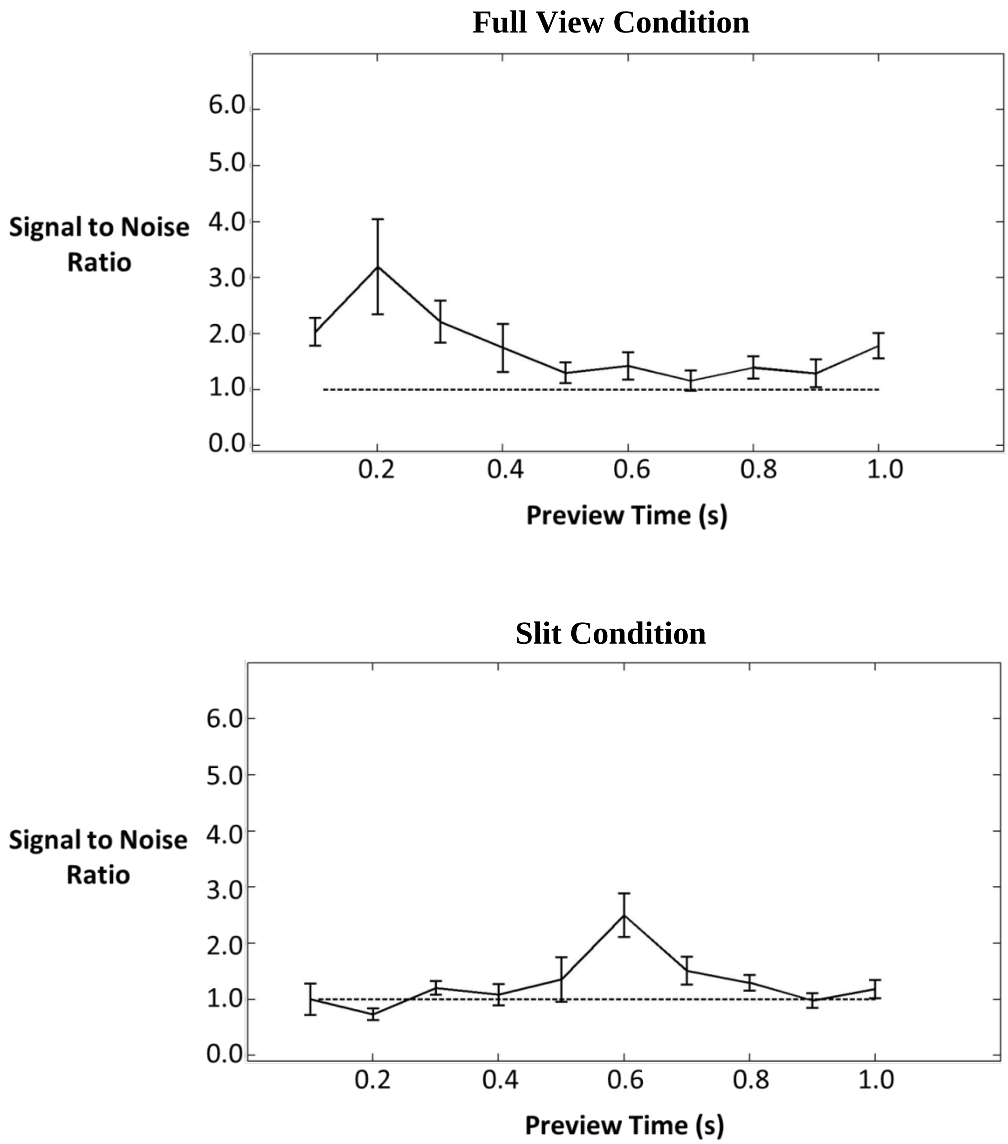


Figure 3. Average attentional allocation for 8 subjects in Full View and Slit conditions. In the Full View condition subjects placed most of their attention at roadway regions around 0.2 s into the future. In the Slit condition only preview around 0.6 s into the future was visible, and it has a high signal-to-noise ratio. The error bars represent ± 1 standard error.

To correct for that issue we determined which preview region between 0.5 s and 0.7 s each subject attended to the most during the Slit condition. We compared the signal-to-noise ratio from that preview region in the Slit condition to the signal-to-noise ratio for that same preview region in the Full View condition. However, the distribution of matched pair signal-to-noise ratios for the two conditions appeared bimodal. Some subjects clearly showed a substantial difference between Full View and Slit, while others almost none at all. This bimodality violated the normality assumption of a matched pairs *t*-test, so a nonparametric approach was used to make the comparison.

Because we expected the effect in a specific direction, we conducted a one-tailed sign test (Siegal & Castellan, 1988) that revealed there was a larger attentional allocation in the Slit condition for 7 out of 8 participants [$p < 0.04$, one-tailed]. This result indicates that the Slit condition made subjects focus on the 0.6 s preview region more than they did under the Full View condition.

We also hypothesized that the highest signal-to-noise ratio in the Slit condition would be higher than any attended region in the Full View condition, where attention might be diffuse. We tested this hypothesis by looking at the maximum signal-to-noise ratios for each subject while in the Slit and Full View conditions. In Full View conditions the maximum signal-to-noise ratio could occur anywhere in the display. We took the maximum signal-to-noise ratio from any of the 10 previewed regions during the Full View condition and compared this to the maximum signal-to-noise ratio of the 0.5 s through 0.7 s preview region in the Slit condition. A matched paired t-test failed to find evidence for our hypothesis; there was no significant difference in the maximum signal-to-noise ratio between Full View and Slit conditions [$t(7) = 2.49$, $p = 0.16$].

Tracking Performance

We tested whether having full preview of the upcoming roadway was functionally significant to tracking performance. To assess this we took the four trials in a block and calculated the root-mean-squared (RMS) error of the tracking performance for each trial. Error in each trial was equal to the input minus the output, i.e., the difference between the cursor subjects controlled and the center of the roadway:

$$RMS\ Error_i = \sqrt{\frac{\int_{t=0}^{T} (input - output)^2\, dt}{T}}; \qquad T = length\ of\ trial\ i$$

We then took the median of these four RMS error scores and used that as the measure of overall error for that block/condition.

We conducted a 2 x 2 analysis of variance on the root mean square error of tracking performance (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials). The analysis revealed a main effect of Trial Type which showed subjects performed better during control trials than with perturbations added [$F(1, 7) = 6.68$, $p < 0.04$; $\bar{x}_{control} = 0.570$, $\bar{x}_{perturbation} = 0.607$], and a main effect for Condition which found subjects exhibited less error during the Full View condition compared to the Slit condition [$F(1, 7) = 11.45$, $p < 0.02$; $\bar{x}_{Full\ View} = 0.544$, $\bar{x}_{Slit} = 0.634$]. No interactions were found. The results indicate there was a performance advantage for the Full View condition.

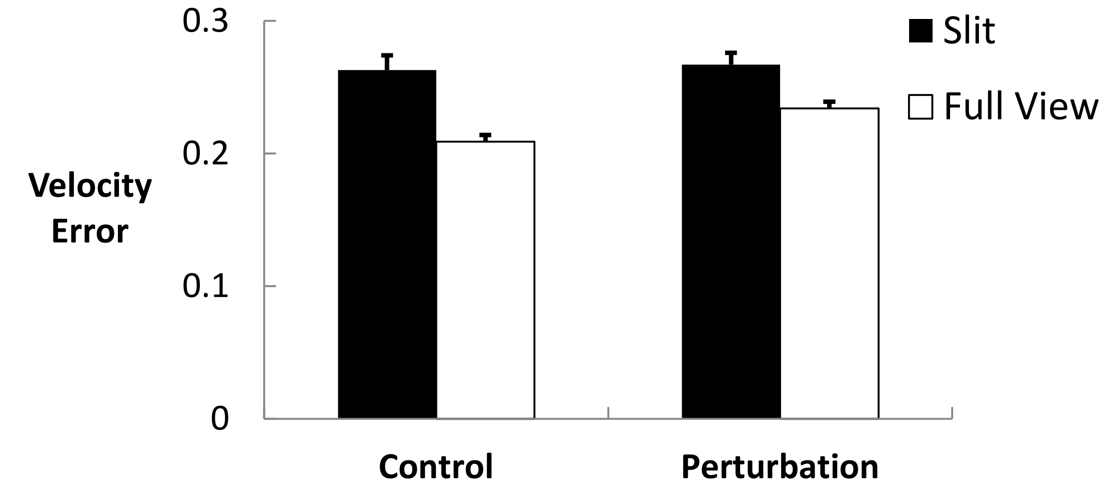
Performance was also analyzed in the frequency domain, using Position Error calculated in the frequency domain as the dependent measure. Position error is calculated from the amplitudes in the Fourier spectrum of the error signal (system input – system output) at the 10 frequencies that generated the roadway. The root mean square of the median magnitudes at each of these frequencies is a measure of Position error (Jagacinski, Hammond, & Rizzi, 2017). Position error showed a high correlation with the root-mean-squared error used in the previous analysis for both Slit conditions [r (6) = 0.78, $p < 0.03$] and Full View conditions [r (6) = 0.92, $p < 0.01$]. A 2 x 2 analysis of variance on this measure (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) revealed no main effects or interactions, though both the Condition main effect and the interaction were close to significant [$F(1, 7)_{\text{Condition}} = 4.88$, $p = 0.06$; $F(1, 7)_{\text{Interaction}} = 5.16$, $p = 0.06$].

The Progression-Regression Hypothesis (Fitts, Bahrick, Briggs, & Noble, 1959) suggested subjects in our task would become more sensitive to higher derivatives of the roadway signal as they became more experienced with the tracking task. We hypothesized that effective use of these higher derivatives would decrease in the Slit condition where it would be difficult for subjects to capture slope and roadway curvature information. We calculated each subjects' Velocity and Acceleration error in the frequency domain by taking the 10 peak amplitudes in the Position error and generating their first and second derivatives. This is done by multiplying each of those 10 peak amplitudes by their frequency for Velocity error, and frequency squared for Acceleration error.

A 2 x 2 analysis of variance on Velocity error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) revealed a main effect of Condition [$F(1, 7) = 20.05$, $p < 0.01$; $\bar{x}_{Slit} = 0.265$, $\bar{x}_{Full\ View} = 0.220$], Trial Type [$F(1, 7) = 12.63$, $p < 0.01$; $\bar{x}_{control} = 0.236$, $\bar{x}_{perturbation} = 0.251$], and an interaction [$F(1, 7) = 13.43$, $p < 0.01$]. Full View had lower velocity error than the Slit condition, and Control trials had lower velocity error than Perturbation trials. The interaction found that Full View conditions with Control trials had the lowest Velocity error of any condition by trial combination.

The 2 x 2 analysis of variance on Acceleration error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) similarly revealed a main effect of Condition [$F(1, 7) = 27.52$, $p < 0.01$; $\bar{x}_{Slit} = 2.352$, $\bar{x}_{Full\ View} = 1.984$], Trial Type [$F(1, 7) = 8.53$, $p < 0.03$; $\bar{x}_{control} = 2.111$, $\bar{x}_{perturbation} = 2.225$], and an interaction [$F(1, 7) = 10.80$, $p < 0.02$]. Again the Full View condition was superior to the Slit condition, and this difference was greater when the roadway was not perturbed. All performance results are summarized in Table 1.

(A)



(B)

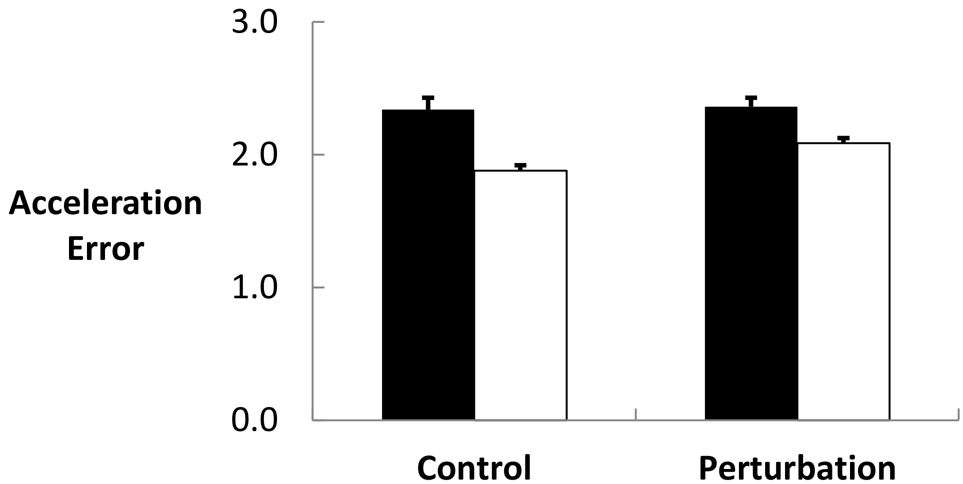


Figure 4. Velocity error (A) and Acceleration error (B) are lower with the Full View rather than Slit view display.

Performance Measure	**F statistic**	**Significance**	**Means**
Root-mean-squared Error			
Trial Type	$F(1,7) = 6.68$	$p < 0.04$	$\bar{x}_{Perturbed} = 0.607$ $\bar{x}_{Control} = 0.570$
Condition	$F(1,7) = 11.45$	$p < 0.02$	$\bar{x}_{Full\ View} = 0.544$ $\bar{x}_{Slit} = 0.634$
Interaction	$F(1,7) = 2.63$	*n.s.*	$\bar{x}_{Full,\ Perturbed} = 0.571$ $\bar{x}_{Slit,\ Perturbed} = 0.643$ $\bar{x}_{Full,\ Control} = 0.516$ $\bar{x}_{Slit,\ Control} = 0.624$
Position Error			
Trial Type	$F(1,7) = 3.36$	*n.s.*	$\bar{x}_{Perturbed} = 0.039$ $\bar{x}_{Control} = 0.037$
Condition	$F(1,7) = 4.89$	*n.s.*	$\bar{x}_{Full\ View} = 0.034$ $\bar{x}_{Slit} = 0.042$
Interaction	$F(1,7) = 5.16$	*n.s.*	$\bar{x}_{Full,\ Perturbed} = 0.036$ $\bar{x}_{Slit,\ Perturbed} = 0.042$ $\bar{x}_{Full,\ Control} = 0.032$ $\bar{x}_{Slit,\ Control} = 0.042$
Velocity Error			
Trial Type	$F(1,7) = 12.63$	$p < 0.01$	$\bar{x}_{Perturbed} = 0.251$ $\bar{x}_{Control} = 0.236$
Condition	$F(1,7) = 20.05$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.222$ $\bar{x}_{Slit} = 0.265$
Interaction	$F(1,7) = 13.43$	$p < 0.01$	$\bar{x}_{Full,\ Perturbed} = 0.209$ $\bar{x}_{Slit,\ Perturbed} = 0.267$ $\bar{x}_{Full,\ Control} = 0.234$ $\bar{x}_{Slit,\ Control} = 0.263$
Acceleration Error			
Trial Type	$F(1,7) = 8.53$	$p < 0.03$	$\bar{x}_{Perturbed} = 2.225$ $\bar{x}_{Control} = 2.111$
Condition	$F(1,7) = 27.52$	$p < 0.01$	$\bar{x}_{Full\ View} = 1.984$ $\bar{x}_{Slit} = 2.352$
Interaction	$F(1,7) = 10.80$	$p < 0.02$	$\bar{x}_{Full,\ Perturbed} = 2.087$ $\bar{x}_{Slit,\ Perturbed} = 2.363$ $\bar{x}_{Full,\ Control} = 1.880$ $\bar{x}_{Slit,\ Control} = 2.341$

Table 1. Tracking performance measures for Experiment 1A. "*n.s.*" indicates not significant.

Experiment 1A Discussion

The data in Figure 3 showed strong evidence that the measurement system can capture how subjects are attending to the roadway. Specifically, the Slit condition data demonstrated that the signal-to-noise ratio peaked around the 0.6 s preview region when no other previewed regions were available. This suggested subjects shifted their attention to the only future roadway information that was available. Even so, subjects did not necessarily focus on the central portion of the slit region. Two subjects showed peak attention at neighboring previewed locations. One subject seemed to be attending at the 0.5 s preview region, and the other subject was focused on both the 0.6 s and 0.7 s preview regions. This suggests that these subjects focused on the lower and upper edge of the slit, respectively, which gave them some information about the neighboring concealed preview region. The 10 preview locations are connected by straight lines to form the roadway. The line above or below a specific preview time therefore carried information about neighboring preview times on the roadway. Depending on whether subjects focus on the upper or lower edge of the slit they may add movements to their joystick that correspond to either one or both of those preview regions.

The upper part of Figure 3 provides further evidence that when full preview was available subjects distributed their attention in regions close to the cursor they were controlling (Miller, 1976; Jagacinski, Hammond, & Rizzi, 2017). We can also see that subjects appeared to pay less attention to preview regions further away. This means the slit was effective in making subjects allocate attention to a region they normally did not attend. Our analysis established that preview at 0.5 s to 0.7 s into the future was less attended during Full View conditions when compared to Slit conditions. However, when looking at subjects individually, it appeared that some subjects did not attend to the slit region as strongly as others. It is possible that for these subjects the location of the slit was counter to their own attentional strategies. If that were the case, then these individuals could be adjusting their tracking performance so that it relied less on anticipatory information. Since tracking is composed of both feedforward and feedback components, they might have no longer emphasized the feedforward aspect of control and instead focused directly on the cursor and central cross to track the roadway via feedback control. However, this approach is likely to be more error prone than utilizing the anticipatory information available in the display.

Counter to our predictions subjects did not demonstrate higher maximum attention to the roadway in the Slit conditions. We hypothesized that if attention was distributed across multiple preview regions, then the signal-to-noise ratio of those regions, a measure of attentional amplitude, would be lower than if attention was focused a single region. Our analyses revealed no difference between the two conditions in terms of maximum attentional amplitude.

Our manipulation was able to demonstrate the flexibility of subjects' attentional allocation, but tracking performance in the Slit condition was not as accurate as in the Full View condition. We assessed subjects using the root-mean-squared error of their performance. Our measurement technique required that subjects track the roadway both with and without visual perturbations. Not surprisingly, the perturbations affected subject performance in a negative way because it distorted the quality of visual information relevant to their tracking. It introduced noise into their joystick movements when they attended to these visual disturbances.

Analysis of their root-mean-squared errors also revealed that subjects performed worse in the Slit condition when compared to the Full View condition. There are a number of possible explanations for this result. The Slit region preview might not be informative enough or too far into the future to be beneficial. We found that subjects generally attended less to preview overall when in the Slit condition, so subjects may have actually relied on less anticipatory information during the Slit condition than they would during the Full View condition. This approach to tracking is more error prone. It is also possible that subjects may not have become experienced enough with the task to make full use of the more distant preview regions and that these regions may become more beneficial to their feedforward control with practice.

Additionally, we analyzed performance using Position error as a measure of performance. This measure assessed subjects' steering movements in the frequency domain. Using a Fourier analysis we compared how well they minimized the difference between the input (center of the roadway) and the output (cursor position relative to center of the roadway). This measure of tracking performance looked at how well subjects matched the amplitudes of the 10 frequencies that made up the roadway. However, this analysis was only marginally significant [$p = 0.06$], even though the results were in the same direction as the analysis of variance on root-mean-squared error in the time domain.

A full roadway display may have another benefit to driver performance according to Fitts et al. (1959). If participants are sensitive to derivatives of the input signal (i.e., velocity and acceleration), their tracking performance accuracy and smoothness increases. Experienced participants learn to utilize this information with practice (Fuchs, 1962). This information is available to participants in the Full View condition, but may be less accessible to them in the Slit condition. Our results demonstrated that subjects had higher Acceleration and Velocity errors in the Slit condition than in the Full View condition. Information about roadway curvature, which is related to their Acceleration error, cannot be easily determined from the restricted preview display. Velocity, which is related to road slant, could still be assessed in the Slit condition but may be degraded by the limited view as well. As subjects became more experienced with the task, they may have relied more on these sources of information to improve the quality of their tracking during Full View conditions.

Overall, this first experiment demonstrated both the effectiveness of our measurement system and revealed some interesting insights to subjects' attention allocation during tracking. Anticipatory information is beneficial to performance, but subjects do not attend to all preview positions equally. Previewed roadway that is too distant into the future may not be beneficial to task performance; subjects focus on more immediate information. However, attention is flexible enough that subjects could be made to look at regions that they do not normally emphasize by using a slit to make one region the only preview information available to them. This Slit did, however, diminish subjects' tracking performance. Full View may provide more information that is relevant to the smoothness of their tracking, which when removed may hinder more experienced trackers.

Chapter 3: Experiment 1B - Moving the Slit Location Closer to the Cursor

Subjects in Experiment 1A did not show as much attention allocation to the Slit region as we expected. It is unclear whether performance differences between the Full View and Slit conditions was due to due to the slit, or a reduction in the use of feedforward information due to the location of the slit being too distant a region into the future. To address this issue we reran the study but relocated the Slit to a preview region that subjects might consider more informative. Figure 3 showed peak attention allocation occurred at about 0.2 s into the future in the Full View condition. We tested a new set of subjects with the slit centered at 0.3 s into the future to see if attention and performance change when the slit is located closer to where subjects are typically attending in the Full View condition. No other changes were made to the procedure besides relocating the slit region.

Method

Participants

Eight additional university students between the ages of 18 and 25 volunteered as part of an introductory psychology course research experience. Their eligibility for the study was determined by completing a short questionnaire and demonstrating 20/25 corrected vision on a basic eye exam. Informed consent was obtained from all participants.

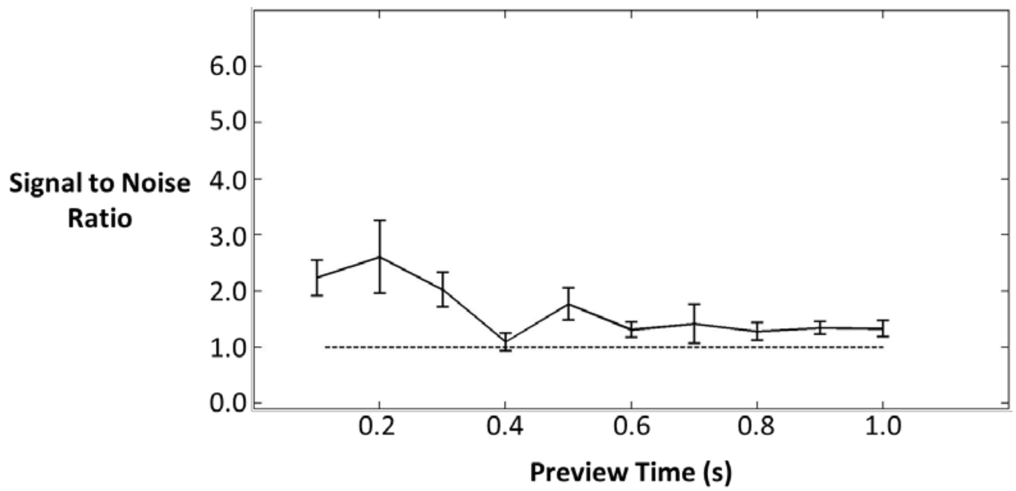
Results

Attentional Distribution

Just as in Experiment 1A, subjects showed two qualitatively different attention allocation patterns. Figure 5 shows that in the Full View condition subjects emphasized the first three preview points much the same way they did in Experiment 1A. The attentional allocation in the Full View condition also looks very different from the Slit condition. A 2 x 10 analysis of variance on the signal-to-noise ratios (Condition: Full View, Slit; Preview Positions: 0.1 s to 1.0 s into the future) revealed a main effect of Preview Position [$F(9, 63) = 13.34$, $p < 0.01$] and an interaction [$F(9, 63) = 8.74$, $p < 0.01$]. The interaction replicates the finding from Experiment 1A that subjects were attending to roadway preview differently in the two conditions.

In Figure 5 it is evident the interaction was due to the large signal-to-noise ratio at 0.3 s in the Slit condition. Unlike Experiment 1A, all subjects successfully allocated a high degree of attention to the slit region. The distribution of matched pair signal-to-noise ratios for the 0.3 s region between Full View and Slit conditions did not appear to violate any normality assumptions. Therefore, we conducted a matched pairs *t*-test on the signal-to-noise ratios. The results show a statistically significant difference demonstrating subjects attended 0.3 s into the future much more in the Slit condition than in the Full View condition [$t(7) = 4.57$, $p < 0.01$; $\bar{x}_{Slit} = 4.916$, $\bar{x}_{Full\,View} = 2.023$].

Full View Condition



Slit Condition

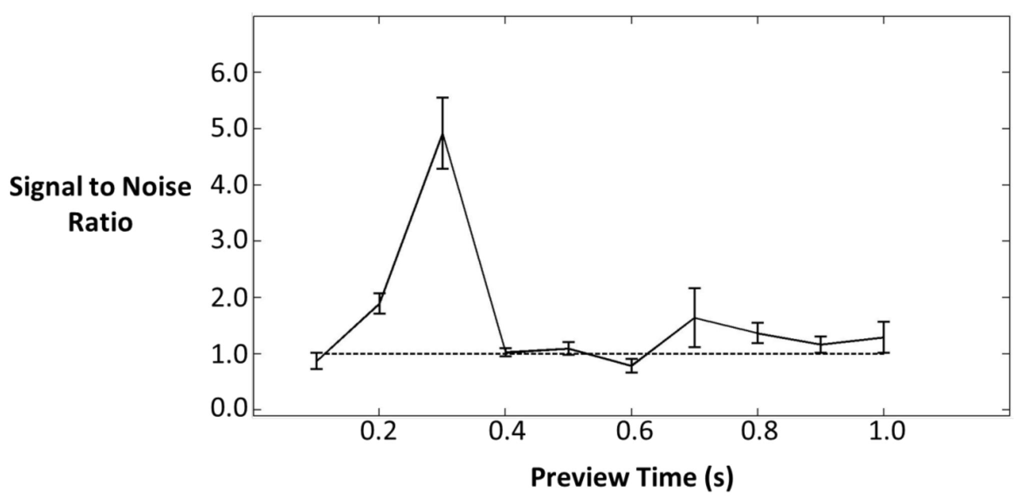


Figure 5. Average attentional allocation for 8 subjects in Full View and Slit conditions. In the Full View condition subjects distributed their attention across roadway regions from 0.1 s to 0.3 s into the future. In the Slit condition 0.3 s into the future shows a clear peak indicating focused attention in the region. The error bars represent ±1 standard error.

We tested our second hypothesis that subjects in the Slit condition would have higher maximum signal-to-noise ratios compared to the Full View conditions where attention is more diffuse. A matched pairs *t*-test found that subjects exhibited a higher maximum attentional signal in the Slit condition [$t(7) = 3.71$, $p < 0.01$; $\bar{x}_{Max\ Slit} = 4.916$, $\bar{x}_{Max\ Full\ View} = 3.1575$].

Tracking Performance

We tested whether tracking performance was different for Slit and Full View conditions. A 2 x 2 analysis of variance on root-mean-squared error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) revealed a main effect for Trial Type indicting again that the perturbation trials did result in poorer tracking [$F(1, 7) = 32.461$, $p < 0.01$; $\bar{x}_{Perturbed} = 0.785$, $\bar{x}_{Control} = 0.698$]. A main effect for Condition indicated less tracking error in the Full View condition [$F(1, 7) = 14.129$, $p < 0.01$; $\bar{x}_{Full\ View} = 0.666$, $\bar{x}_{Slit} = 0.817$]. There was no interaction.

We analyzed performance in the frequency domain by using Position error as in Experiment 1A. In this experiment Position error was still significantly correlated with root-mean-squared error for both Slit conditions [$r\ (6) = 0.87$, $p < 0.01$] and Full View conditions [$r\ (6) = 0.76$, $p < 0.01$]. A 2 x 2 analysis of variance (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) found a main effect for Trial Type [$F(1, 7) = 9.37$, $p < 0.02$; $\bar{x}_{Perturbed} = 0.057$, $\bar{x}_{Control} = 0.050$], a main effect for Condition [$F(1, 7) = 25.02$, $p < 0.01$; $\bar{x}_{Full\ View} = 0.044$, $\bar{x}_{Slit} = 0.063$], and no interaction. These findings match those we found for root-mean-squared error. It demonstrates that subjects tracked better in the Full View condition.

Performance Measure	**F statistic**	**Significance**	**Means**	
Root-mean-squared Error				
Trial Type	$F(1,7) = 32.46$	$p < 0.01$	$\bar{x}_{Perturbed} = 0.785$	$\bar{x}_{Control} = 0.698$
Condition	$F(1,7) = 14.13$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.666$	$\bar{x}_{Slit} = 0.817$
Interaction	$F(1,7) = 2.91$	*n.s.*	$\bar{x}_{Full,\ Perturbed} = 0.731$	$\bar{x}_{Slit,\ Perturbed} = 0.840$
			$\bar{x}_{Full,\ Control} = 0.601$	$\bar{x}_{Slit,\ Control} = 0.795$
Position Error				
Trial Type	$F(1,7) = 9.37$	$p < 0.02$	$\bar{x}_{Perturbed} = 0.057$	$\bar{x}_{Control} = 0.05$
Condition	$F(1,7) = 25.02$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.044$	$\bar{x}_{Slit} = 0.063$
Interaction	$F(1,7) = 0.21$	*n.s.*	$\bar{x}_{Full,\ Perturbed} = 0.047$	$\bar{x}_{Slit,\ Perturbed} = 0.066$
			$\bar{x}_{Full,\ Control} = 0.041$	$\bar{x}_{Slit,\ Control} = 0.059$
Velocity Error				
Trial Type	$F(1,7) = 6.44$	$p < 0.04$	$\bar{x}_{Perturbed} = 0.269$	$\bar{x}_{Control} = 0.250$
Condition	$F(1,7) = 16.36$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.239$	$\bar{x}_{Slit} = 0.279$
Interaction	$F(1,7) = 0.19$	*n.s.*	$\bar{x}_{Full,\ Perturbed} = 0.250$	$\bar{x}_{Slit,\ Perturbed} = 0.287$
			$\bar{x}_{Full,\ Control} = 0.229$	$\bar{x}_{Slit,\ Control} = 0.271$
Acceleration Error				
Trial Type	$F(1,7) = 4.00$	*n.s.*	$\bar{x}_{Perturbed} = 2.131$	$\bar{x}_{Control} = 2.012$
Condition	$F(1,7) = 7.81$	$p < 0.03$	$\bar{x}_{Full\ View} = 2.009$	$\bar{x}_{Slit} = 2.134$
Interaction	$F(1,7) = 0.19$	*n.s.*	$\bar{x}_{Full,\ Perturbed} = 2.082$	$\bar{x}_{Slit,\ Perturbed} = 2.179$
			$\bar{x}_{Full,\ Control} = 1.937$	$\bar{x}_{Slit,\ Control} = 2.088$

Table 2. Tracking performance measures for Experiment 1B. "*n.s.*" indicates not significant.

The Progression Regression Hypothesis also appears to be well supported by analyses on the Velocity and Acceleration error; higher derivatives of Position error reflect subjects' smoothness of tracking. A 2 x 2 analysis of variance was conducted on both of these measures of performance (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials). Velocity error revealed a main effect for Trial Type and Condition, while Acceleration error revealed a main effect only for Condition. Both analyses showed no interactions. They both demonstrate smoother tracking in the Full View condition compared to the Slit condition (Table 2).

Comparison of Experiment 1A and Experiment 1B

We compared subjects' attentional allocation in the two studies. In the Full View conditions in Experiment 1A and 1B, the shape of subjects' attentional allocation is very similar (Figure 6). A 2 x 10 analysis of variance (Experiment:1A, 1B; Preview Positions: 0.1 s to 1.0 s into the future) found a main effect of Preview position; subjects had higher signal-to-noise ratios in the preview regions 0.1 s to 0.3 s [$F(9, 126) = 5.09$, $p < 0.01$]. A main effect of Experiment indicated higher average signal-to-noise ratios in Experiment 1A [$F(1, 1) = 345.94$, $p < 0.01$; $\bar{x}_{Exp\ 1A} = 1.753,\ \bar{x}_{Exp\ 1B} = 1.641$], but no interaction. The lack of interaction confirms subjects distributed their attention similarly in Full View conditions for both Experiments 1A and 1B.

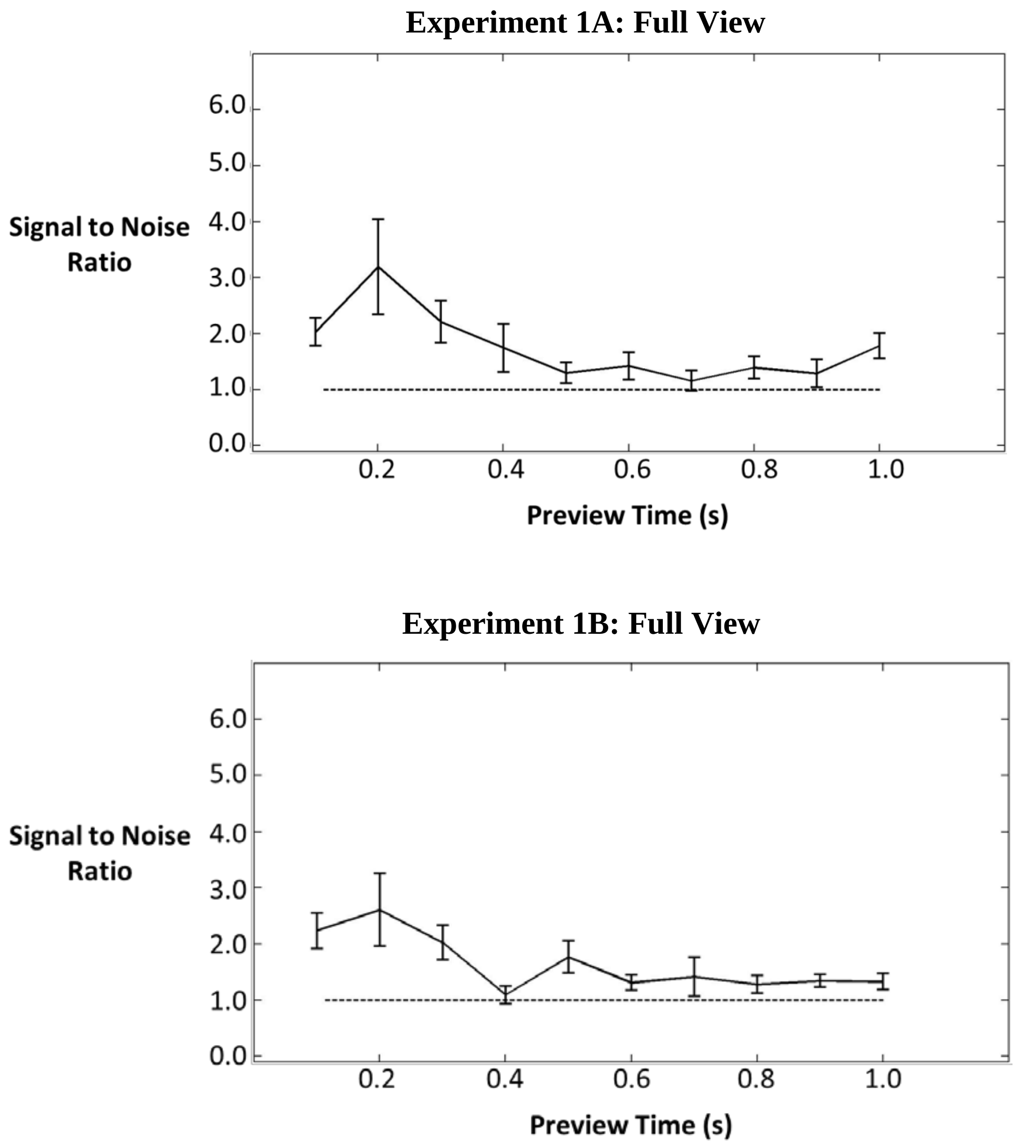


Figure 6. Average attentional allocation for 8 subjects in Full View conditions for Experiments 1A and 1B. Attentional distribution in both studies shows a similar emphasis on preview regions between 0.1 s and 0.3 s into the future. The error bars represent ±1 standard error.

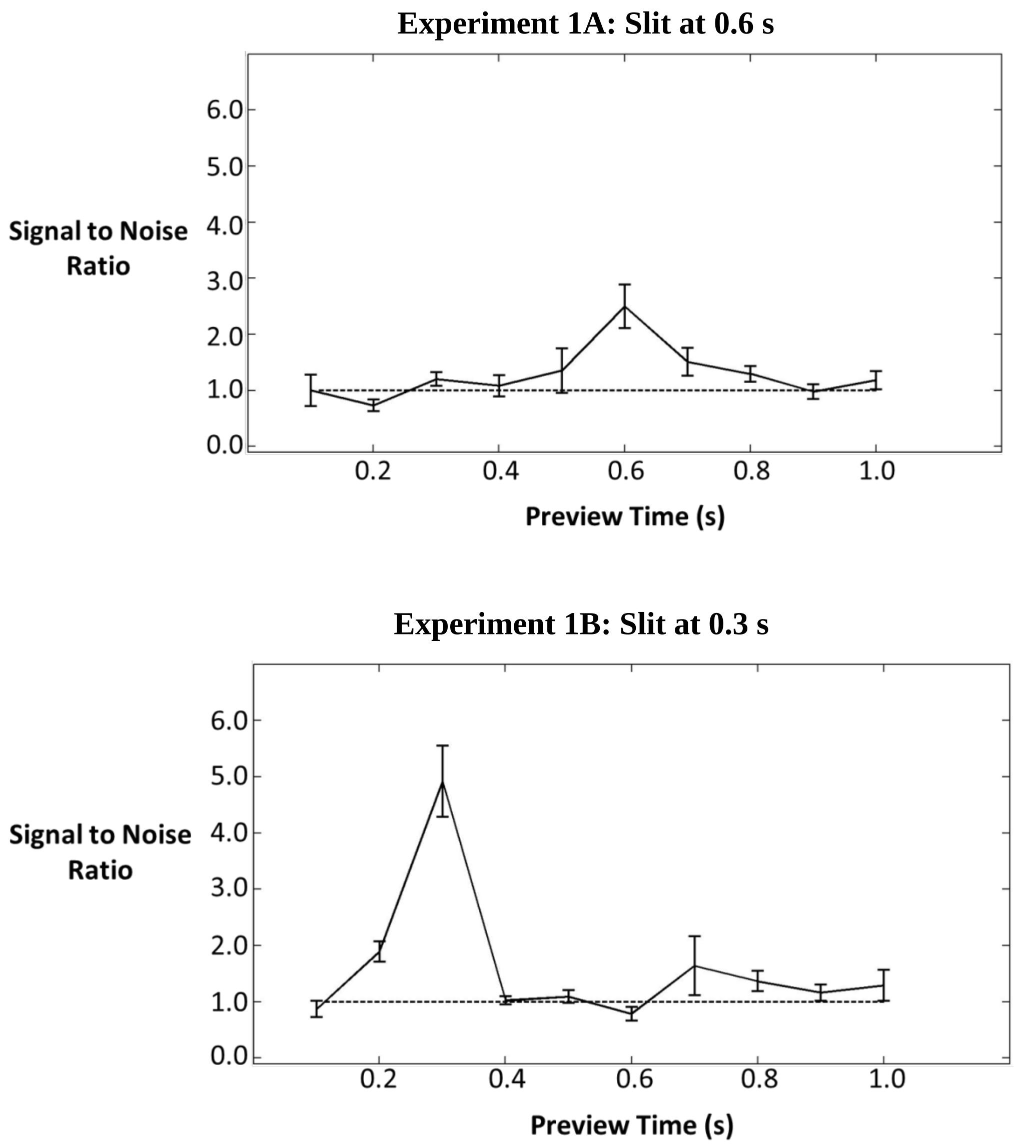


Figure 7. Average attentional allocation for 8 subjects in Slit conditions in Experiments 1A and 1B. The slit region in Experiment 1B showed a higher attentional signal than the slit region in Experiment 1A. The error bars represent ± 1 standard error.

A comparison of attention allocation in the Slit conditions (Figure 7) indicated that subjects attended to the Slit at the 0.3 s region in Experiment 1B with greater intensity than the 0.6 s region in Experiment 1A. A 2 x 10 mixed analysis of variance (Experiment: slit at 0.3 s region, slit at 0.6 s region; Preview Position: 0.1 s to 1.0 s into the future; Experiment was between subjects, and Preview Position was within subject) revealed a main effect of Preview [$F(9, 126) = 5.93$, $p < 0.01$]. This main effect reflected that the 0.3 s and 0.6 s preview positions showed the largest signal-to-noise ratios among the 10 preview positions. A main effect for Experiment found that subjects had higher average signal-to-noise ratio in Experiment 1B, suggesting subjects attended to the 0.3 s preview position with greater intensity than subjects that attended to the 0.6 s preview position [$F(1, 1) = 307.17$, $p < 0.01$; $\bar{x}_{Exp\ 1A} = 1.281$, $\bar{x}_{Exp\ 1B} = 1.603$]. An interaction was also found between the Experiment and Preview Position [$F(9, 9) = 14.39$, $p < 0.01$]; subjects in Experiment 1A had the highest signal-to-noise ratios at 0.6 s into the future, while subjects in Experiment 1B had the highest ratios at 0.3 s into the future. The attentional signal at the slit was higher for Experiment 1B, which was further confirmed with a *t*-test comparing the signal-to-noise ratios for the 0.6 s region in Experiment 1A with the 0.3 s region in Experiment 1B [$t(14) = 3.266$, $p < 0.01$; $\bar{x}_{0.3\ s\ region} = 4.916$, $\bar{x}_{0.6\ s\ region} = 2.497$].

Likewise, we tested whether there were performance differences in tracking between Experiment 1A and 1B. We examined root-mean-squared error, Position error, Velocity error, and Acceleration error with a 2 x 2 x 2 mixed analysis of variance (Trial

Type: Control trials, Perturbation trials; Condition: Full View, Slit; Experiment: 1A vs. 1B; Condition and Trial Type were within-subject, Experiment was between-subject). A few findings were consistent across all analyses of performance. Main effects for Condition and Trial Type were consistently found across all performance measures. This confirmed that across both studies Full View conditions had lower error than Slit conditions, and that Control trials had lower error than Perturbation trials. Statistically significant two-way interactions are detailed below, but none of the analyses revealed a three-way interaction. Key findings are summarized in Table 3.

The root-mean-squared error analysis found a Trial Type by Experiment interaction [$F(1, 14) = 5.79$, $p < 0.04$] which likely resulted from subjects' performance in Experiment 1B (slit at 0.6 s) being more negatively affected by the Perturbation manipulation than subjects in Experiment 1A (slit at 0.3s). The analysis also found a Trial Type by Condition interaction [$F(1, 14) = 4.91$, $p < 0.05$] due to Full View Control conditions having the lowest performance root-mean-squared error out of all the condition by trial combinations. No other meaningful effects were found.

Position error analysis yielded slightly different findings than its root-mean-squared error counterpart. It did not replicate either of the two interactions mentioned above. However, it found a main effect of Experiment [$F(1, 14) = 9.77$, $p < 0.01$; $\bar{x}_{Exp\ 1A\ (slit\ at\ 0.3s)} = 0.038$, $\bar{x}_{Exp\ 1B\ (slit\ at\ 0.6s)} = 0.053$] which indicated that subjects from Experiment 1B performed worse than subjects from 1A. This seems to be reflected

Performance Measure	F statistic	Significance	Means	
Root-mean-squared Error				
Trial Type	$F(1,14) = 35.16$	$p < 0.01$	$\bar{x}_{Perturbed} = 0.696$	$\bar{x}_{Control} = 0.634$
Condition	$F(1,14) = 25.02$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.605$	$\bar{x}_{Slit} = 0.726$
Experiment	$F(1,14) = 3.32$	*n.s.*	$\bar{x}_{Exp\ 1A} = 0.589$	$\bar{x}_{Exp\ 1B} = 0.742$
Trial Type x Experiment	$F(1,14) = 5.79$	$p < 0.04$	$\bar{x}_{Exp\ 1A,\ Control} = 0.570$ $\bar{x}_{Exp\ 1A,\ Perturbed} = 0.607$	$\bar{x}_{Exp\ 1B,\ Control} = 0.698$ $\bar{x}_{Exp\ 1B,\ Perturbed} = 0.785$
Condition x Experiment	$F(1,14) = 1.62$	*n.s.*	$\bar{x}_{Exp\ 1A,\ Slit\ 0.6\ s} = 0.634$ $\bar{x}_{Exp\ 1A,\ Full\ View} = 0.544$	$\bar{x}_{Exp\ 1B,\ Slit\ 0.3\ s} = 0.817$ $\bar{x}_{Exp\ 1B,\ Full\ View} = 0.666$
Trial Type x Condition	$F(1,14) = 4.91$	$p < 0.05$	$\bar{x}_{Full\ View,\ Control} = 0.559$ $\bar{x}_{Full\ View,\ Perturbed} = 0.651$	$\bar{x}_{Slit,\ Control} = 0.710$ $\bar{x}_{Slit,\ Perturbed} = 0.741$
Position Error				
Trial Type	$F(1,14) = 12.71$	$p < 0.01$	$\bar{x}_{Perturbed} = 0.048$	$\bar{x}_{Control} = 0.044$
Condition	$F(1,14) = 26.50$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.039$	$\bar{x}_{Slit} = 0.052$
Experiment	$F(1,14) = 9.77$	$p < 0.01$	$\bar{x}_{Exp\ 1A} = 0.038$	$\bar{x}_{Exp\ 1B} = 0.053$
Trial Type x Experiment	$F(1,14) = 3.08$	*n.s.*	$\bar{x}_{Exp\ 1A,\ Control} = 0.037$ $\bar{x}_{Exp\ 1A,\ Perturbed} = 0.039$	$\bar{x}_{Exp\ 1B,\ Control} = 0.050$ $\bar{x}_{Exp\ 1B,\ Perturbed} = 0.057$
Condition x Experiment	$F(1,14) = 4.44$	$p < 0.06$	$\bar{x}_{Exp\ 1A,\ Slit\ 0.6\ s} = 0.042$ $\bar{x}_{Exp\ 1A,\ Full\ View} = 0.034$	$\bar{x}_{Exp\ 1B,\ Slit\ 0.3\ s} = 0.063$ $\bar{x}_{Exp\ 1B,\ Full\ View} = 0.044$
Trial Type x Condition	$F(1,14) = 0.60$	*n.s.*	$\bar{x}_{Full\ View,\ Control} = 0.037$ $\bar{x}_{Full\ View,\ Perturbed} = 0.042$	$\bar{x}_{Slit,\ Control} = 0.051$ $\bar{x}_{Slit,\ Perturbed} = 0.054$
Velocity Error				
Trial Type	$F(1,14) = 15.51$	$p < 0.01$	$\bar{x}_{Perturbed} = 0.260$	$\bar{x}_{Control} = 0.243$
Condition	$F(1,14) = 36.32$	$p < 0.01$	$\bar{x}_{Full\ View} = 0.230$	$\bar{x}_{Slit} = 0.272$
Experiment	$F(1,14) = 1.14$	*n.s.*	$\bar{x}_{Exp\ 1A} = 0.243$	$\bar{x}_{Exp\ 1B} = 0.259$
Acceleration Error				
Trial Type	$F(1,14) = 10.76$	$p < 0.01$	$\bar{x}_{Perturbed} = 2.178$	$\bar{x}_{Control} = 2.062$
Condition	$F(1,14) = 35.13$	$p < 0.01$	$\bar{x}_{Full\ View} = 1.997$	$\bar{x}_{Slit} = 2.423$
Experiment	$F(1,14) = 1.13$	*n.s.*	$\bar{x}_{Exp\ 1A} = 2.168$	$\bar{x}_{Exp\ 1B} = 2.072$
Condition x Experiment	$F(1,14) = 8.63$	$p < 0.02$	$\bar{x}_{Exp\ 1A,\ Slit\ 0.6\ s} = 2.352$ $\bar{x}_{Exp\ 1A,\ Full\ View} = 1.984$	$\bar{x}_{Exp\ 1B,\ Slit\ 0.3\ s} = 2.134$ $\bar{x}_{Exp\ 1B,\ Full\ View} = 2.009$

Table 3. Comparing tracking performance measures in both Experiments 1A (slit at 0.3s) and 1B (slit at 0.6s). "*n.s.*" indicates not significant.

in the means of all the interactions that include Experiment as a factor. Even though these comparisons did not reach statistical significance they all showed higher mean error values for Experiment 1B; this is true for both root-mean-squared error and Position error analysis. These findings are carefully interpreted in the general discussion.

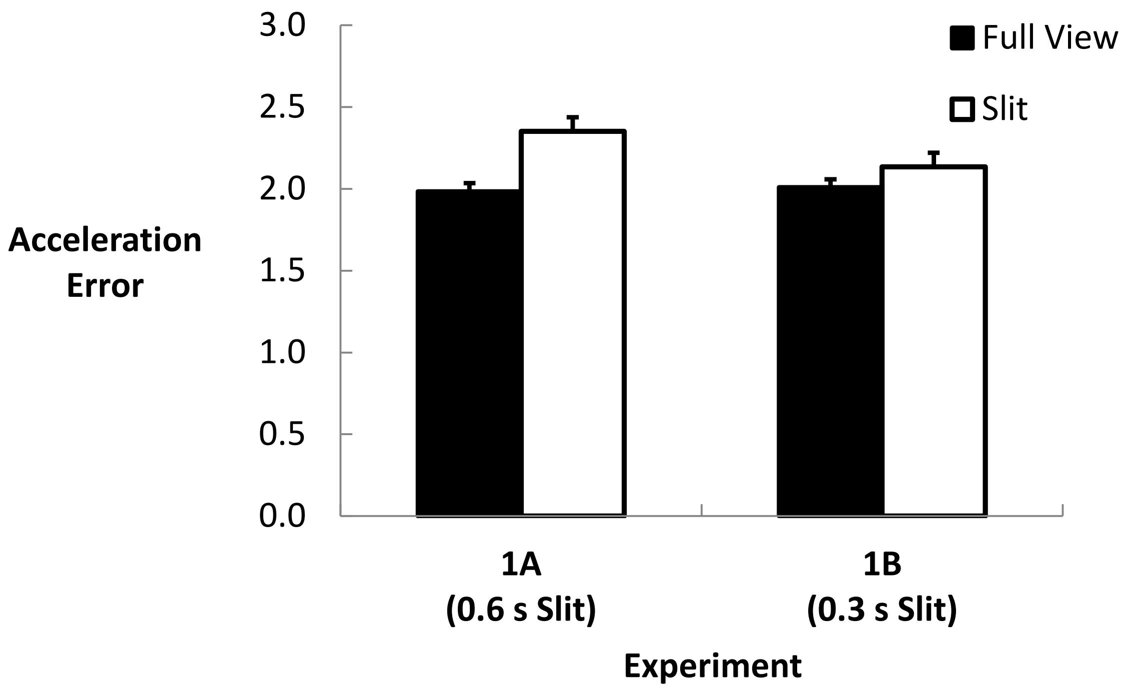


Figure 8. Interaction between Experiment and Condition showing subjects in Experiment 1A had higher Acceleration error than those in 1B. Slit conditions in Experiment 1A had the slit centered at the 0.6 s preview region whereas in 1B the slit was centered at the 0.3 s preview region.

Analysis of Velocity error found no additional effects beyond the ones that were consistent across analyses. Subjects showed equivalent Velocity error scores across both Experiments 1A and 1B. Similarly, analysis of Acceleration Error found no main effect for Experiment, suggesting overall subjects in Experiment 1A had similar Acceleration error scores as subjects in Experiment 1B. However, an interesting interaction between Condition and Experiment was found for Acceleration error [$F(1, 14) = 8.63$, $p < 0.02$; Figure 8]. This result reveals that subjects had significantly higher Acceleration error for Experiment 1A than for Experiment 1B during Slit conditions, but nearly equal Acceleration error in the Full View condition. The implication is that the slit region used in Experiment 1A (where the 0.6 s preview region visible) was more detrimental to subjects' ability to match Acceleration error than when it was located closer to the vehicle in Experiment 1B (when located at 0.3 s preview region).

Prevalence of Noise in Attentional Measure

The Slit condition in Experiments 1A and 1B provided a method for estimating the prevalence of noise in our measurement of attention (i.e., signal-to-noise ratios). Occasionally a subject's attentional allocation graph showed small signal-to-noise peaks in preview positions outside of the visible slit region. These parts of the roadway were occluded, so it would be impossible for these peaks to reflect actual attention to those regions. We counted how often a signal-to-noise ratio was above 2 in the concealed preview regions during Slit conditions across the two days of the study for all subjects. This value was divided by the total number of concealed preview regions present in the studies across the two days for all subjects. This calculation determined that 6.5% of the attentional signal-to-noise ratios had values of 2 or more due to noise in the measurement procedure. If we used a stricter criterion, only 2.3% of the attentional signal-to-noise ratios in the concealed preview regions had values of 2.5 or more. Noise was very minimal when we considered the strictest criterion of signal-to-noise ratios above 3.0, occurring less than 1% of the time. These noise estimates in the measurement system verified that most of the signal-to-noise ratios we calculated were reliable depictions of subjects' attentional allocation.

Experiment 1B Discussion

Findings from Experiment 1B

The purpose of Experiment 1B was to test whether the location of the slit on the previewed roadway had any effect on subjects' ability to attend to it. Individual differences in Experiment 1A revealed that not all subjects showed attentional allocation to the slit region when it was located 0.6 s into the future. One hypothesis for this was that the 0.6 s region was not useful to subjects and that other previewed regions might be preferred. The Full View condition in that study (Figure 6, top) demonstrated strong attentional signal for preview regions 0.1 s to 0.3 s. Therefore, in Experiment 1B we decided to test the effectiveness of attentional allocation to a slit close to this preferred region.

Miller (1976) predicted that an optimal controller in a similar tracking task would emphasize closer regions of the preview. Experiment 1A and 1B both qualitatively corroborate this prediction because subjects tended to place most of their attention at preview positions 0.1 s – 0.3 s into the future (Figure 7). These results motivated us to test whether centering the slit at the 0.3 s region would result in a stronger attentional signal for the Slit condition than we saw in Experiment 1A. This region is close enough to subjects' preferred focus area in the Full View condition while requiring them to attend slightly further out than they normally would.

From Figure 7 it is evident that subjects were successful in attending to this preview region. Subjects attended to the 0.3 s region much more effectively than they did to the 0.6 s region. This result suggests that subjects were better able to focus their attention to preview positions closer to where they normally attended when full view was available. The analysis also revealed that there was no overall difference between Slit and Full View conditions for the total average attentional signal subjects exhibited in Experiment 1B. One possible interpretation of these two findings is that subjects distributed their full attentional capacity across multiple regions in the Full View condition, but in the Slit condition placed the totality of their attentional capacity to the 0.3 s region alone. This differs from Experiment 1A where the Full View condition showed a larger average attentional signal than the Slit condition at 0.6 s into the future. Capacity limits on attention have been examined in other task (Kahneman, 1973), but the factors affecting it in a tracking context require further investigation.

We investigated whether subjects' successful allocation of attention to the 0.3 s region benefitted their performance in any way. Even though subjects were able to place a lot of attention to the Slit region, their performance was worse than in the Full View condition. Full View seems to allow subjects to acquire other pertinent information about the roadway that is being limited by the slit. This result falls in line with the Progression-Regression interpretation for our results. All measures of performance error and higher derivates of performance error (i.e., velocity and acceleration error) were worse in the Slit condition in Experiment 1B. The Progression-Regression Hypothesis (Fitts, Bahrick, Briggs, & Noble, 1959) predicted that subjects would utilize these sources of information with increased tracking experience such that their performance would become both more accurate and smoother. The Slit condition limited subjects' ability to anticipate roadway slope and curvature. Therefore, a single well attended preview region may not be enough for subjects to improve their tracking performance.

Land and Horwood (1995) had similar findings in their investigation of where subjects look during a realistic driving simulation. They also manipulated the amount of preview subjects had access to: full view, a single close region, a single far region, or a close region and a far region. They found subjects performed the worst with a single preview region. In fact, if the visible roadway region was close to the vehicle, subjects' tracking in their study was more "unstable and jerky". Their results match ours in that subjects struggle to match these higher derivatives of performance with a single close preview point. From their findings they concluded that a single segment of roadway preview is insufficient for effective steering control (Land and Horwood, 1995, p. 170).

Comparing Experiments 1A and 1B

Our measurement technique revealed that subjects could shift their attention to the roadway region in the slit, but they did so more effectively if the slit was located closer to the vehicle. When the slit was centered on a region halfway down the roadway some subjects showed lower attentional signal-to-noise ratios in that region. The reason for this may be that subjects do not require such distant preview to successfully track the roadway. The regions they tended to focus on the most were between 0.1 s – 0.3 s into the future when full view was available. That amount of preview appeared to be sufficient for effective tracking control. This could be a possible explanation as to why subjects showed higher attentional signal to the slit region when it was at the 0.3 s into the future region when compared to the 0.6 s region. Looking too far down the roadway might not be informative to the task; subjects may not plan their steering actions that far in advance. Miller (1976) predicted this would be the case, calculating that attentional allocation should exponentially decrease with preview time into the future for the rate control dynamic our subjects used.

However, there is a confounding issue with this interpretation of the difference between the attention allocated to near and far preview positions. There was an important limitation in our study's attentional measurement technique. The 10 frequency labels we used to tag the 10 preview positions were in decreasing order with longer preview times. Thus the location of the slit on the previewed roadway is confounded with the frequency label used at that position. Any difference between attention for the slit at 0.3 s and 0.6 s could be the result of attention being captured by the specific frequency label present in the slit region. This could put into question our result showing that subjects were actually able to better attend the 0.3 s region over the 0.6 s region.

Additional behavioral measures in Experiments 1A and 1B were subjects' tracking error scores. In the identical Full View conditions, subjects in Experiment 1B had higher root-mean-squared and Position error. Therefore, comparisons of these error measures in the slit conditions are difficult to interpret. These difficulties were addressed in the next experiment by equating the frequency labels for the two slits and using a within subjects design.

On the other hand, something more interesting resulted from comparing Experiments 1A and 1B on Acceleration error, a measure of how well subjects tracked roadway curvature. Compared to Full View, subjects struggled to track curvature with the limited roadway visible in the slit region. What was unexpected was that subjects were even worse at tracking curvature when the slit was further away. Subjects in the two experiments had comparable Acceleration error during Full View conditions, but Acceleration error was higher when the slit was in the 0.6 s preview region (Figure 8). This result is in contradiction to a similar study looking at the effects of preview location in a simulated driving environment. Land and Horwood (1995) found that when subjects could only see distant roadway during driving, they tracked road curvature well but their lane keeping suffered. The higher Acceleration error with the slit at 0.6 s is the opposite of what Land and Horwood (1995) found. It might be that our tracking task differed from the realistic driving simulation Land and Horwood used for their study, but this discrepancy merits investigating further in the following experiment.

We can still conclude that restricted preview is detrimental to performance. In both Experiments 1A and 1B subjects performed better during Full View conditions than Slit conditions. This is particularly relevant for Experiment 1B where the slit was located closer to where subjects typically attended during Full View conditions. Having the slit closer did not make subjects' Slit performance comparable to their Full View performance. It suggests subjects are losing out on beneficial information when parts of the preview are no longer visible. This is further evidenced by the fact that in Full View conditions subjects did not just focus on a single roadway region close to the vehicle. Instead they distributed their attention over multiple regions with systematically less attentional allocation to roadway regions further away. Consistent with previous studies, we conclude that a single region of focused attention does not yield the same level of performance as distributed attention (Land & Horwood, 1995), and that a distribution of attention concentrated on nearer preview is expected for good tracking performance (Miller, 1976).

In summary, these two Experiments have demonstrated the importance of available preview in shaping both attentional allocation and quality of tracking. Subjects performed best when there was sufficient anticipatory roadway information, but there is a limit to how much information they will actually attend to. If preview was restricted subjects were still capable of shifting their attention to where preview was available even if it was a region they did not normally attend to. However, it is unclear if it is easier for subjects to shift attention to regions closer to the vehicle being controlled due to the confounding of the location of the slit or the frequency labels used to measure attention.

Chapter 4: Experiment 1C - Revisiting the Comparison of Preview Regions at 0.3 s and 0.6 s

In Experiment 1A and 1B we found differences in both the attentional signal-to-noise ratios and error measures depending on whether subjects' roadway preview was limited to a slit region centered on 0.3 s or 0.6 s into the future. Though the results aligned with predictions made by Miller (1976), these experiments failed to account for the frequency labels covarying with the slit regions being investigated. Jagacinski, Hammond, and Rizzi (2017) found that the frequency perturbations used do not change the overall pattern of attentional allocation but could have an effect on the magnitude of the signal-to-noise measurements.

This experiment attempts to correct this issue by replicating the comparison between preview regions 0.3 s and 0.6 s as a within-subjects experiment controlling for the frequency labels used at both preview regions. By doing so we can gain a better understanding of what happens when subjects are forced to look at preview regions that lay both closer and farther from the cursor they are controlling.

Hypotheses

In this experiment we tested the effect of forcing subjects to attend to one of two different preview regions of the roadway. When the slit used in the study limited subjects' available roadway preview to the 0.3 s region, we expected the following effects:

(1) In accordance with our hypothesis from Experiments 1A and 1B, we predicted subjects would show a higher signal-to-noise ratio when attending to close preview regions (0.3 s) compared to far (0.6 s).

(2) We predicted that attending to 0.3 s preview will also result in better tracking performance because this region is closer to where subjects typically prefer to attend during full view conditions. These subjects are expected to have lower root-mean-squared, Position, Velocity, and Acceleration error scores.

Method

Participants

Thirteen university students between 18 and 30 years of age volunteered for this experiment as part of an introductory psychology course. Eight participants were male, and five were female. To assess their eligibility for the study, they completed a short questionnaire and demonstrated 20/25 corrected vision on a basic eye exam. Informed consent was obtained from all participants. One female subject was excluded from the final data because her error scores exceeded 3 standard deviations from the mean of the group. This left twelve counterbalanced subjects for our analysis.

Procedure

The same control dynamics and slit procedure as the previous two experiments were used. We compared the effects of centering the slit at 0.3 s versus 0.6 s into the future. However, this manipulation was within-subjects so we could compare subjects' attentional signal-to-noise ratios to themselves. All subjects first block was a two-trial full-view condition to give them experience with the task without the observational constraint imposed by the slit. For the remaining blocks half of the subjects started with the slit centered on 0.3 s and half with the slit centered on 0.6 s into the future. Subjects then performed both a Control and Perturbation block of tracking for their initial slit condition before moving to the other slit condition. Whether they received a Control or Perturbation block first was counterbalanced across subjects.

To control for the effect of frequency label on signal-to-noise ratios, we assigned the same three frequency disturbances to the preview regions in both slits: the visible position centered in the slit and the two occluded positions surrounding it (see Figure 2). The visible preview position at the center of the slit received a 6.94 rad/s frequency disturbance, the position below it received a 8.94 rad/s disturbance, and the preview position above it was assigned a 5.02 rad/s disturbance. These frequencies were chosen because these disturbance frequencies provided the highest signal-to-noise ratios in Experiments 1A and 1B, making for easier comparison.

Results

Attentional Distribution

To determine the effects of the slit manipulation on signal-to-noise ratios we restricted our analysis to the three preview regions in the vicinity of the slit. This allowed us to make a direct comparison between the frequency labels when they were assigned to either the slit centered at 0.3 s or 0.6 s into the future.

From Figure 9 we can see subjects did in fact attend to the slit regions in each condition. Furthermore, there is no qualitative difference between the 0.3 s and 0.6 s conditions. A 2 x 3 analysis of variance on the signal-to-noise ratios (Slit Preview Time: 0.3 s, 0.6 s; Relative Slit Position: Bottom, Center, Top of slit) revealed only a main effect of Relative Slit Position [F (2, 22) = 28.31, p < 0.01; $\bar{x}_{Bottom} = 2.431$, $\bar{x}_{Center} = 5.42$, $\bar{x}_{Top} = 1.26$]. Regardless of where the slit was positioned, subjects showed the most attention to the center of the slit, but also directed substantial attention to the bottom of the slit. The lack of a main effect of Slit Region confirms that there was no difference in subjects' abilities to direct their attention to either 0.3 s or 0.6 s into the future of the roadway (mean signal-to-noise ratio at the 0.3 s and 0.6 s center frequency was 5.58 and 5.25, respectively). We failed to find evidence for our hypothesis regarding the effect of the slit position. Figure 9 shows possible evidence that when the slit was centered at 0.3 s, the bottom Relative Slit Position had a slightly higher signal-to-noise ratio than when it was centered at 0.6 s, but this interaction did not reach statistical significance.

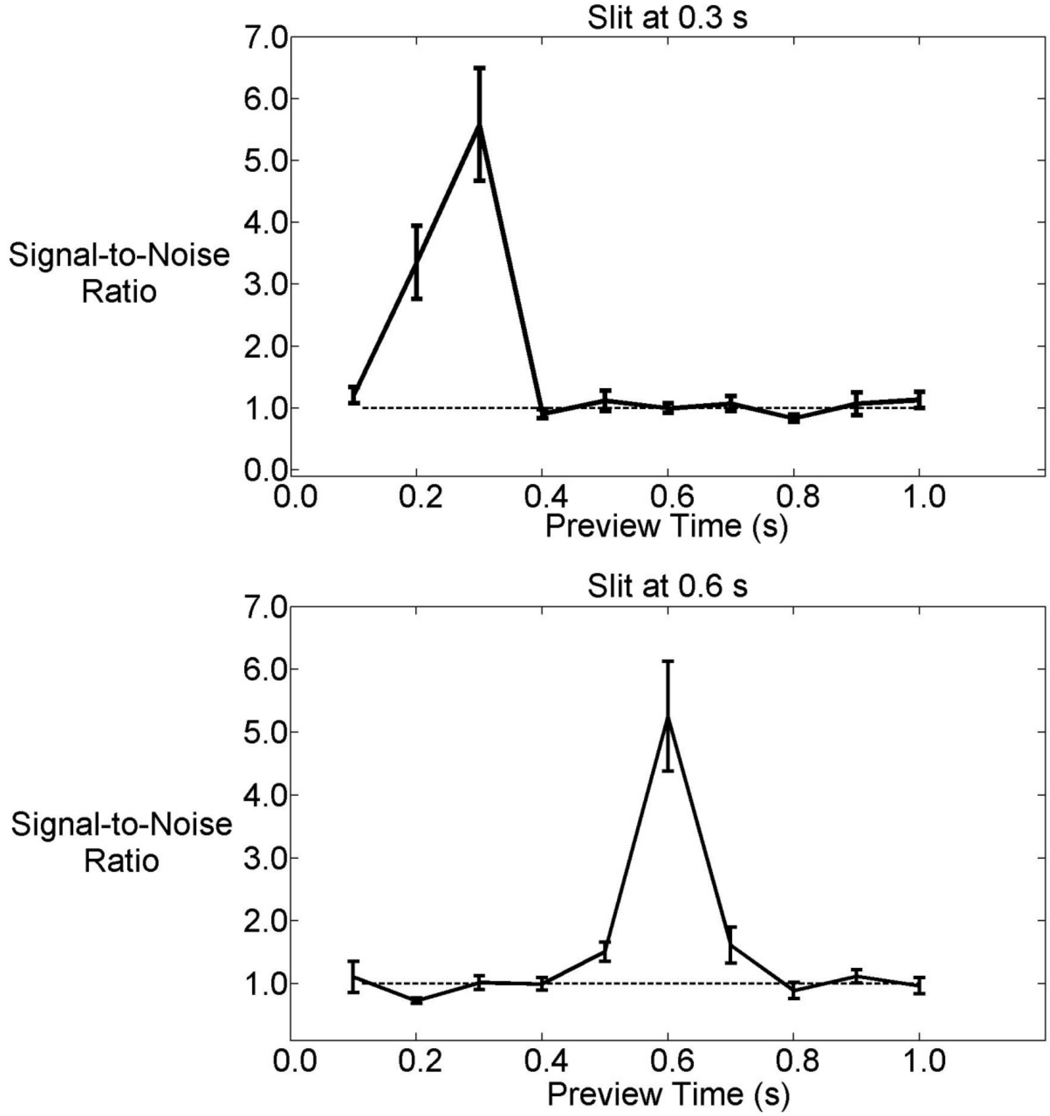


Figure 9. The attentional distributions of 12 subjects when the slit was centered at 0.3 s and 0.6 s. There was no effect of the slit preview time on subjects' signal-to-noise ratios (mean signal-to-noise ratio at the 0.3 s and 0.6 s center frequency was 5.58 and 5.25, respectively). The error bars represent ± 1 standard error.

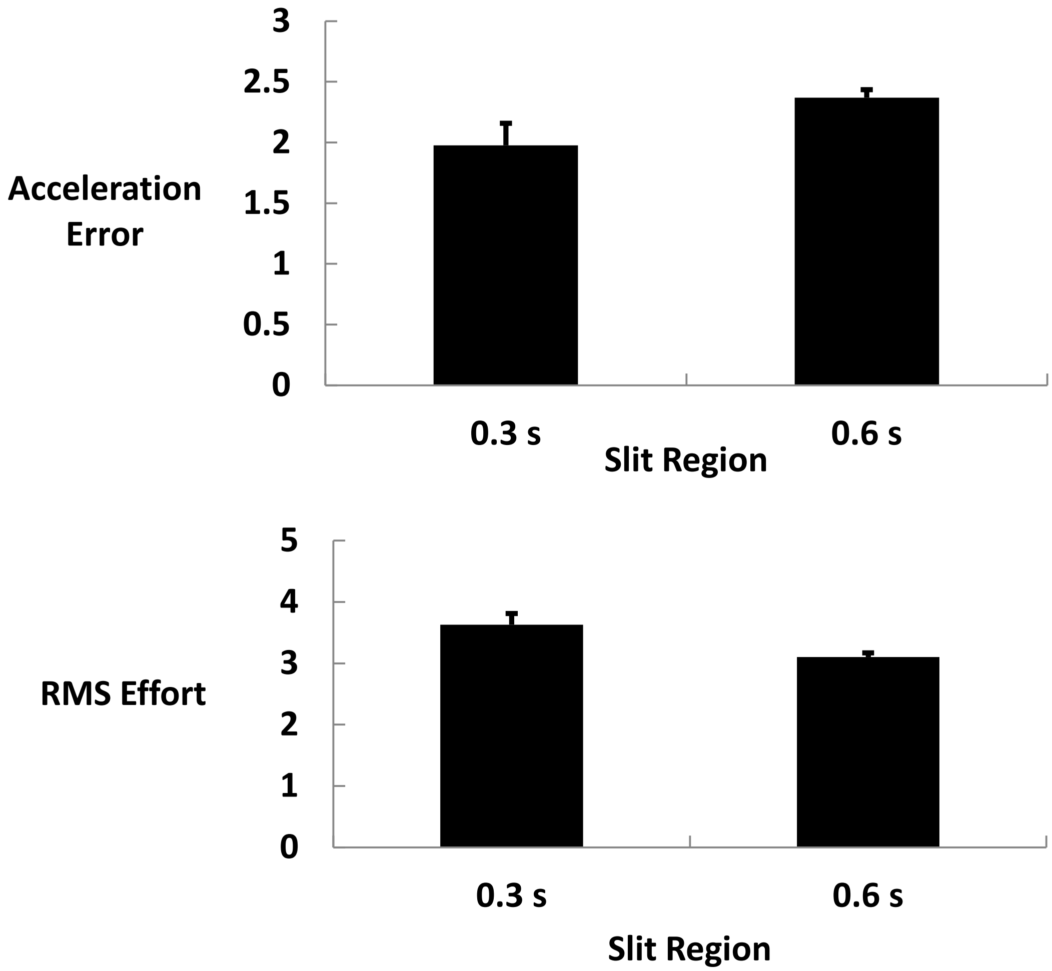


Figure 10. Top graph is the average Acceleration error for 12 subjects for two different slit locations. The bottom graph shows average root-mean-squared joystick (i.e., effort).

Tracking Performance

We analyzed whether subjects' ability to attend equally to the two slit regions had any effect on their tracking performance. We conducted paired samples t-tests to compare subjects' error scores with the slit at 0.6 s to their error scores with the slit at 0.3 s. There was no effect of the slit manipulation on root-mean-squared error, Position error, or Velocity error, suggesting that overall performance was comparable between the two slit conditions. However, we did find an effect of the slit on Acceleration error [t (11) = -3.05, p < 0.02; $\bar{x}_{Slit\ at\ 0.3\ s} = 1.98$, $\bar{x}_{Slit\ at\ 0.6\ s} = 2.37$]. This replicated the finding when comparing Experiments 1A and 1B that subjects showed lower Acceleration error scores when they attended to closer preview than when they attended to further preview (Figure 10).

Performance Measure	***t* statistic**	**Significance**	**Means**	
Root-mean-squared Error	t (11) = 0.72	*n.s*	$\bar{x}_{Slit\ at\ 0.3\ s} = 0.66$	$\bar{x}_{Slit\ at\ 0.6\ s} = 0.64$
Position Error	t (11) = 1.66	*n.s*	$\bar{x}_{Slit\ at\ 0.3\ s} = 0.05$	$\bar{x}_{Slit\ at\ 0.6\ s} = 0.05$
Velocity Error	t (11) = -1.45	*n.s*	$\bar{x}_{Slit\ at\ 0.3\ s} = 0.248$	$\bar{x}_{Slit\ at\ 0.6\ s} = 0.272$
Acceleration Error	t (11) = -3.05	p < 0.02	$\bar{x}_{Slit\ at\ 0.3\ s} = 1.976$	$\bar{x}_{Slit\ at\ 0.6\ s} = 2.369$
Root-mean-squared Joystick	t (11) = 10.42	p < 0.01	$\bar{x}_{Slit\ at\ 0.3\ s} = 3.672$	$\bar{x}_{Slit\ at\ 0.6\ s} = 3.104$

Table 4. Tracking performance measures for Experiment 1C. “*n.s.*” indicates not significant.

We also tested whether the slit location affected performance effort. Effort was measured as the root-mean-squared control stick displacement, which was the amount of lateral joystick displacement away from the center position. A paired samples t-test on the root-mean-square of the lateral displacement of the joystick found a statistically significant effect [t (11) = 10.42, p < 0.01; $\bar{x}_{Slit\ at\ 0.3\ s} = 3.63$, $\bar{x}_{Slit\ at\ 0.6\ s} = 3.10$]. Subjects were more effortful when the slit was centered at 0.3 s into the future (Figure 10). All results are summarized in Table 4.

Experiment 1C Discussion

This experiment replicated Experiments 1A and 1B while controlling for a confound that was present when comparing them. In those experiments the frequency perturbations (i.e., frequency labels) we used to assess attention covaried with the slit region. In this study we compared subjects' attention and performance when centering a slit at either 0.3 s or 0.6 s preview roadway regions. We tested whether subjects' tendency to focus attention to closer preview regions when they have full view of the upcoming roadway would affect the relative amount of attention they would allocate when preview was restricted to either of these two slit regions. To ensure that the effect on attention was driven by cognitive factors and not the frequency labels themselves, we used the same set of frequency labels to measure attention at each slit region. After controlling for this, we were surprised to find that there was no effect of the slit location. Subjects could redirect their attention to both close and far preview with equal focus. This result indicated that Miller's (1976) predictions that more distant roadway preview would be weighted significantly less when permitted fuller view does not generalize to slit conditions involving highly restricted view. This experiment showed that if preview is restricted subjects can allocate their attention equally well to near and far preview while tracking. The two slit regions were only 0.3 s apart, so it is still possible that there might a preview region beyond 0.6 s to which allocating attention becomes more difficult.

Given attention was equally allocated to both near and far preview we had a better test of how this shift in attention might affect performance in the tracking task. Position and Velocity error scores were comparable regardless of where subjects were forced to look. However, we did find an effect of the slit location on Acceleration error, which captured how smoothly subjects were tracking the roadway. This replicated the finding from the previous two experiments that contrary to Land and Horwood (1995) subjects, in our experiment were smoother in their tracking when focusing on the close preview region. Land and Horwood found that in a simulated vehicle environment tracking was smoother when subjects' view of the roadway was restricted to more distant preview compared to closer. A possible explanation for this discrepancy is that the present experiment used a simple rate control dynamic, whereas car dynamics are more closely approximated by an acceleration control.

We also found an effect of slit location on effort as measured by the amount of joystick movement. When the slit was located at 0.3 s into the future, subjects exhibited greater joystick movement than when it was further away. The higher effort measure is the result of subjects tracking the higher frequency components of the roadway more accurately. This is supported by our finding of an Acceleration error difference between the two groups. The Position error signal subjects generated had to be differentiated twice to determine Acceleration error, so higher frequencies contributed more heavily to this measure of effort. The Fourier spectra of subjects' joystick movements when tracking with the slit at 0.3 s revealed higher amplitudes for high frequency roadway components. By increasing their effort on tracking the higher frequency components of the roadway subjects were able to produce smoother steering movements, i.e., lower acceleration error scores. This did not result in any significant difference in their positional tracking error between the two slit conditions because positional error emphasizes lower frequency roadway components.

This experiment clarified that the attentional effects of slit location we found when comparing Experiments 1A and 1B were driven by the frequency labels we used, not where we were forcing subjects to look on the roadway. The attentional signal-to-noise ratios in the two slit conditions were not significantly different when we equated the frequency labels. In Experiments 1A and 1B, we used frequency labels that had generated the highest signal-to-noise ratios in the previous research, but it is possible that the labels we used had differing capture effects on attention. Future studies may benefit from having a more restricted range of frequency labels to minimize such differences.

General Discussion

When measuring subjects' attention to roadway preview in similar tracking studies in the past, some researchers have used techniques such as eye tracking to determine which roadway preview regions are being emphasized (Land & Lee, 1994; Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Underwood, G., Chapman, Brocklehurst, Underwood, J., & Crundall, 2003; Cooper, Medieros-Ward, & Strayer 2013). However, it is still possible for individuals to direct their gaze at something without actually attending to it (Land, 1998). Instead, the technique we present in Experiments 1A through 1C deliver a promising alternative. These experiments provide evidence that subjects' steering movements carry information about subjects' attentional allocation. We can use their action response as a means to measure aspects of the cognitive plan (e.g., attention) that lead up to their motor execution.

Using our measurement of attention we were able to investigate its flexibility. The previewed roadway provided subjects with information that they could use to plan their future steering actions more effectively. What we wanted to address was whether there was a preferred preview region for subjects doing our task and whether this region could be manipulated. In accordance with predictions from previous analysis (Miller, 1976; Sharp, 2005), when subjects had full view of the upcoming roadway they tended to distribute their attention mainly on regions immediately ahead of the "vehicle" they were controlling. During this Full View condition subjects showed almost no attention to regions beyond 0.5 s seconds into the future.

Even so, we were able to force subjects to attend to specific roadway regions by making only a particular preview position visible during Slit conditions. We managed to shift subjects' attention to preview regions they were not normally attending during Full

View conditions. However, we found that these restricted view conditions were detrimental to their performance. Subjects had lower error scores during Full View conditions, even if they showed higher maximum attentional signal-to-noise ratios during the Slit conditions, as was the case when comparing Full View to the Slit centered at 0.3 s. During Full View subjects also demonstrated lower Velocity and Acceleration error, meaning their tracking was both more accurate and smoother. This result might also explain why subjects distributed their attention during Full View conditions rather than focusing on a single future preview region, even though it should have been more demanding on their attentional resources to distribute than to focus on a single region (Kahneman, 1973). One of the benefits of fuller preview is that subjects could perform more accurately by allocating attention to multiple preview regions to track higher derivative elements of the roadway.

When comparing the two slit regions, we found that subjects attended equally well to either preview location regardless of whether it was centered at 0.3 s or 0.6 s into the future. Moreover, subjects demonstrated comparable Position error scores for both of these slit conditions. This is surprising because Miller's (1976) model of attentional weighting indicated that the 0.6 s roadway region would not be very helpful during full view tracking. This result suggests his model of feedforward attentional weighting does not generalize to cases in which preview is strongly restricted. This discrepancy between his analysis of full preview and our analysis of restricted preview suggests that it is likely that feedforward information undergoes an additional processing layer before being translated into steering movements.

One mechanism that's been proposed is that subjects' feedforward control retains upcoming roadway information in a real-time buffer for a length of time roughly equal to the how far into the future they are previewing the roadway (Land, 1998). That information is then translated into joystick movements that coincide with the temporal onset of the roadway previewed. However, this information has to be constantly updated during continuous tracking as new preview information is observed. This may result in less effectively retaining the higher frequency roadway detail as the length of the buffer is increased. This would correspond to the higher Acceleration error we observed in subjects attending to the 0.6 s preview regions. This can be thought of as analogous to individuals retaining a sequence in working memory before reciting it. The longer the sequence or the longer one has to retain it in memory, the more that certain details are lost or errors increase. In this way, both the tracking buffer and working memory can be thought of as a type of low pass filter.

Another possible mechanism is for subjects to adapt different dynamics during tracking to simulate the time delay necessary to match their steering responses to the roadway onset. Subjects could behave like a first-order lag, which is a system that approaches a desired output exponentially. At low frequency input signals, a lag can approximate a time delay or buffer by the time constant it sets (Jagacinski & Flach, 2003). If subjects act as a lag with a time constant roughly equal to the preview time, this would allow them to implement the necessary delay in their steering movements without needing to continuously update roadway information in a memory buffer. The lag with a

0.6 s time constant would more heavily filter high frequency roadway features, which would lead to greater acceleration error.

This study demonstrated that subjects were able to adapt to the available preview in order to maintain good tracking performance. Full view of preview led to better performance but subjects could shift attention in conditions where preview was restricted. The smoothness and effortfulness of their tracking also changed in response to restricted preview, though Position error scores did not. Miller's model which approximated steering movements with a differential weighting of preview did not adequately capture the results we found for the Slit conditions, so we may need to consider other mechanisms that could better describe how our subjects were behaving with highly restricted preview.

Chapter 5: Experiment 2 - Error vs. Effort Tradeoff

In this experiment we investigated how subjects' performance styles might shape feedforward and feedback control.

Miller (1976) used optimal control theory to calculate how attention to future roadway regions would be weighted in a tracking task. According to him the distribution of attention depends on the tradeoff between an individual's emphasis on mean squared error and mean squared control movement. In cognitive terms this could be thought of as a tradeoff between minimizing error and minimizing effort. Highly accurate performance would result in a controller being very effortful, i.e., requiring many control movements to minimize error. If participant wanted to have more relaxed performance with minimal control movement, such performance would result in higher error values.

Miller determined that a controller that emphasized minimizing error more would place a high attentional weighting on regions immediately in front of the vehicle being controlled (i.e., on closer roadway preview regions) with regions further into the future becoming systematically deemphasized. For a rate control system like the one used in our study, Miller (1976) predicted that attentional allocation to preview would exponentially decrease as preview time into the future increased. If minimal effort is prioritized, however, then Miller predicted that the magnitude of the attentional weighting on close regions would be much lower and participants would maintain this lower attentional focus across a wider range of the available preview. In other words, participants may attend to various regions both close and far away with lower attentional weights.

D. C. Miller (1965) found that different emphases on minimizing error or effort also changed feedback control during tracking. In his study a trained subject used a joystick to keep a dot centered on a stationary target circle while adapting his tracking to meet different error versus effort performance criteria. When the performance criteria heavily weighted joystick effort, a lower gain was measured in subjects' feedback loop then when the criteria weighted joystick effort much lower.

It is important to distinguish how optimal control researchers such as Miller (1976) and D. C. Miller (1965) describe effort versus cognitive researchers such as Kahneman (2011). Optimal control researchers see effort as a quantification of control movements, whereas Kahneman (1973) described effort as an attentional resource that gets allocated to a task based on how demanding it was. This distinction is important because in this experiment we want to understand the effects of movement effort on attentional effort if a link does exist. Furthermore, the voluntary allocation attention is also limited by the difficulty of the task, unlike control movements that seem easily adaptable to different performance styles (D. C. Miller, 1965). In simple or well-practiced tasks an automatic and quick responding system is active which requires little to no attentional effort, whereas in more complex tasks more directed attentional effort might be required (Kahneman, 2011).

To test this hypothesis we manipulated subjects' relative emphasis on error and effort in a tracking task we consider demanding for both attention and movement effort. We used performance criteria to instruct subjects to either track in a joystick effort minimizing or error minimizing way. We then compared the two performance styles to see how the attentional allocation was shaped by these instructions.

Furthermore, we also tested how attention to preview positions might be influenced by the frequency labels we assigned to previewed roadway regions. In Experiment 1A through 1C we found the frequency labels we assigned to parts of the roadway affected the signal-to-noise ratios measured when a slit region was located 0.3 s into the future compared to 0.6 s. Jagacinski, Hammond, and Rizzi (2017) suggested the order of the frequency labels affects the magnitude of signal-to-noise ratios measured but not the shape of the attentional distribution. We further investigate this effect of frequency labels on attention in this experiment.

Hypotheses

Subjects in our study were instructed to adopt either one of two performance styles: effort minimizing or error minimizing. In accordance with Miller's (1976) predictions we expected that manipulating subjects' performance style would affect the feedforward and feedback components of tracking control in the following ways:

(1) Effort, as measured by the amount of control stick movement, should be lower for subjects who adopted a more relaxed performance.

  a. We expected effort minimizers to have lower attentional signal-to-noise ratios for the experimentally-selected preview regions on the display when compared to error minimizers.
  b. We expected effort minimizers to have higher root-mean-squared (RMS) error scores and lower RMS joystick values (a measure of effort) than error minimizers.
  c. We predicted effort minimizers would have worse tracking performance than error minimizers as measured by Position, Velocity, and Acceleration error.
  d. We predicted effort minimizers would show less sensitivity to error as measured by the gain of their feedback control behavior.

We investigated the frequency labels that caused the confound in Experiment 1. We looked at error minimizers in the current experiment because their performance style would most closely match those of subjects in Experiment 1. We compared the signal-to-noise ratios for these subjects in identical slit conditions but with different frequency labels assigned to the previewed roadway that was visible in that slit.

(2) We predicted that we should find no significant difference between the signal-to-noise ratios for these subjects regardless of how frequency labels were assigned to the previewed roadway visible in the slit region. In other words,

the frequency label should have a negligible effect on attentional allocation. By concentrating subjects' attention to the slit region (Jagacinski, Hammond, & Rizzi, 2017).

Method

Participants

Twenty-four university students taking an introductory psychology course volunteered for this study. Their ages were 18 and 30; eleven were male, and 13 were female. To assess their eligibility for the study, they completed a short questionnaire and demonstrate 20/25 corrected vision on a basic eye exam. Informed consent was obtained from all participants.

Procedure

This experiment utilized the same apparatus and a similar procedure as Experiment 1. As in Experiment 1C, subjects were given 2 trials of the Full View condition at the beginning of each session (Day 1 and Day 2) so that they might understand the nature of the task and how to utilize preview. Subjects then performed 3 additional blocks on both Day 1 and Day 2 which were all Slit conditions centered around the 0.3 s previewed roadway region. For these 3 Slit conditions subjects ran a Control block and a Perturbation block with the same roadway visual perturbation technique used in Experiment 1 (used to assess attentional allocation). We also included an Input Disturbance block identical to the one Jagacinski, Hammond, and Rizzi (2017) used to measure feedback performance. The ordering of the 3 block types was counterbalanced across subjects.

During Input Disturbance blocks wind gusts were introduced into the control loop (Figure 11). The wind gusts were composed of a set of 10 sinewaves whose frequencies were different and orthogonal to the sinewaves used to generate the roadway. These wind gusts produced unwanted errors in the subjects’ tracking performance by generating unexpected lateral deviations in the cursor subjects were controlling. For subjects to maintain adequate performance they had to correct for these unwanted errors by making adjustments with their joystick movements. These adjustment movements stem from subjects’ feedback control during tracking because the wind gusts primarily affect the feedback loop due to them not being previewed (Figure 11). The wind gusts unexpectedly increase the error the feedback loop. Therefore, by analyzing the Fourier spectrum of subjects’ steering responses to the 10 sinewaves that compose the wind gust disturbances we can determine the responsiveness of their feedback control loop separately from their feedforward attentional allocation system.

A between subjects manipulation was introduced in which subjects were instructed to track the roadway in an error or effort minimizing mode. Just as in Experiment 1, tracking was done with a rate control system. According to McRuer and Jex (1967) higher-order control systems require more anticipation to control; therefore, subjects would require more distant regions of the previewed roadway in such a system. However, higher-order control systems are also more prone to noise and degraded

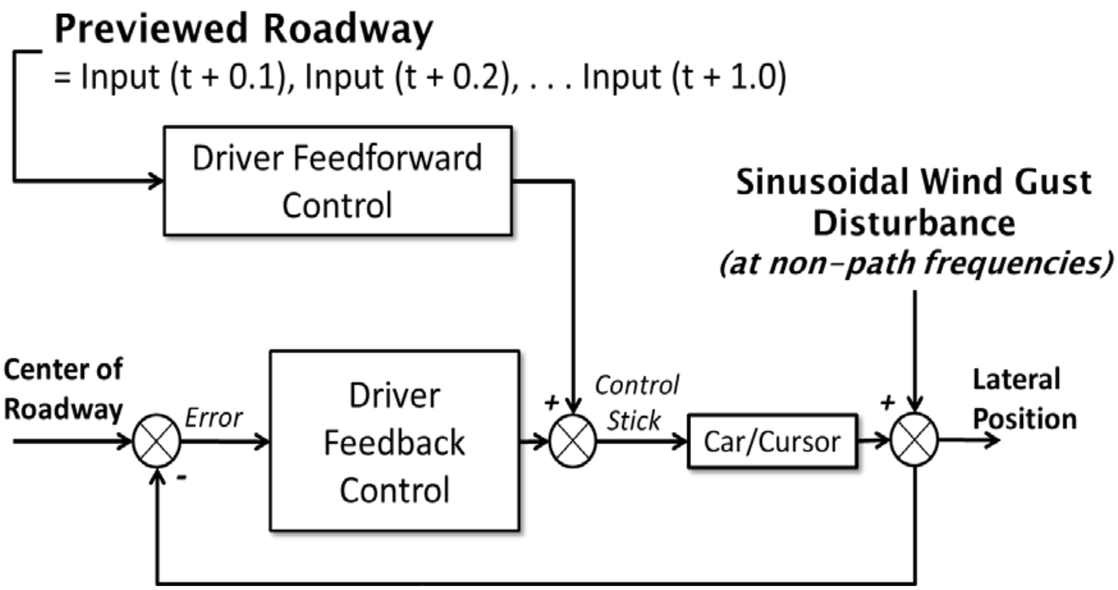


Figure 11. Unpreviewed wind gusts are introduced at the end of the control loop. The driver's feedback control must nullify the errors produced by the wind gust disturbances in order to keep the cursor centered in the middle of the roadway. Therefore, analyzing the Fourier spectrum at wind gust frequencies provides insight into subjects' feedback control.

performance. Using a rate control system provides a good tradeoff between anticipatory reliance and adequate performance on the task. We hoped this would provide greater sensitivity to manipulating subjects' relative emphasis on error and effort.

Because our measurement system relies on subjects' joystick movements to determine their attentional allocation, there is a measurement limitation in its ability to distinguish signal from noise when movements are lessened. We expected subjects in effort minimization mode to reduce both the amplitude of their joystick movements as well as their reliance on anticipatory information. If effort minimizers had full view of the roadway, we expected them to distribute their attention across multiple regions of the display which could result in low signal-to-noise ratios. The limited resolution of our measurement technique might make these subjects indistinguishable from subjects who were not attending to the display at all. Therefore, it would be difficult to tell which regions were unattended and which regions' were merely being attended less.

To combat this issue, we used only the Slit condition for this Experiment rather than allowing for full view of the preview. We centered the Slit around 0.3 s into the future since this provided some anticipatory information and a very high signal-to-noise ratio, as seen in Experiment 1. By focusing our analysis in this way we tested if the manipulations functioned as intended. Subjects in the error minimization mode were expected to place a lot of their attention in the visible slit region, which would result in strikingly high signal-to-noise ratios. Subjects in the effort minimization mode were expected to place less emphasis on these same regions, which should still result in enough signal to identify attentional allocation, but at lower signal-to-noise ratio than error minimizers. If effort minimizers reduced the overall amount of attention they allocated, we would be able to measure more signal from them if this reduction was concentrated to one region rather than across the entire roadway display. This specific contrast between error minimization and effort minimization would also be sufficient evidence to show that the performance mode we asked subjects to execute resulted in them attending very differently to the same roadway regions.

To test a confounding issue from our Experiment 1 results, we manipulated how we assigned the frequency labels during Perturbation blocks. Half of our subjects had frequency labels assigned to the previewed positions in a *descending* order, such that the highest frequency label was assigned to preview position 0.1 s and the lowest frequency label was assigned to preview position 1.0 s; the other half of our subjects received *ascending* frequency label ordering, in which the frequency label ordering was reversed (Jagacinski, Hammond, & Rizzi, 2017). With this manipulation we were able to compare how subjects' attention was shaped by the frequency label ordering in the slit region. Half of our subjects had a higher frequency assigned to position 0.3 s in the slit, and the other half had a lower frequency assigned to that same position. Now we could further test the effect of different frequencies on attentional signal-to-noise ratio.

Effort vs. Error Tradeoff Manipulation

Subjects were given instructions on how they should execute the tracking task. We utilized a between subjects design to make half the subjects perform the task by minimizing error and the other half by minimizing effort.

Subjects in both groups were given feedback on their performance. On a trial-by-trial basis we gave subjects measures of their performance accuracy and effort. "Accuracy" was reported as the root-mean-squared (RMS) error which was calculated as a difference between the input to the system (the roadway) and the output of the system (the cursor's lateral position). "Effort" was reported as RMS joystick which corresponded to the root-mean-squared joystick displacement. The joystick was measured as the amount of lateral displacement subjects made away from its center position; the more movements they made, the higher their RMS joystick scores.

This feedback was utilized to manipulate the style of performance. Subjects in the error minimizing conditions were told to maintain their error scores low, less than 0.9 RMS error which corresponded to the cursor being off the center of the road approximately 1° of visual angle on average. The 0.9 RMS value was chosen because it was approximately half of what the RMS error score would be if subjects simply did nothing (1.76 RMS); this provided reasonable challenge to our novice subjects. Subjects in effort minimizing conditions were instructed to maintain effort low, less than 2.3 RMS joystick which corresponded to the joystick being off the center position by approximately 6.9° on average. Subjects with low RMS errors in previous experiments tended to have about 3.6 RMS joystick scores, so our threshold was about a 36% reduction in effort; lower RMS joystick thresholds resulted in more nonproportional joystick control. Both groups received numerical feedback on both accuracy and effort with the only difference between them being which aspect of the feedback was emphasized. This insured any changes in their performance would be the result of differences in the cognitive strategies used to minimize either error or effort.

It is relevant to note that effort minimizers were told to perform “less effortfully” even though the term *effort* might be vague to subjects in our study. We wanted to avoid a more deliberate instruction such as “make less movements” because that would have a more direct impact on how they used the joystick. We aimed to show that when subjects were told to be less effortful this would in turn lead to performance with different ranges of movements than those subjects who are told to be more accurate.

Results

Manipulation Check

Before analyzing the data in detail we plotted subjects' accuracy against their effort. We used RMS error and RMS joystick as our measures of accuracy and effort, respectively. Figure 12 shows that subjects were able to successfully meet our performance criteria and adopt either an error minimizing or effort minimizing style. This was true for two of the block types in our study; the figure shows that error minimizers were mostly unable to keep their error scores below our threshold during Input Disturbance blocks. That is not surprising because the injected wind gust disturbances make this condition significantly more challenging, which tended to result in much higher RMS error scores than other blocks. Note that there is little overlap of the two groups in Figure 12, even for Input Disturbance Blocks.

A 2 x 2 x 3 analysis of variance (Performance Style: Error minimizing, Effort minimizing; Frequency Label Order: Ascending, Descending; Block Type: Control, Perturbation, Input Disturbance; Performance Style and Frequency Label were between-subject, and Block Type was within-in subject) found a main effect of Performance Style on RMS joystick [$F(1, 20) = 176.66$, $p < 0.01$; $\bar{x}_{Error\ minimizing} = 3.70$, $\bar{x}_{Effort\ minimizing} = 2.25$]. Subjects were able to successfully adopt distinct modes of tracking. Additionally, a two-way interaction between Performance Style and Block type

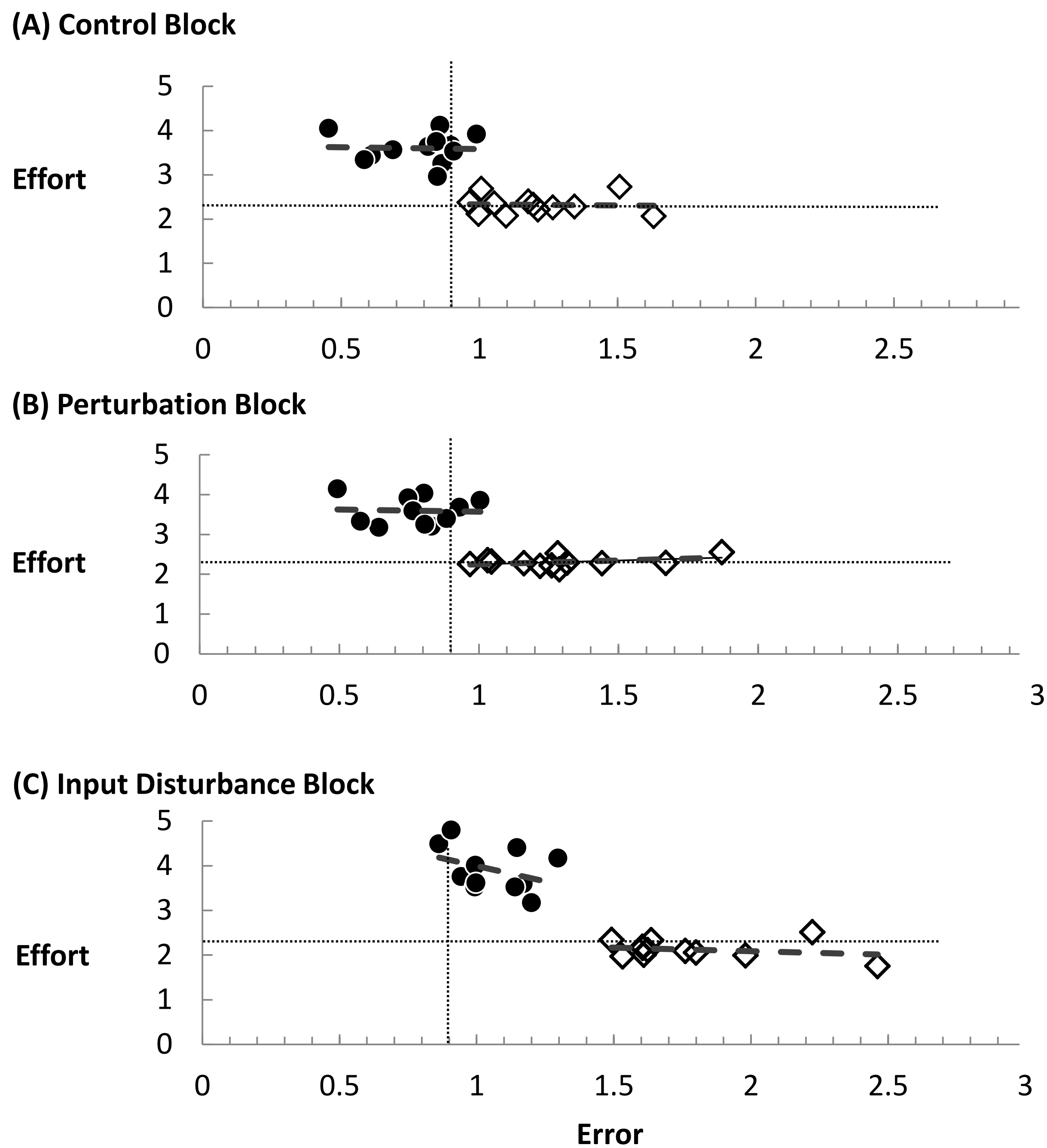


Figure 12. Relationship between error and effort in the three block types of Experiment 2. Vertical small dotted lines represent the error thresholds given to error minimizing subjects; horizontal small dotted lines are effort thresholds given to effort minimizing subjects. The large dash lines correspond to the linear relationship between error and effort within each performance style group.

was found [$F(2, 40) = 10.50$, $p < 0.01$]. Error minimizers tended to show similar RMS joystick values (i.e., effort) for Control and Perturbation blocks but significantly higher values during Input Disturbance blocks, whereas effort minimizers showed similar values for Control and Perturbation blocks but significantly lower values during Input Disturbance blocks. Essentially, during Input Disturbance blocks error minimizers used more control movement and effort minimizers used less (Figure 13).

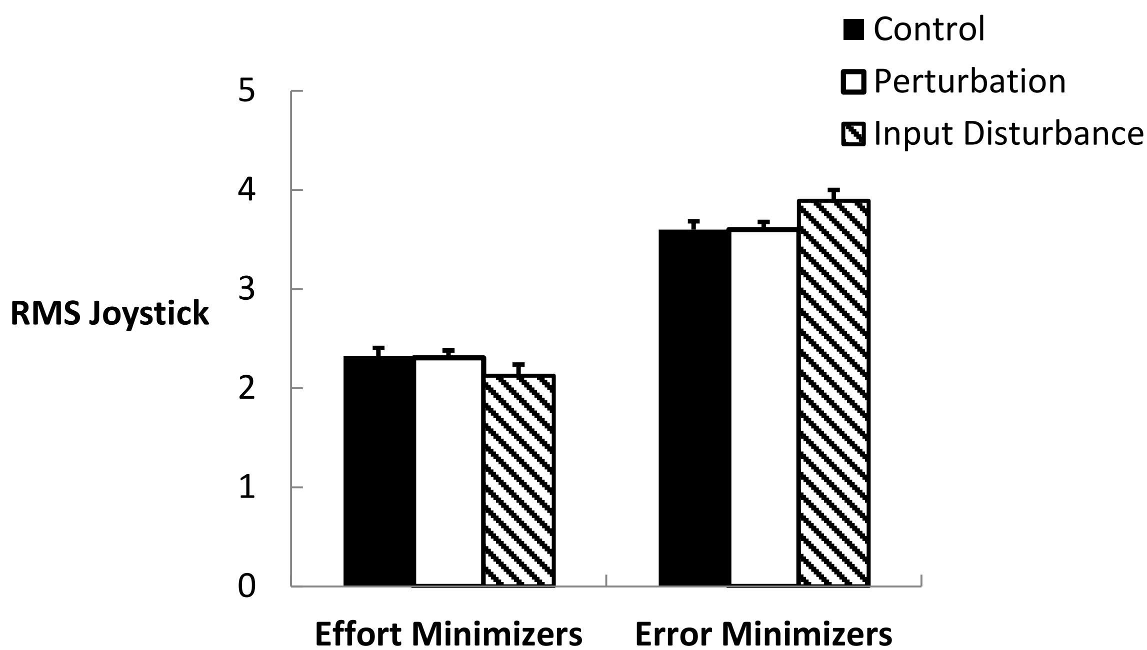


Figure 13. Graphs shows a main effect of Performance Style and Block type on root-mean-squared (RMS) joystick, a measure of effort during tracking.

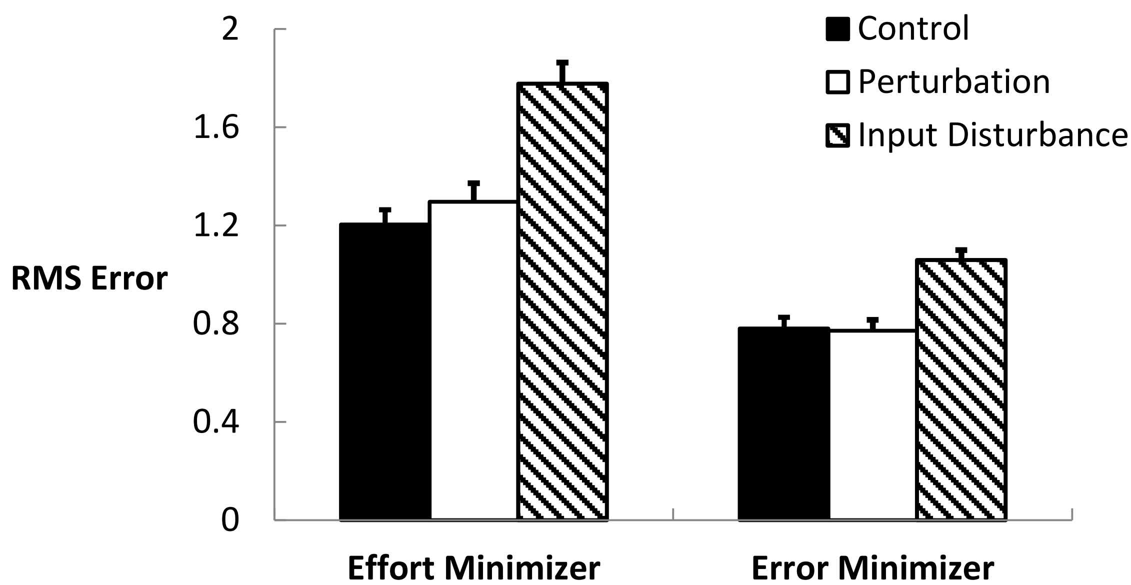


Figure 14. Graphs shows a main effect of Performance Style and Block type on root-mean-squared (RMS) error.

To determine Performance Style's effect on tracking accuracy we conducted an analysis using RMS error as our measure of tracking ability (same as in Experiments 1A – 1C). A 2 x 2 x 3 analysis of variance on RMS error (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending; Block Type: Control, Perturbation, Input Disturbance; Performance Style and Frequency Label Order were between subjects, Block Type was within-subject) uncovered a main effect of Performance Style. Error minimizers had lower RMS error scores [$F(1, 20) = 43.97$, $p < 0.01$; $\bar{x}_{Error\ minimizers} = 0.88$, $\bar{x}_{Effort\ minimizers} = 1.43$] indicating that our performance feedback was affective. We also found a main effect of Block Type on performance [$F(2, 40) = 221.27$, $p < 0.01$; $\bar{x}_{Control\ block} = 0.99$, $\bar{x}_{Perturbation\ block} = 1.04$, $\bar{x}_{Input\ Disturbance\ block} = 1.42$]; it was easier for subjects to track the roadway during Control blocks, and unsurprisingly most difficult during Input Disturbance blocks (Figure 14).

The analysis also revealed a Performance Style by Block type interaction [$F(2, 40) = 21.57$, $p < 0.01$]. Input Disturbance blocks were particularly challenging for effort minimizers whose decrement in performance was amplified during these blocks. A three-way interaction among all the variables was also significant [$F(1.6, 40) = 5.33$, $p < 0.02$, Greenhouse-Geisser adjusted]. Surprisingly, Error minimizing subjects in Control blocks had substantially lower error if they had experienced the descending frequency label order during Perturbation blocks than if they had experienced the ascending frequency label order. This result suggests that the Control block performance of error minimizing subjects somehow benefitted from exposure to the descending perturbation block.

Attentional Distribution

To determine whether performance style had on effect on our attentional measure, we compared the signal-to-noise ratios of these two groups. We incorporated the slit from Experiment 1 into this study and centered it on 0.3 s. We hoped that by limiting the amount of preview available to subjects we could get a more sensitive measure of the effect of performance style within the restricted preview region. Figure 15 shows that the attentional distribution of error minimizers and effort minimizers are practically indistinguishable within the slit. This suggested that our manipulation may not have had an effect on how subjects attend to the roadway within the slit.

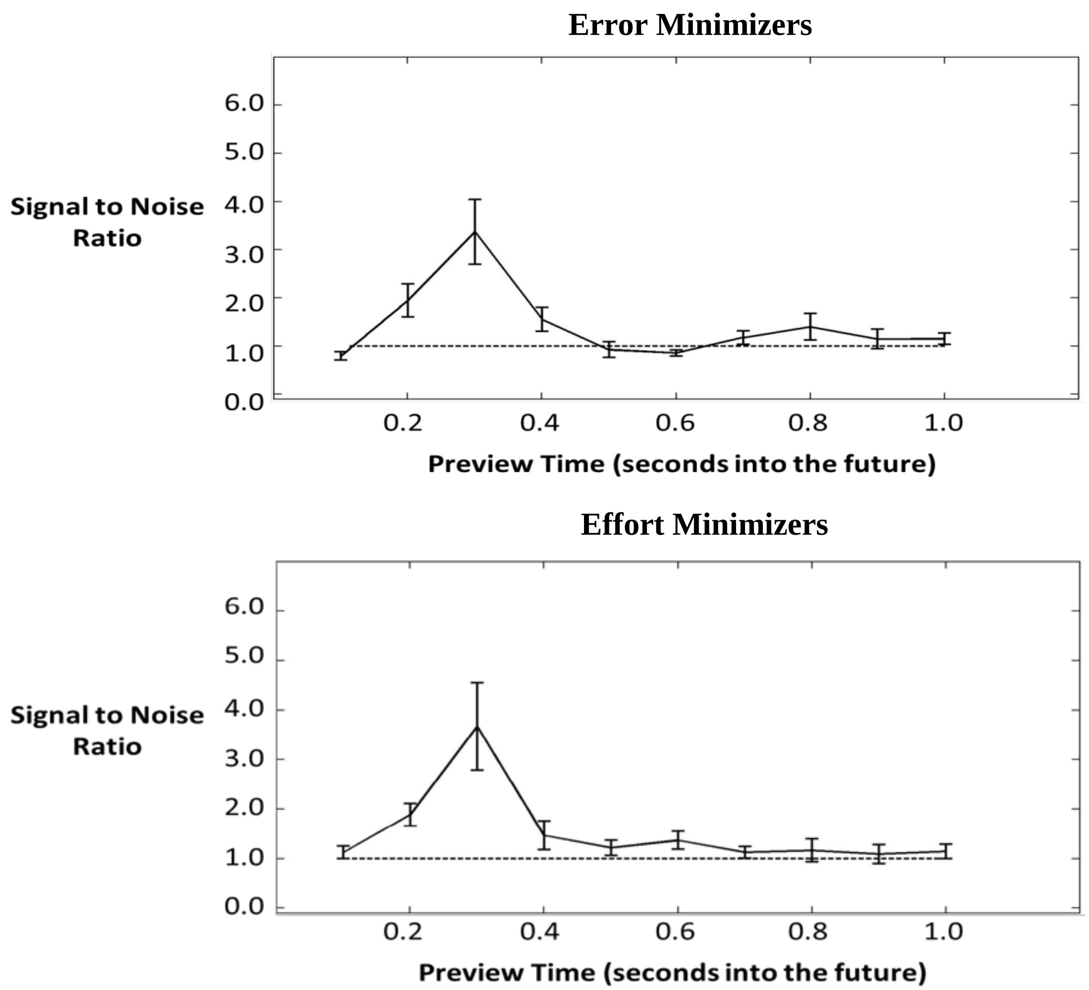


Figure 15. Average attentional allocation for 12 error minimizing subjects and 12 effort minimizing subjects tracking with roadway preview being restricted by a slit centered on 0.3 s into the future. The shape of these graphs suggests performance style had no effect on attentional allocation. The error bars represent ± 1 standard error.

We examined the signal-to-noise ratios within 0.2 s to 0.4 s preview regions, the only regions in which roadway information was not fully concealed by the slit. We conducted a 2 x 2 x 3 analysis of variance (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending; Preview Position: 0.2 s, 0.3 s, 0.4 s; Performance Style and Frequency Label Order were between subjects; Preview Position was within-subject). This analysis confirmed there was no main effect of Performance Style on the attentional measure [$F(1, 20) = 0.03$, $p > 0.05$; $\bar{x}_{Error\ minimizers} = 2.29$, $\bar{x}_{Effort\ minimizers} = 2.34$]. A main effect of Preview Position was found which affirmed the tendency for subjects to focus most of their attention in the central area of the slit [$F(2, 40) = 12.70$, $p < 0.01$; $\bar{x}_{0.2\ s} = 1.92$, $\bar{x}_{0.3\ s} = 3.52$, $\bar{x}_{0.4\ s} = 1.51$]. To our surprise, we also found a main effect of Frequency Label Order [$F(1, 20) = 22.39$, $p < 0.01$; $\bar{x}_{Ascending} = 1.58$, $\bar{x}_{Descending} = 3.05$]. This result implied that higher-frequency visual perturbations resulted in higher signal-to-noise ratios (Figure 16). In other words, these visual disturbances may have had a capturing effect on attention.

An interaction between Preview Position and Frequency Label order was also found [$F(2, 40) = 20.82$, $p < 0.01$]. Subjects that experienced ascending frequency label order had low signal-to-noise ratios across all 3 preview positions visible in the slit, but subjects who were in the descending frequency label order had substantially higher ratios at 0.3 s and 0.2 s preview positions (Figure 16).

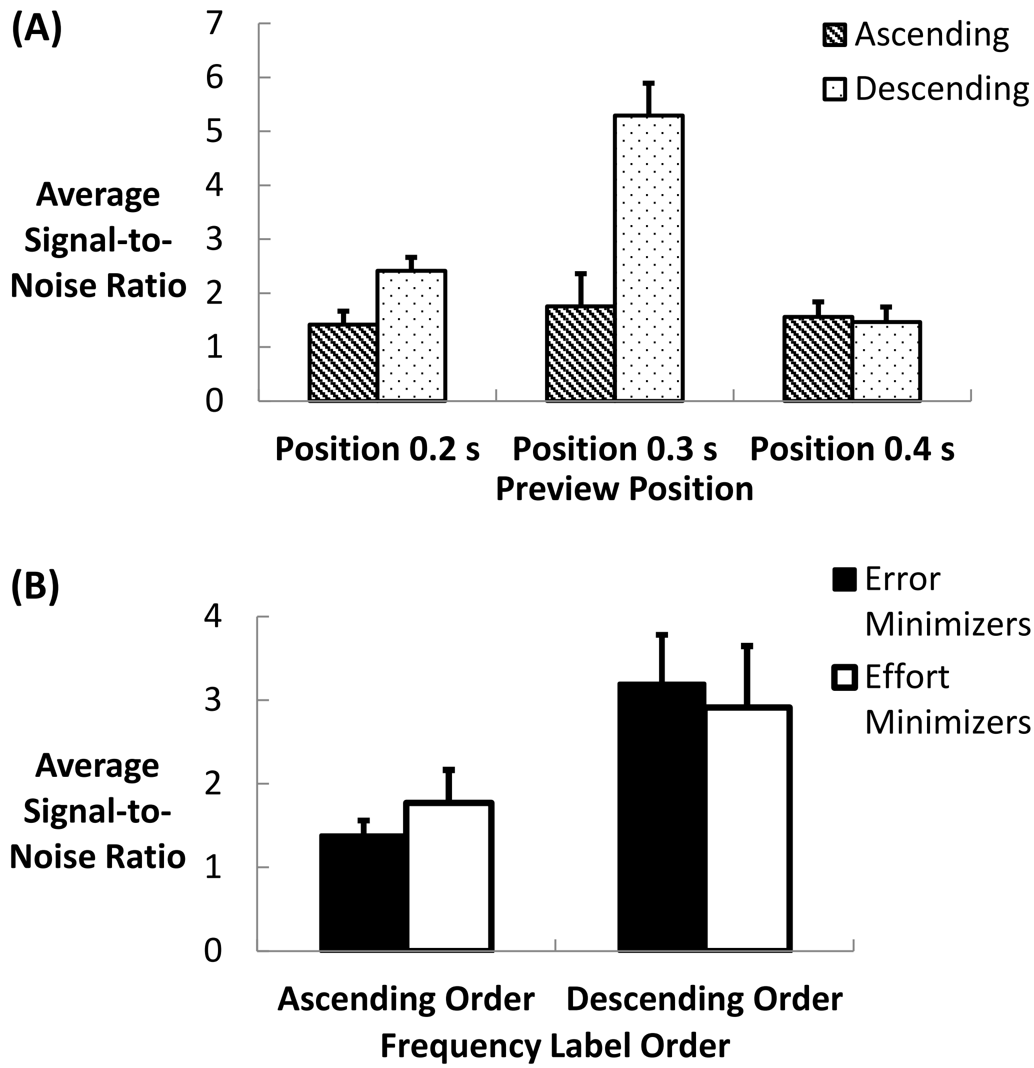


Figure 16. (A) The interaction between Preview Position and Frequency Label Ordering shows that subjects with the ascending frequency label order had similar signal-to-noise ratios across all three preview positions, but subjects with the descending frequency label order showed substantially more attentional signal at position 0.3 s. (B) Frequency Label Order had an effect on attention; descending frequency order resulted in higher signal-to-noise ratios. Performance style did not show evidence of affecting attentional allocation.

Tracking Performance

As with the previous experiments, we looked at tracking error in the frequency domain to assess how higher derivatives of tracking error were affected. For this analysis we only considered Perturbation and Control blocks. We were interested in how feedforward affected the smoothness of tracking the roadway. The Input Disturbance blocks emphasized error correction when unexpected errors were introduced into the feedback loop, and were not included in this analysis.

A 2 x 2 x 2 analysis of variance on Position error (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending; Block Type: Control, Perturbation; Performance Style and Frequency Label Order were between subjects, Block Type was within-subject) found similar results as the RMS error analysis. A main effect of Performance Style showed error minimizers performed better [$F(1, 20) = 76.73$, $p < 0.01$; $\bar{x}_{Error\ minimizers} = 0.06$, $\bar{x}_{Effort\ minimizers} = 0.12$], and a main effect of Block Type found subjects had lower Position error scores during the Control block [$F(1, 20) = 5.20$, $p < 0.04$; $\bar{x}_{Control\ block} = 0.085$, $\bar{x}_{Perturbation\ block} = 0.090$]. A two-way interaction of Performance Style by Block Type revealed effort minimizing subjects performed slightly worse during the Perturbation block than during the Control block, but error minimizing subjects performed similarly in both [$F(1, 20) = 4.76$ $p < 0.05$]. Finally a three-way interaction [$F(1, 20) = 6.39$, $p < 0.04$], seems to be driven by error minimizers who were exposed to the descending Perturbation blocks having lower Position error scores during Control blocks.

We took derivatives of the Position error in the frequency domain to create the Velocity and Acceleration error scores. These signals represented how smoothly subjects tracked. A 2 x 2 x 2 analysis of variance on Velocity error (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending; Block Type: Control, Perturbation; Performance Style and Frequency Label Order were between subjects, Block Type was within-subject) found a main effect of Performance Style [$F(1, 20) = 9.26$, $p < 0.01$; $\bar{x}_{Error\ minimizers} = 0.27$, $\bar{x}_{Effort\ minimizers} = 0.33$] and Block Type [$F(1, 20) = 4.93$, $p < 0.04$; $\bar{x}_{Control\ block} = 0.30$, $\bar{x}_{Perturbation\ block} = 0.31$]. The rate of change of lateral position on the roadway was tracked better by error minimizers and during Control blocks.

A 2 x 2 x 2 analysis of variance on Acceleration error (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending; Block Type: Control, Perturbation; Performance Style and Frequency Label Order were between subjects, Block Type was within-subject) found no significant effects. This was expected because a slit was utilized for all conditions of this study. As seen in Experiment 1A – 1C, it is difficult to track the curvature of the roadway when there is a slit limiting the availability of this information; failing to track curvature well results in higher acceleration errors.

Feedback Sensitivity

Input Disturbance blocks injected wind gusts into the tracking task that could not be previewed by subjects, but had a clear effect on the position of the cursor they controlled. For subjects to effectively track the roadway they needed to nullify these injected output errors. By analyzing subjects' joystick movements in response to these wind gust disturbances we could characterize their feedback performance using the McRuer crossover model (McRuer & Jex, 1967). This model posits that the human-plus-vehicle transfer function can be approximated as a gain (K), time delay (τ), and an integrator. The gain represents how sensitive a system is to error; it determines the bandwidth of frequencies for which the system is effective at error nulling. The time delay represents the human's processing time for translating error into appropriate corrective movements. By determining our subjects' gains and time delays we can assess whether they were affected by the performance style manipulation.

To generate gain and time delay estimates we used the same procedure that was conducted in Jagacinski, Hammond, and Rizzi (2017). The error signal and output signal from Input Disturbance trials were multiplied by a Hanning filter, and then analyzed with a Fourier analysis. For each of the 10 frequencies used to generate the wind gusts, a median amplitude ratio and a phase shift from error to output was calculated from the 4 trials in the Input Disturbance block. The gain can be determined by graphing the logarithm of amplitude ratios versus the logarithm of frequency. The wind gust amplitude ratios will generally form a line with a slope close to -1, and the frequency at which the amplitude ratio equals 1 corresponds to the gain (K) of the system (Figure 17). The middle 6 frequencies were used for this calculation. Similarly, if we graph the phase shift of the error versus output against frequency, the line formed by the phase shift at wind gust frequencies will be negative and its slope will be an estimate of the time delay of the

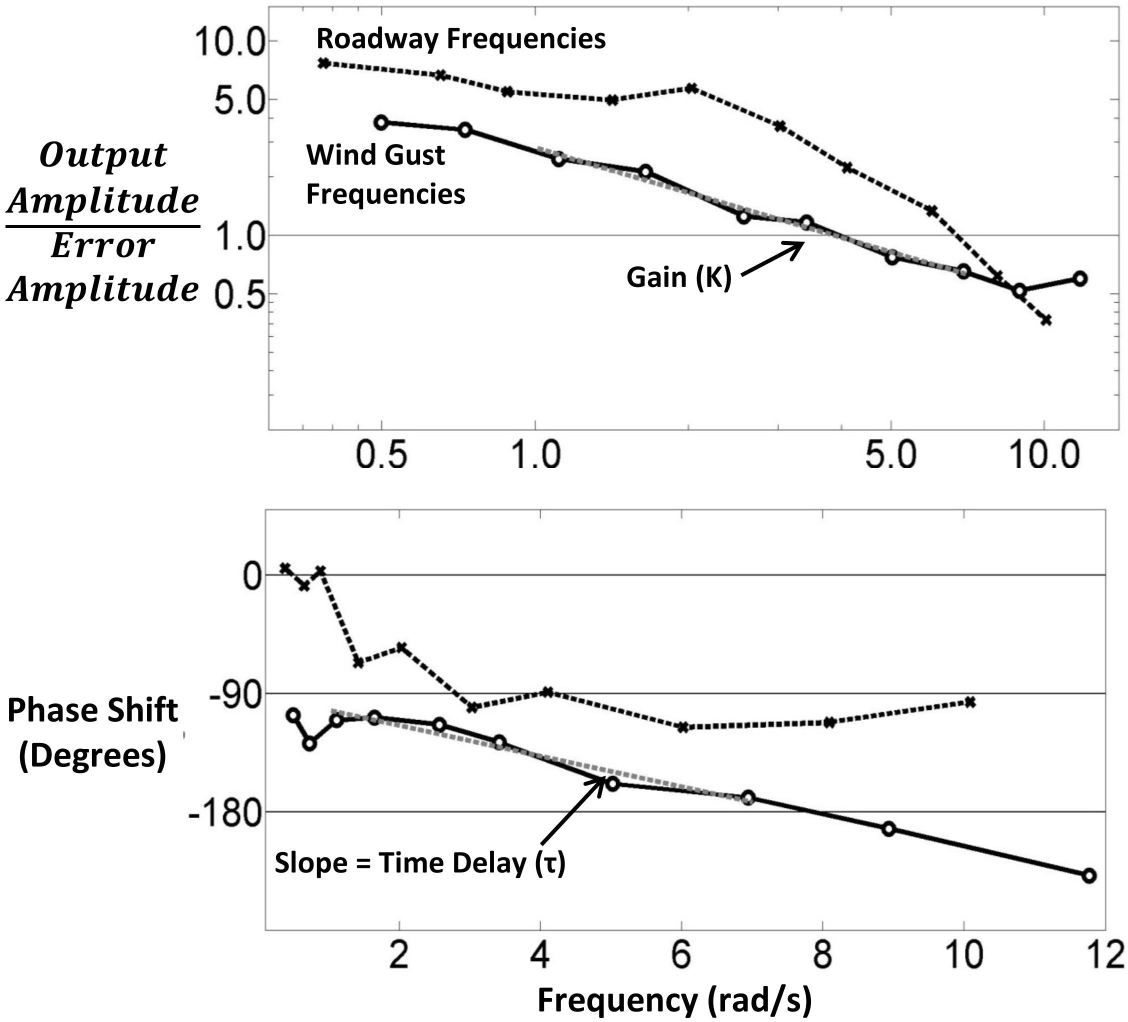


Figure 17. Responses to wind gusts during the tracking task were used to determine feedback characteristics of subjects (McRuer & Jex, 1967). (A) Amplitude ratio of output versus error. The point at which amplitude ratio to wind gust frequencies crosses 1 is known as the crossover frequency. (B) Phase shift versus frequency. Slope of the system's response to wind gust frequencies corresponds to time delay of the system.

system. The y-intercept of this line will also be close to -90° on this graph reflecting the integrator characteristic of this model (For a more thorough explanation of this model see McRuer and Jex, 1967). An example of these graphs from an error minimizing subject can be seen in Figure 17.

Figure 18 clearly shows that when graphing gain against time delay, effort and error minimizers grouped together. We conducted 2 x 2 analysis of variance on the gains (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending); we included Frequency Label Order into the analysis for completeness even though it applied during Perturbation blocks. We found a main effect of Performance Style [$F(1, 20) = 80.40$, $p < 0.01$; $\bar{x}_{Error\ minimizers} = 2.56$, $\bar{x}_{Effort\ minimizers} = 0.94$]. Error minimizers had significantly higher gains than effort minimizers (Figure 19). No other effects emerged. Similarly, a 2 x 2 analysis of variance on the time delay (Performance Style: Error minimizing, Effort Minimizing; Frequency Label Order: Ascending, Descending) found a main effect of Performance Style indicating error minimizers had lower time delays than effort minimizers [$F(1, 20) = 5.61$, $p < 0.03$; $\bar{x}_{Error\ minimizers} = 0.21$, $\bar{x}_{Effort\ minimizers} = 0.25$]. No other effects were found for the time delay measure (Figure 19).

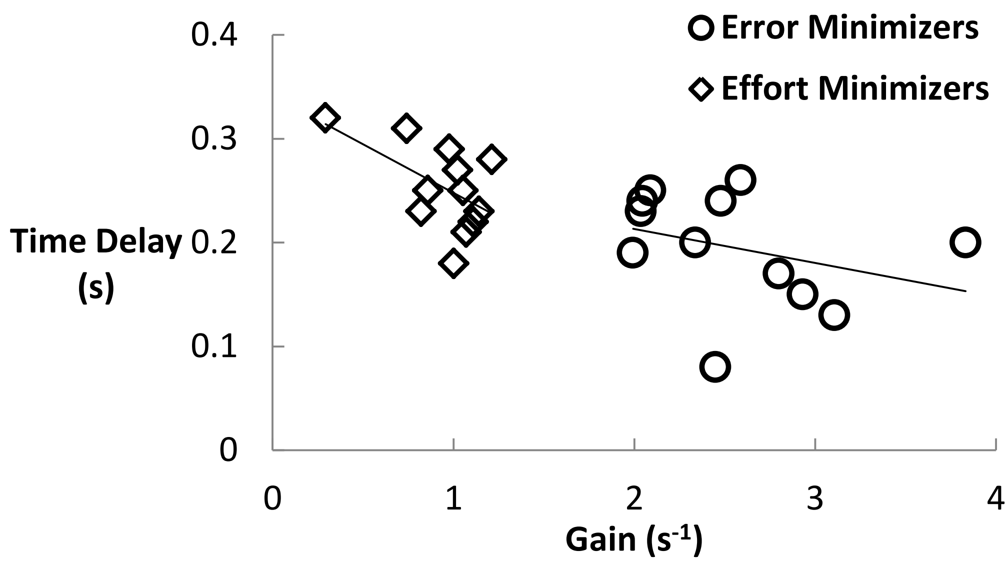


Figure 18. Subjects' gains versus time delays shows a negative correlation between the two measures, and a clear grouping based on Performance Style.

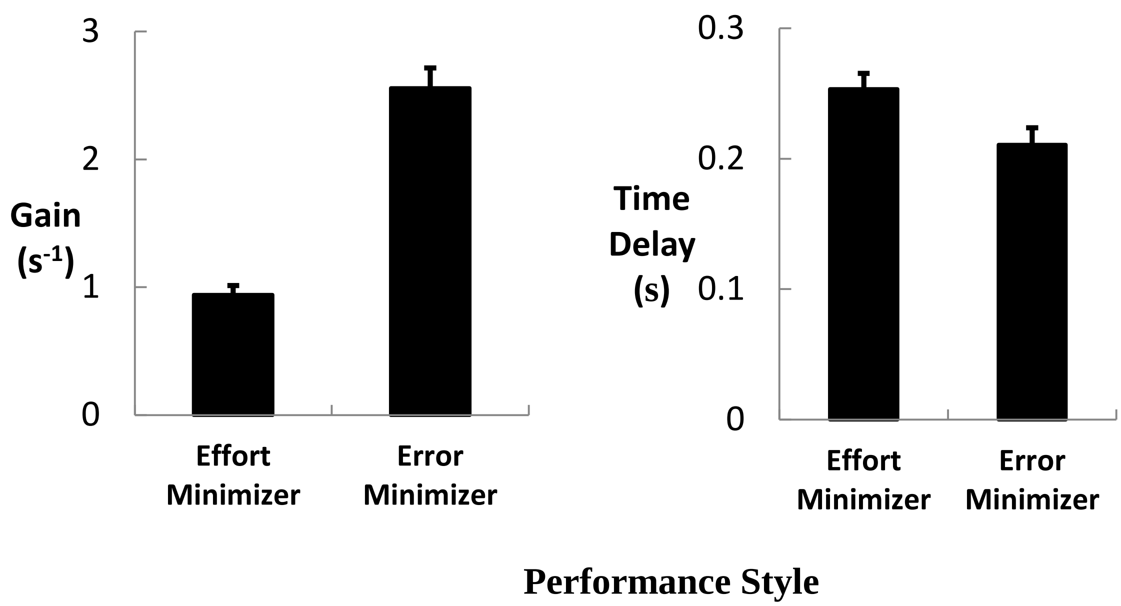


Figure 19. Main effect of Performance Style on gain (left) and time delay (right).

Prevalence of Noise in Attentional Measure

Experiment 2 occluded parts of the previewed roadway by utilizing a slit as was done in Experiment 1A and 1B. This allowed us to calculate how much measurement noise was present in our study by counting how often signal-to-noise ratios were fairly large in regions that were being occluded by the slit on the display. 10.7% of the occluded roadway preview regions had attentional signal-to-noise ratios of 2 or more due to noise in the measurement procedure. This was higher than the 6.5% noise rate in Experiments 1A and 1B. However, a stricter criterion of looking for signal-to-noise ratios above 2.5 found only 3.0% of the attentional signal-to-noise ratios were due to noise. This was higher but closer to the 2.3% prevalence we found previously. We also considered signal-to-noise values of 3.0 or greater as an even stricter criterion, and found that noise in the measurement reached this level only 1.0% of the time in this study, same as in Experiment 1. These findings increase our confidence in the accuracy of our attentional measurement procedure.

General Discussion

In this study we investigated how performance style affected tracking a moving roadway. In previous studies, some highly motivated subjects put a lot of effort into minimizing their error score, while others appeared more relaxed in their tracking, even at the expense of their own accuracy. We were curious as to what effect these distinct tracking styles may have on attentional allocation to the previewed roadway. We manipulated subjects' performance style by emphasizing either their error or effort feedback during tracking, though all subjects received feedback on both. This allowed us to test predictions made by Miller (1976) regarding the optimal weighting of preview. According to his model there is a tradeoff between minimizing error and minimizing effort while tracking. This tradeoff would result in different attentional weightings being placed on the available preview.

The instructions provided to subjects had a clear effect on their performance. From Figure 12 we could see that meeting our error or effort criteria changed how they tracked the target. These emphases resulted in one group of subjects with lower root-mean-squared error scores and higher root-mean-squared control stick scores than the other. Therefore, we labeled these two groups as either error minimizing or effort minimizing subjects depending on the criterion they were instructed to meet. Subjects were mostly able to meet our requirements, except during Input Disturbance Blocks in which we added wind gusts that unpredictably pushed the cursor they controlled. The added noise to their task made this type of block particularly challenging; however, a clear distinction between the performance styles of error and effort minimizers remained (Figure 12).

We examined Miller's (1976) predictions that a subject's error or effort emphasis should affect their attentional distribution to preview. However, our results found the attentional distributions of the two groups were practically identical. Miller (1976) predicted that a rate control system with an error minimizing emphasis would place the highest attentional weights on preview regions closest to the vehicle, with the weightings exponentially decreasing as one moved further into the future. In contrast, if the system emphasized minimizing effort we should expect relatively low attentional weights across most of the available preview with slower decrease in weightings across preview. Our experimental results did not confirm this difference between the two emphases.

Our manipulation changed subjects' movement effort in hopes of finding an effect on attentional effort (i.e., attentional distribution), but Kahneman (1973) argued that the attentional effort in a task is instead influenced by the demands of the task. For tracking this would mean a very difficult tracking task would require more attentional effort allocated to preview, which could then result in more movement effort. This means it is possible to have a subject that is allocating a lot of attention to preview still respond with minimal movement effort. This is the dichotomy we saw in our results; subjects attentional distributions remained the same though their performance styles changed. The interesting question that remains is whether subjects could voluntarily reduce their attentional effort during difficult tracking, and would this reduction affect movement effort?

It is worth noting that there are some differences between Miller's calculations and our experiment. For one, Miller did not consider a system with a time delay, whereas our model of tracking behavior includes it. It may be possible that his exclusion of a time delay in his calculation could have some effect on the predicted attentional weights. The more striking difference is that our experiment limited the amount of preview information available to subjects by a slit. Subjects could only see a small region of the preview display centered on 0.3 s into the future. We thought that by restricting the preview information we could increase the sensitivity of our comparison between error minimizers and effort minimizers. However, by imposing this limitation it is possible that we may have fundamentally changed the attentional process in the tracking task. We can conclude that if preview is limited to a small region, the effortfulness of a trackers' control seems to have no significant effect on the attention they will place on available preview. It remains possible that if our subjects had a fuller amount of preview available to them (0.1 s – 1.0s), we might have found a difference in the attentional distribution of error and effort minimizers as predicted by Miller.

In Experiment 1 we found that the frequency labels we used had an effect on the signal-to-noise ratios we measured in subjects. In Experiments 1A and 1B subjects showed higher measures of attentional signal when the preview was restricted to 0.3 s into the future compared to 0.6 s into the future. However, the 10 previewed roadway regions on the display always had the same frequency labels assigned to them, which meant the 0.3 s region had a higher frequency label than 0.6 s region. When we compared these two preview regions in Experiment 1C by controlling for the frequency labels assigned in each slit region, we found no difference between the attentional signal-to-noise ratios; this suggested that the results from Experiment 1A and 1B could have resulted from attention being captured by the specific frequency label present at the slit location.

We investigated this effect by manipulating the order in which frequency labels were assigned to the preview locations. Because all subjects were restricted to preview at

0.3 s, we could determine if attention would be affected by whether we assigned a high or low frequency label to it. We applied a method used in a previous tracking experiment by Jagacinski et al. (2017) in which they compared two approaches to assigning the labels to the roadway, either in ascending order or descending order. Frequency labels could be organized to roadway positions 0.1 s – 1.0 s from lowest frequency to highest (i.e., ascending) or from highest frequency to lowest. The logic behind this arrangement was that randomly assigning the frequency labels to the roadway could result in visual artifacts that might disrupt attention, such as when a particularly low frequency label might occur directly adjacent to a particularly high frequency label. By assigning frequency labels in either of the two orders avoided attentional allocation being shaped by large neighboring differences in the frequency labels. Jagacinski et al. (2017) found that regardless of frequency label order, subjects attended most heavily to the closest preview regions. However, the magnitudes of their attentional signals were lower for the ascending arrangement (i.e., lowest frequencies labels closer to the vehicle and higher frequencies labels further away).

This study found a similar effect of frequency label ordering. Subjects who had the ascending frequency label ordering showed lower signal-to-noise ratios than those who had the descending ordering. This suggests our subjects' attention was at least somewhat influenced by the frequency label used. Our expectation was that the use of the slit would reduce the effect of the frequency label ordering because concentrating subjects' attention to a small preview region would increase the attentional signal-to-noise ratios. We thought this increase should make the difference between ascending and descending orderings minimal, but that was not the case. The difference this experiment found between frequency label orderings confirms that the differences in signal-to-noise ratio between slits at 0.3 s and 0.6 s in Experiment 1A and 1B was also influenced by the labels themselves.

Though our manipulation did not affect attention, it did show clear effects on tracking performance. As mentioned before, error minimizers had lower error and higher effort scores than effort minimizers. The effect of performance style on tracking was equally evident when looking at performance in the frequency domain. Error minimizers had lower Position error scores than effort minimizers, implying that they could track the frequency components of the roadway more accurately than effort minimizers. Furthermore, they also demonstrated lower Velocity error scores than their counterparts, indicating they tracked the rate of change of the roadway more accurately as well. In contrast, no difference was found between the two Performance Style groups for Acceleration error, a measure representing how well subjects matched the curvature of the roadway with their joystick movement. This result was expected because we utilized a slit in our study, and Experiment 1A – 1C found that curvature is tracked poorly without full view of the previewed roadway. Therefore, Acceleration error was expected to be high in both performance style groups.

Performance style also had a noticeable effect on our measures of feedback sensitivity. We utilized the McRuer Crossover model, which approximates a tracking system as a gain, an integrator, and time delay for feedback control (McRuer & Jex, 1967). According to the model, a system with a sufficiently high gain and low time delay would respond best to the error signal, which would result in effective tracking performance. Our analysis revealed that error minimizers showed larger gain values and lower time delays than effort minimizers. This means they were effective at tracking the roadway over a wider bandwidth of lateral roadway deviations. Their lower time delays suggest they could process the roadway changes into control responses faster than effort minimizers. Similar results on gain were found in a previous study in which a trained subject adjusted his compensatory tracking to meet specified error and effort criteria (D.C. Miller, 1965). This study found the subject varied his gains in response to these criteria. However, this study did not report an effect for time delays. Other studies that used optimal control to model tracking behavior have found that lower bandwidth input resulted in higher feedback time delays (McRuer & Jex, 1967). A likely explanation for the results in our study is that Effort minimizers ignored higher frequency roadway information, and tracked the roadway as if it had a lower bandwidth.

All these results taken together shed some light onto two aspects of control during tracking. Our Performance style manipulation showed no evidence of affecting how subjects were attending to the preview information, yet the two groups showed differences in feedback control. This suggests feedback and feedforward control are two different aspects of motor planning during tracking. It was in fact surprising that attention in this experiment was only affected by the frequencies of the visual perturbations used to measure it (i.e., frequency labels). This can be thought of as a bottom-up effect on attention rather than a top-down effect of executive control.

The distinction between the feedback and feedforward systems was also seen in Jagacinski et al. (2017) in which subjects tracked either a 1 or 3 rad/s roadway. They found the bandwidth of the roadway affected feedback response but not feedforward attentional distributions. Neither Miller (1976) nor Sharp (2005) predicted an effect of bandwidth on feedforward control, but they did predict that a relative emphasis on error and effort should affect attention. Our results from this experiment indicate that their analyzes of fuller preview do no generalize to much more restricted preview as in the Slit condition. Subjects clearly adopted different emphases of error and effort and the only effects we observed were on feedback gains and time delays and not attentional distributions. From this experiment we concluded that feedback control is sensitive to both task and instructional demands, while feedforward attention was most affected by bottom-up aspects of the task environment.

Chapter 6: Experiment 3 - Effects of Dynamics on Tracking Performance

In this experiment we tested whether the attentional distribution to previewed roadway changed with different vehicle dynamics. Subjects in Experiments 1 and 2 used a rate control dynamic during tracking. In this study we compare the effects of different control dynamics on performance and attention. Steering control of an actual car is more closely simulated by an acceleration control system in which the steering actions of the controller affect the curvature of the car's trajectory. Studies have shown that second-order control systems tend to have less accurate subject tracking performance (Burgess-Limerick, Zupanc, & Wallis, 2013). According to McRuer and Jex (1967) higher-order controls make tracking more difficult because these systems require more anticipation. Miller (1976) calculated how an optimal controller would weight preview based on different control dynamics, and demonstrated that the shape of those weights would be very different from one another. These findings taken together suggest that we should expect subjects' signal-to-noise ratios to be concentrated on preview regions that lie increasingly further away from the vehicle as control dynamic become more complex (Miller, 1976; Sharp, 2005).

The 3 rad/s bandwidth we have used for our roadway's lateral movements in Experiments 1 and 2 would make tracking with an acceleration control very difficult for subjects with only 1 day of practice. Therefore, to test the effects of different dynamics we compared a rate control to a lag control dynamic. The step response of a lag dynamic is an exponential approach to an asymptotic value. The lag's time constant is a measure of the amount of time to reduce the remaining distance from asymptote by a factor of *e* (2.718). We used a lag time constant of 1.5 s, a sluggish system, in the present experiment.

Hypotheses

We expect the dynamics of the system to have the following effects on subjects' performance measures:

(1) Feedforward control:

  a. We expected subjects using a rate control would show the same shape of attentional distribution we found in Experiments 1 and 2. Therefore, higher signal-to-noise ratios (i.e., attentional allocation) were expected at closer preview regions between 0.1 s and 0.3 s into the future with this dynamic.

  b. We expected the dynamics to affect the attentional signal-to-noise distributions. More specifically, Miller's (1976) modeling predicted that attentional distribution patterns of rate and lag control dynamics would both be exponentially decreasing for more distant preview. However, compared to lag control, rate control dynamics would have higher weights to closer preview and a somewhat sharper exponential decrease to more distant preview (Figure 20).

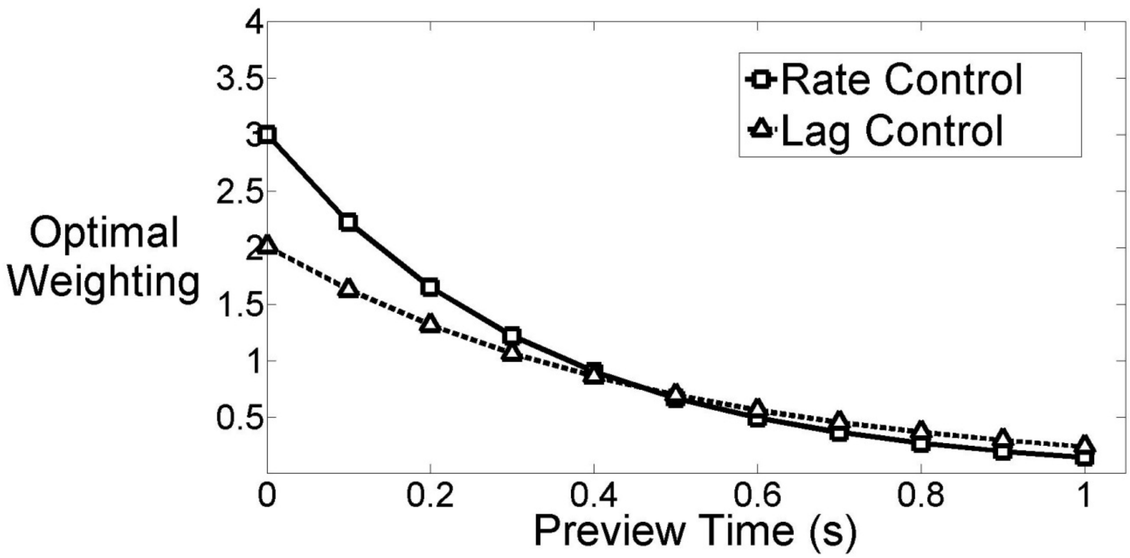


Figure 20. Predictions for the attentional weights to preview for rate and lag control dynamics based on Miller (1976). A similarly shaped attentional distribution is predicted for both dynamics, but rate control has higher weights at closer preview and sharper exponential decrease in weights. The prediction assumes identical error-versus-effort emphasis for both dynamics, as well as no time delay. The time constant for the lag control was 1.5 s.

c. Based on the results from Experiment 2, we expected the frequency label ordering to have an effect on the amplitudes of signal-to-noise ratios across the full view display. We predicted higher signal-to-noise ratios with descending frequency label orderings, particularly at close preview regions.

(2) Feedback control:

a. We expected to find higher root-mean-squared error scores for subjects when using a lag control than when using a rate control because their error nulling would be more difficult due to the sluggishness of the lag system (McRuer & Jex, 1967).

b. We predicted subjects' sensitivity to error would be higher in the lag control dynamic to partly overcome the sluggishness of the system. This should translate to higher gains than for subjects using rate control.

We compared the signal-to-noise ratios for subjects with different frequency label orderings assigned to the previewed roadway to test the effect the ordering would have on signal-to-noise ratios with full view of the roadway preview.

(3) Based on the results from the previous experiments, we predicted the frequency label ordering (ascending versus descending) on preview positions would have an effect on signal-to-noise ratios we measure. Specifically, the ascending frequency label order would reduce the overall attentional signal-to-noise ratios but not

change the general pattern of attentional distribution (Jagacinski, Hammond, & Rizzi, 2017).

Method

Participants

Twelve university students between 18 and 30 years of age volunteered for this experiment as part of an introductory psychology course. Seven participants were male, and five were female. To assess their eligibility for the study, they completed a short questionnaire and demonstrate 20/25 corrected vision on a basic eye exam. Informed consent was obtained from all participants.

Procedure

The same apparatus and similar procedures as the previous experiments were used. Subjects controlled a vehicle with full view of up to 1.0 s of preview. Subjects used either a rate control or a lag control dynamic. The gain of both dynamics was identical to that used in the previous experiments. The time constant of the lag dynamic was 1.5 s.

Half of the subjects used a rate control system, and the other half used a lag system. Similar to Experiment 2, all subjects performed a Control block, a Perturbation block to assess feedforward attention, and an Input Disturbance block to assess feedback control. The order of presentation was counterbalanced across subjects. Similar to Experiment 2, we manipulated the ordering of the frequency labels during Perturbation blocks. Half of our subjects received a descending order, and half received an ascending order.

Results

Attentional Distribution

Signal-to-noise ratios were calculated for all subjects to determine their attentional allocation to specific previewed roadway regions. Control blocks were compared to Perturbation blocks at 10 non-roadway frequencies that were added to preview positions 0.1 s apart down the roadway. Using Fourier analysis of subjects' joysticks movements, we took a ratio of the amplitude at each frequency during Control and Perturbation blocks to generate attentional signal-to-noise ratios at each preview region.

The attentional allocation distributions for subjects with rate and lag control dynamics did not appear to be qualitatively different (Figure 21). Consistent with our previous findings, subjects showed mainly an attentional focus on closer regions (0.1 s – 0.3 s) and less attention to more distant regions (0.5 s or greater). A 2 x 2 x 10 analysis of variance on the signal-to-noise ratios was conducted (Control Dynamic: Rate, Lag; Frequency Label Order: Ascending, Descending; Preview Positions: 0.1 to 1.0 seconds into the future). No main effects or interactions were found for rate versus lag control dynamics. The control dynamics did not significantly affect the subjects' attention to the upcoming roadway. Though frequency label order did not have a main effect as it did in the previous study, its effect was still present in an interaction between Preview Position and Frequency Label Order [$F(9, 72) = 3.99$, $p < 0.01$]. The interaction demonstrated that when full preview is available the descending ordering of frequency labels had higher signal-to-noise ratios than the ascending order in preview positions 0.1 s – 0.3 s,

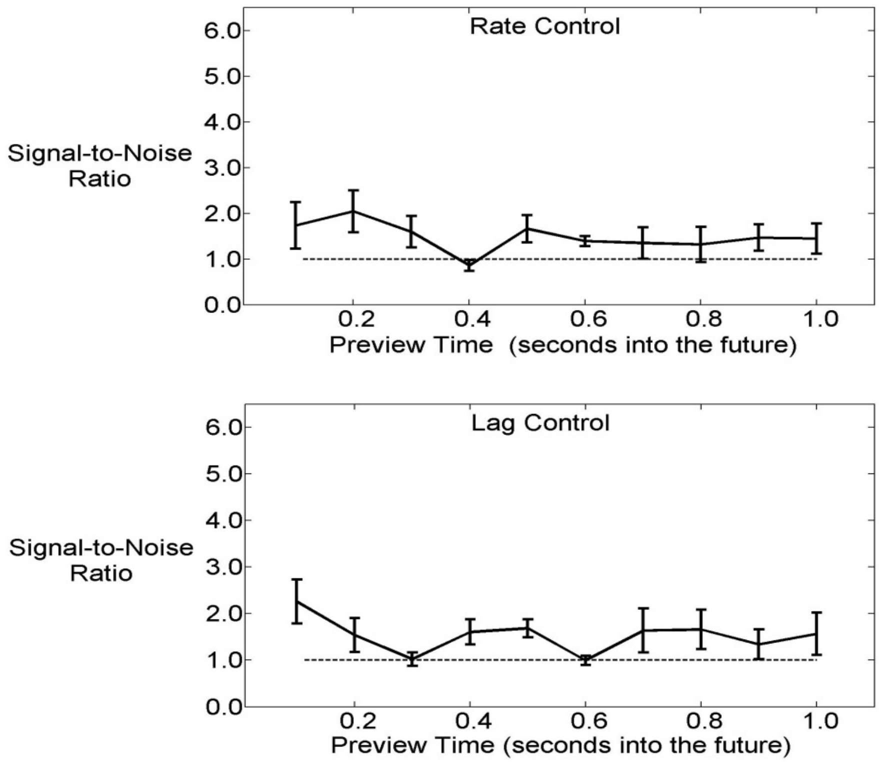


Figure 21. The attentional distributions of 6 subjects using a rate control and 6 subjects using a lag control dynamic during tracking. The graphs suggest there is no difference between the attentional allocations of these two dynamics. The error bars represent ± 1 standard error.

and slightly lower ratios in some of the more distant positions (Figure 22). Therefore, we can conclude that the frequency label ordering had a complex effect on the shaping of the attentional distributions of our subjects.

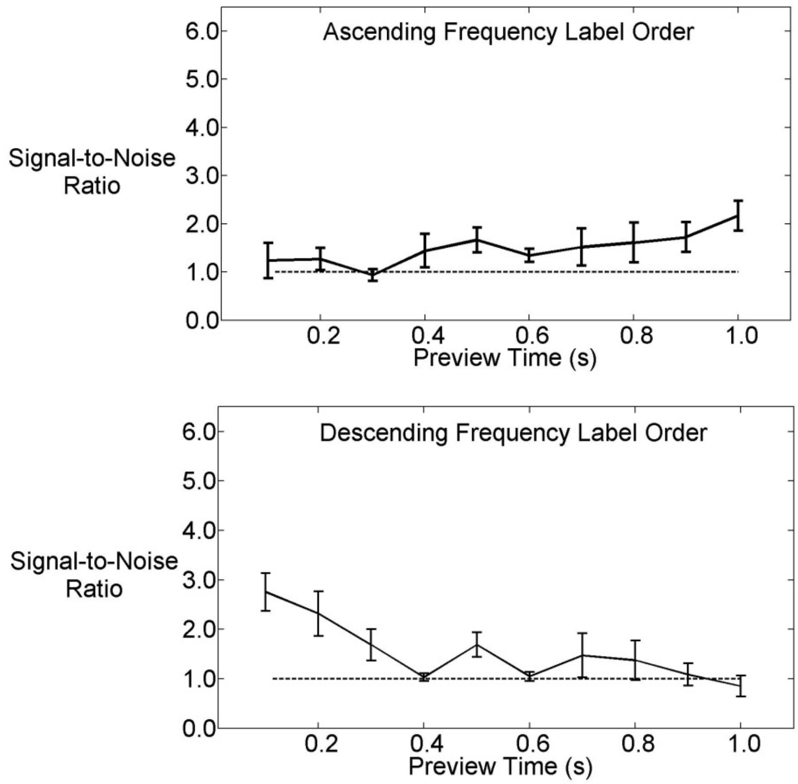


Figure 22. The attentional distributions of 6 subjects who received ascending and 6 subjects who received descending frequency label ordering during Perturbation blocks. The graphs show that ascending frequency label order biased subjects to look further down the roadway. The error bars represent ±1 standard error.

Tracking Performance

Tracking error was examined in both the time domain and the frequency domain to determine whether control dynamics affected subjects' performance. Root-mean-squared error was calculated for each of four trials in a block, and a median of those values was taken as an index of performance. Position error was calculated by calculating the median amplitudes in the Fourier spectrum of the error signal (system input – system output) at the 10 frequencies that generated the roadway, and then calculating its root-mean-squared value (Jagacinski, Hammond, & Rizzi, 2017); velocity and acceleration error were derived by taking the first and second derivatives of the position error, respectively.

A 2 x 2 analysis of variance on root-mean-squared error (Control Dynamic: Rate, Lag; Frequency Label Order: Ascending, Descending) found no main effects or interactions (Table 5). Similar results were found in the frequency domain. A 2 x 2 analysis of variance on Position error, Velocity error, and Acceleration error (Control Dynamic: Rate, Lag; Frequency Label Order: Ascending, Descending) all found no main effects or interactions.

We also examined at whether there were differences in "effort" measures between the two control dynamics. Effort was the root-mean-square of the lateral joystick displacement away from the center position (i.e., root-mean-squared joystick). A 2 x 2 analysis of variance on this measure (Control Dynamic: Rate, Lag; Frequency Label Order: Ascending, Descending) found a main effect of Control Dynamics; subjects with lag control dynamics had higher root-mean-squared joystick meaning they showed more effortful tracking [$F(1, 8) = 43.43$, $p < 0.01$; $\bar{x}_{Rate\ Control} = 3.22$, $\bar{x}_{Lag\ Control} = 4.63$]. No main effect or interaction was found for Frequency Label Order. All the results from our analysis on performance measures are summarized in Table 5.

Performance Measure	F statistic	Significance	Means
Root-mean-squared Error			
Control Dynamic	$F(1, 8) = 0.47$	*n.s.*	$\bar{x}_{Lag} = 0.571$ $\bar{x}_{Rate} = 0.498$
Frequency Label Order	$F(1, 8) = 0.03$	*n.s.*	$\bar{x}_{Ascending} = 0.543$ $\bar{x}_{Descending} = 0.526$
Interaction	$F(1, 8) = 0.01$	*n.s.*	$\bar{x}_{Lag,\ Ascending} = 0.586$ $\bar{x}_{Rate,\ Ascending} = 0.501$ $\bar{x}_{Lag,\ Descening} = 0.557$ $\bar{x}_{Rate,\ Descending} = 0.495$
Position Error			
Control Dynamic	$F(1, 8) = 1.06$	*n.s.*	$\bar{x}_{Lag} = 0.039$ $\bar{x}_{Rate} = 0.0.32$
Frequency Label Order	$F(1, 8) = 0.17$	*n.s.*	$\bar{x}_{Ascending} = 0.0.34$ $\bar{x}_{Descending} = 0.0.37$
Interaction	$F(1, 8) = 0.06$	*n.s.*	$\bar{x}_{Lag,\ Ascending} = 0.037$ $\bar{x}_{Rate,\ Ascending} = 0.031$ $\bar{x}_{Lag,\ Descening} = 0.042$ $\bar{x}_{Rate,\ Descending} = 0.032$
Velocity Error			
Control Dynamic	$F(1, 8) = 1.06$	*n.s.*	$\bar{x}_{Lag} = 0.223$ $\bar{x}_{Rate} = 0.206$
Frequency Label Order	$F(1, 8) = 0.31$	*n.s.*	$\bar{x}_{Ascending} = 0.210$ $\bar{x}_{Descending} = 0.219$
Interaction	$F(1, 8) = 0.02$	*n.s.*	$\bar{x}_{Lag,\ Ascending} = 0.218$ $\bar{x}_{Rate,\ Ascending} = 0.203$ $\bar{x}_{Lag,\ Descening} = 0.229$ $\bar{x}_{Rate,\ Descending} = 0.210$
Acceleration Error			
Control Dynamic	$F(1, 8) = 0.72$	*n.s.*	$\bar{x}_{Lag} = 1.924$ $\bar{x}_{Rate} = 1.852$
Frequency Label Order	$F(1, 8) = 0.42$	*n.s.*	$\bar{x}_{Ascending} = 1.860$ $\bar{x}_{Descending} = 1.915$
Interaction	$F(1, 8) = 0.00$	*n.s.*	$\bar{x}_{Lag,\ Ascending} = 1.894$ $\bar{x}_{Rate,\ Ascending} = 1.827$ $\bar{x}_{Lag,\ Descening} = 1.954$ $\bar{x}_{Rate,\ Descending} = 1.876$
Root-mean-squared Joystick			
Control Dynamic	$F(1, 8) = 43.43$	$p < 0.01$	$\bar{x}_{Lag\ Control} = 4.629$ $\bar{x}_{Rate} = 3.217$
Frequency Label Order	$F(1, 8) = 0.01$	*n.s.*	$\bar{x}_{Ascending} = 3.911$ $\bar{x}_{Descending} = 3.934$
Interaction	$F(1, 8) = 0.18$	*n.s.*	$\bar{x}_{Lag\ x\ Ascending} = 4.571$ $\bar{x}_{Rate\ x\ Ascending} = 3.251$ $\bar{x}_{Lag\ x\ Descending} = 4.686$ $\bar{x}_{Rate\ x\ Descending} = 3.183$

Table 5. Results of Control Dynamic & Frequency Label analysis on tracking performance. "*n.s.*" indicates not significant.

Feedback Sensitivity

Similar to Experiment 2, subjects' joystick movements were analyzed in response to wind gusts that were injected into the output of the tracking control system during Input Disturbance blocks. These responses were used to characterize their feedback performance using the McRuer Crossover Model (McRuer & Jex, 1967) that posits the human-plus-vehicle describing function can be approximated as a gain (K), time delay (τ), and an integrator (Figure 17). The gain indicates subjects' sensitivity to error, and the time delay represented the human processing time for translating error into appropriate corrective movements. These two parameters were measured for each subject to assess whether rate versus lag dynamics had any effect on their feedback control.

A 2 x 2 analysis of variance performed on gain (Control Dynamic: Rate, Lag; Frequency Label Order: Ascending, Descending) revealed a main a main effect of dynamics [$F(1, 8) = 6.49$, $p < 0.04$; $\bar{x}_{Rate\ Control} = 2.55$ $\bar{x}_{Lag\ Control} = 1.98$]. Rate control subjects showed higher gains (Figure 23). No other effects were found. A 2 x 2 analysis of variance on time delay (Control Dynamic: Rate, Lag; Frequency Label Order: Ascending, Descending) did not reveal any main effects or interactions. Dynamics' effect on feedback was limited to the gain parameter only. We also failed to find the inverse correlation of gain and time delay with error that we observed in Experiment 2 (Figure 18). The correlations between these parameters were in the same direction as they were in Experiment 2, but they did not reach significance. It is possible we lacked the statistical strength to capture this effect because we had half as many subjects in this study as we did in Experiment 2.

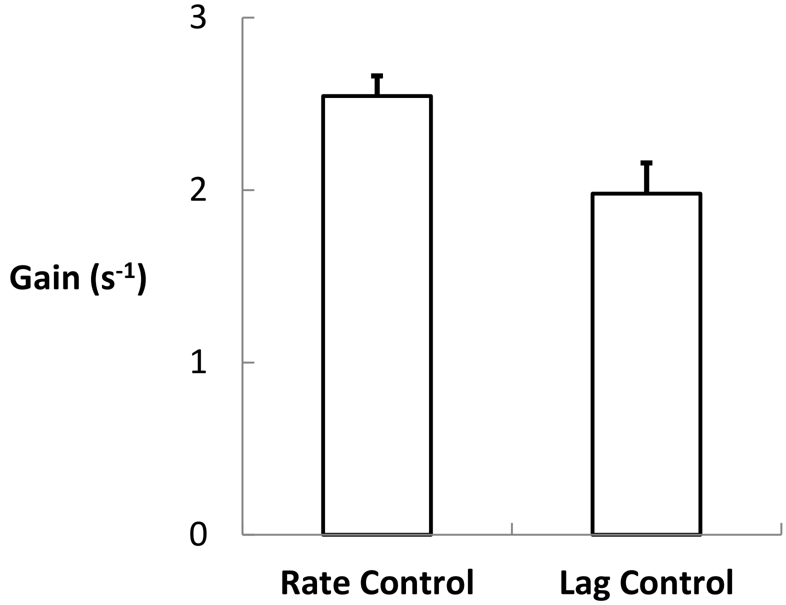


Figure 23. Average of Gains for 6 subjects using either a rate control or lag control dynamic.

General Discussion

In this experiment we tested how different system dynamics affected subjects' feedforward and feedback control. Other studies suggest that higher-order systems are more difficult to control (Burgess-Limerick, Zupanc, & Wallis, 2013) and would therefore require more anticipatory information (McRuer & Jex, 1967), which can be represented as a higher weighting of more distant preview information (Miller, 1976). In our experiment subjects tracked with either a rate control or lag control dynamic. For rate control, subjects' joystick movements controlled the rate of lateral displacement of the cursor on a display. For lag control subjects, their joystick response was like a sluggish positional control (Jagacinski & Flach, 2003). We also reintroduced the Frequency Label Ordering manipulation from Experiment 2 to determine whether its effect on attentional distributions would still be present when full preview was available.

Our experiment failed to support our hypothesis that lag control dynamics would show lower signal-to-noise ratios at short preview times (Figure 20). We found no significant difference between rate and lag control systems, even though optimal control calculations have suggested preview weightings should be different between the two systems (Miller, 1976; Figure 20). We did, however, find an interaction between Frequency Label Ordering and Preview Times on the attentional distributions. We predicted an effect of Frequency Label Ordering based on our results from Experiment 2, but the effect was more complicated in this study because subjects had full view of the roadway display. The interaction between frequency label ordering and preview times can be seen in Figure 21. Subjects who received the descending frequency label order had higher signal-to-noise ratios in Preview regions 0.1 s – 0.3 s, with very low signal-to-noise ratios elsewhere. In contrast, ascending frequency label subjects showed very little attentional signal in early preview and slightly higher signal-to-noise ratios at 0.9 s – 1.0 s. The ascending frequency label order shifted subjects' attention to more distant roadway preview, but the overall amount of attentional signal-to-noise ratios we measured was not different as evidenced by our lack of a main effect of frequency label order.

We predicted differences in the attentional distributions of subjects using rate versus lag control dynamics. Our results did not support our expectations and instead we found that exogenous aspects of the task environment (e.g., frequency label used) played a role in influencing our subjects' attention. It may be that the higher frequency labels we used may have been too salient for subjects to ignore. Previous research found subjects were sensitive to high frequency visual flickers in digital images (Walden, Waldner, & Viola, 2017). If subjects are sensitive to high frequency visual information, then perhaps the high frequency labels occasionally directed their attention to the preview regions in which they were located.

If we only compare lag and rate dynamics with descending frequency label order across the two systems, their attentional distributions were very similar (Figure 24). The pattern of attentional distribution we see in the figure matches results from Jagacinski, Hammond, & Rizzi (2017) and more closely resembles the optimal weighting of preview predicted by Miller (1976). Descending frequency label order may provide a more accurate measure of attention because the exogenous influence of the higher frequency labels at short preview regions may be aligning with the endogenous attentional allocation pattern. Across studies, the data suggests that subjects typically attend to closer preview, and the effect of the ascending order was to pull their attention away from where they naturally focused, whereas the descending order reinforced where they attended. The descending frequency label order is also more ecologically valid in that in our visual environment closer objects tend to move faster than more distant ones.

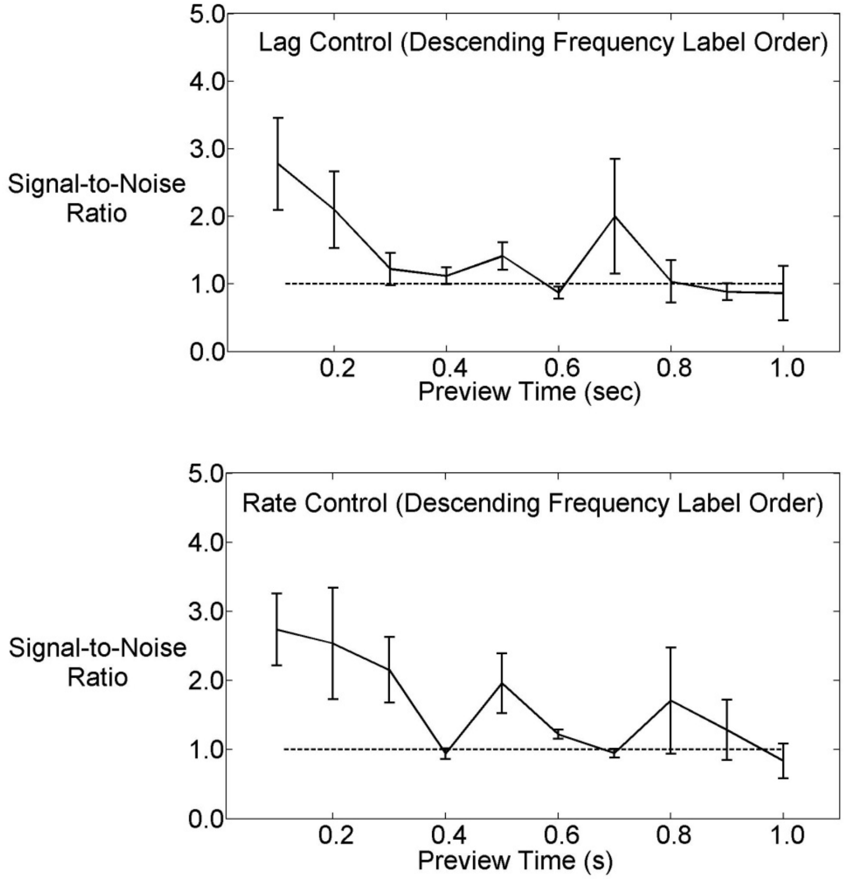


Figure 24. The attentional distributions of three Rate and three Lag control dynamic subjects with descending frequency label order. Both attentional distributions show higher signal-to-noise ratios to near preview regions 0.1s – 0.3 s over farther regions. The error bars represent ± 1 standard error.

Dynamics also did not affect tracking accuracy; the sluggish response of the lag control system did not make tracking more ineffective for our subjects. Tracking performance was comparable between the two systems. Dynamics did, however, have an effect on root-mean-squared joystick, which corresponds to our measure of effort in this task. Subjects made more joystick movements tracking with a lag control compared to a rate control dynamic, likely to overcome the sluggishness. This suggests that the ease at which similar accuracy is achieved between different control systems varies.

The McRuer Crossover Model describes the controller-plus-system as a gain, a time delay, and an integrator. We used this model to characterize our subjects' error nulling. Time delay in the model corresponded to the process time for the system to respond to input, analogous to a reaction time for the system. We found no difference in this measure between the two system dynamics. The gain measures a bandwidth of input values at which error nulling was effective (Jagacinski & Flach, 2003). A higher gain was expected in lag control subjects to overcome their control system's sluggish response. However, if they set their gains too high, tracking would have been oscillatory because of the presence of the sluggishness of the system response. Our lag control subjects showed lower gains than rate control subjects, which suggested they adopted a more cautious control strategy than we predicted, possibly in order to avoid instability.

One lag control subject in our experiment adopted a gain that was closer to the average of the rate control subjects (2.61 s^{-1}). This subject's tracking was more oscillatory compared to the rest of the lag subjects. We can see this in Figure 25 which compares the feedback impulse response to that of a subject whose gain was closer to the lag group's mean (1.98 s^{-1}). The impulse response of the crossover model is a graphical representation of how input signals (i.e., roadway movements) travel through the

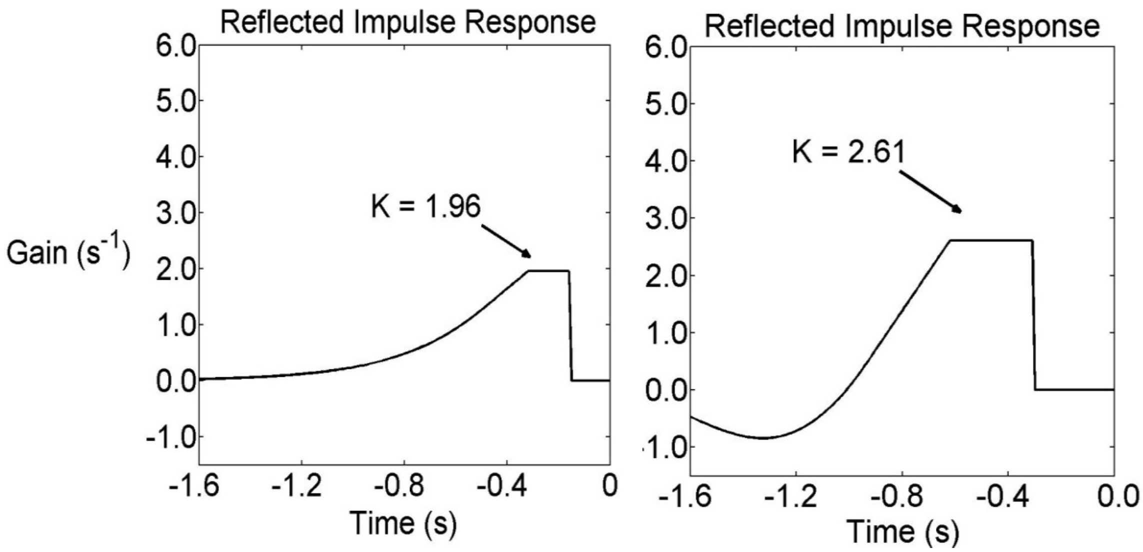


Figure 25. Impulse response graphs for two lag control subjects in Experiment 3. The subject on the left had a gain close to the lag dynamic group's mean and shows no oscillations in their response graph suggesting good tracking control. Subject on the right had a gain closer to the rate control group's mean; this impulse graph shows slight oscillatory behavior (dipping below 0) suggesting the system was less stable. The subject on the left had a RMS error of 0.43, while the one on the right had a RMS error of 0.88.

feedback loop. First a roadway maneuver enters the system and circulates through the feedback loop for one time delay (τ) before generating an error signal (Figure 1). That error signal is then multiplied by the gain of the controller to generate an output response that is constant for the length of time τ (Wierwille, Gagné, & Knight, 1967; Jagacinski, Hammond, & Rizzi, 2017). The controller's response results in the output gradually matching the input as the response then gradually decays out of the feedback loop (Figure 25). Typically higher gains result in more effective error nulling (i.e., lane correcting).

However, if the gain is set too high in a system with a time delay, it could result in an overcorrection which can be graphically represented by an oscillation in the impulse response graph. This oscillation means the controller's tracking behavior leads to slight instability (Figure 25).

Another aspect of the lag control behavior is that subjects may have behaved more nonlinearly due to the sluggish response of the system. It possible their more effortful performance was due to them making more extreme movements joystick control movements. Our measurement of feedback behavior relies on subjects responding proportionally to the error signal; therefore, characterizing our subjects with a crossover model could have been hindered if subjects adopted more nonlinear movements. The crossover model estimate of gain might be biased by this nonliniearity.

The only effect of rate versus lag was on subjects' feedback gains and failed to show any effect on feedforward attention. It is possible the difference between the lag and rate control dynamics was not dramatic enough to capture differences in feedforward control of our subjects. The difference we found in gain and lack of difference in signal-to-noise ratios further supports that feedforward and feedback systems are independent.

Chapter 7: Meta-Analysis of Tracking Experiments

This series of experiments has investigated the relationship between attention and action while subjects used a joystick to track a moving roadway. We have tested predictions of a model of tracking developed by Miller (1976) that described a tradeoff between effort and error. According to this model, this tradeoff in combination with the vehicle dynamics are responsible for shaping how a human controller should weight different regions of roadway preview. This weighting represents attentional allocation to the available preview. To test Miller's predictions, a method was developed that analyzed subjects' steering movements to measure their attentional allocation and tracking behavior. We compared our results to the predictions made by Miller and findings from other studies of driving behavior.

The Influence of the Error-Effort Tradeoff on Feedforward

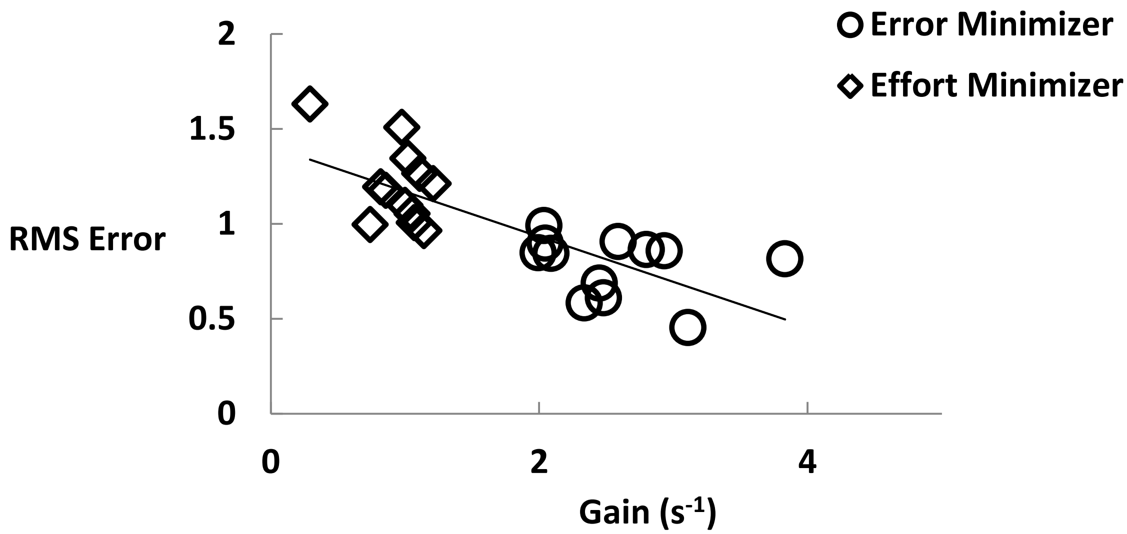
In Experiment 2, we tested a key aspect of Miller's model; the error-effort tradeoff that determined how preview is weighted. In his model he quantified this tradeoff using a ratio of the relative importance of error and effort. In this section, we characterize our subjects using this ratio and compare it to his model so that we can elaborate on our empirical findings.

Miller's (1976) model assumed a cost function, J, based on a weighted combination of error and effort:

$$J = q\frac{\int_0^l e^2(t)dt}{l} + r\frac{\int_0^l u^2(t)dt}{l} = q\,RMS_e{}^2 + r\,RMS_u{}^2$$

where J is a cost function, which served a measure of performance that accounted for both error and effort over the tracking period, l. Error squared, e^2, and effort squared, u^2, were weighted by *q* and *r* respectively, which corresponded to how much each component contributed to the overall performance cost for tracking. Subjects can adopt different *q* and *r* values which depend on whether subjects tend towards minimizing error or effort. If *q* is relatively large, then error will be weighted more heavily to assess performance. If *r* is relatively large, then subjects would instead avoid being too effortful.

The $\frac{q}{r}$ ratio was important in Miller's (1976) model because it determined how preview would be weighted to generate control movements, i.e., attentional allocation in the task. To make an equitable comparison between Miller's model and our empirical results we estimated the value of $\frac{q}{r}$ our subjects adopted in our experiments. As we could not measure this cognitive parameter directly, we generated a proxy for it from our subjects' measured gains. In Experiment 2, we found a strong correlation between their gains (K) and their RMS error [r (10) = -0.78, $p < 0.01$] and RMS effort scores [r (10) = 0.88, $p < 0.01$] (Figure 26).



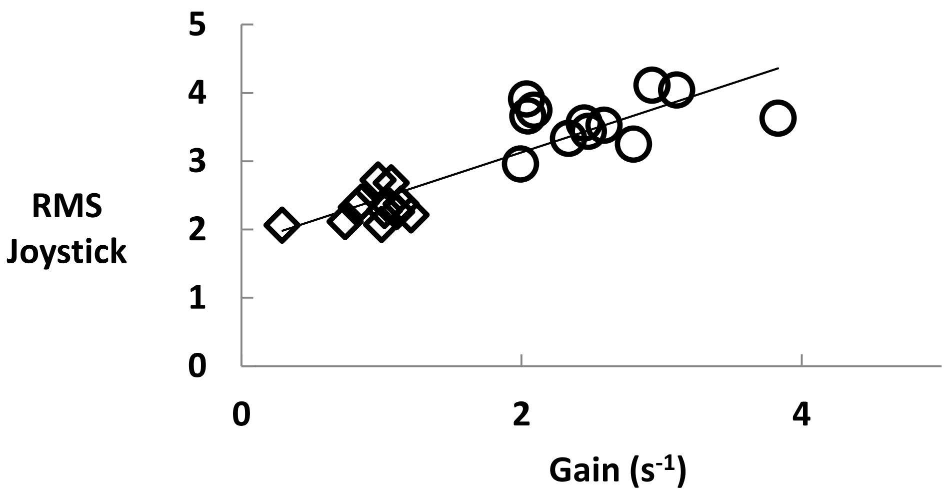


Figure 26. Error and effort minimizer data from Experiment 2. Top shows the correlation between subjects' gain and their root-mean-squared error. Bottom shows the correlation between subjects' gain and their root-mean-squared joystick, which was our measure of control effort.

Using these two correlations we formed two regression equations that predicted error and effort from gain (K):

$$RMS_e = -0.238K + 1.409$$

$$RMS_u = \frac{RMS\ joystick}{1.5} = \frac{0.671K + 1.784}{1.5}$$

We divided by 1.5 in the lower equation because our measure of RMS joystick was 1.5 times subjects' control movements, *u*. Substituting these expressions into the equation for *J*:

$$J = q(-0.238K + 1.409)^2 + r\left(\frac{0.671K + 1.784}{1.5}\right)^2$$

The model predicted that subjects minimized this function once they selected a $\frac{q}{r}$ ratio. By taking this new cost function's derivative with respect to K, then setting it to 0, we derived an equation so that $\frac{q}{r}$ becomes a function of the subjects' gain:

$$\frac{dJ}{dK} = 2q(-0.238)(1.409 - 0.238K) + 2r(0.448)(0.448K + 1.190) = 0$$

$$\frac{q}{r} = \frac{0.448\ (0.448K + 1.190)}{0.238\ (1.409 - 0.238K)}$$

Using this equation we were able to calculate an effective $\frac{q}{r}$ ratio for each subject in Experiments 2 and 3 based on their measured gains. As predicted by Miller, the subjects that made the most control movements (Error Minimizers) had the higher $\frac{q}{r}$ ratios (Figure 27); these subjects' cost functions penalized higher values of error, e, over effort, u.

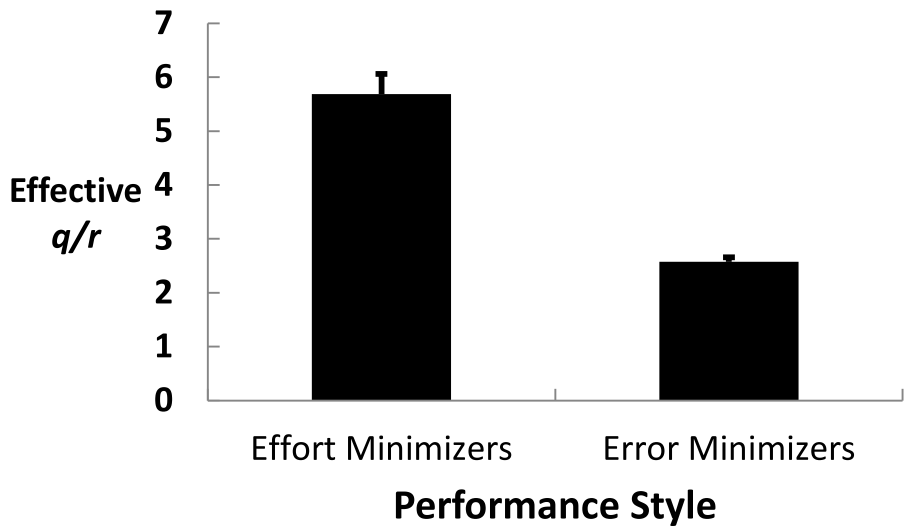


Figure 27. The average $\frac{q}{r}$ ratios calculated for the two groups of subjects in Experiment 2.

As Figure 27 shows, the average $\frac{q}{r}$ ratio of Effort Minimizers was 2.6, while for Error Minimizers it was 5.7. By using these values in Miller's (1976) model we could generate predicted preview weightings that corresponded to the attentional allocation measures we expected to find in our subjects if they had fuller view. Figure 28 shows how attentional allocation is predicted to change under different values of $\frac{q}{r}$ for a rate control system. Attention allocation for short preview times is larger with higher emphasis on minimizing error.

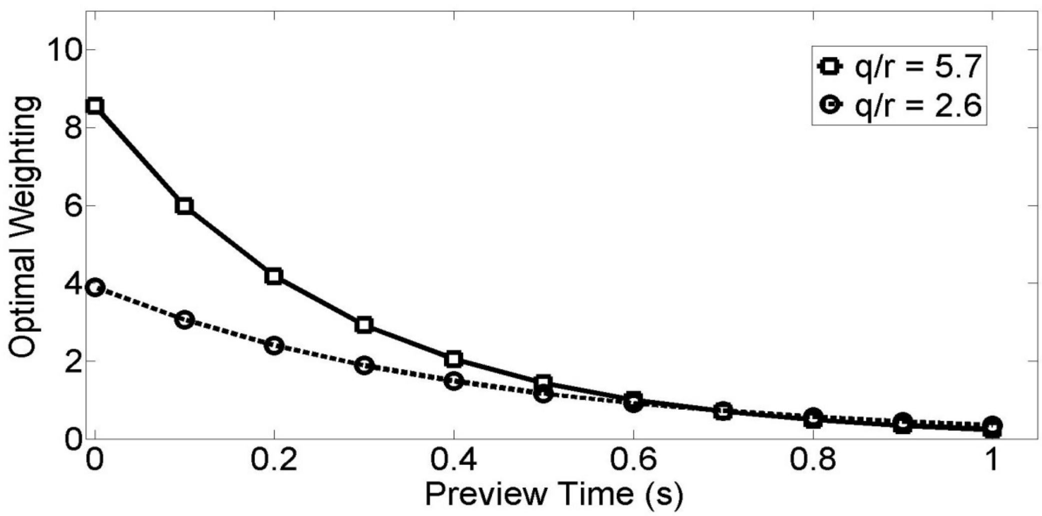


Figure 28. Different weightings of preview for a rate control system based on the error-effort ratio, $\frac{q}{r}$, in Miller's (1976) optimal control model.

We did not find evidence for this prediction from our subjects in Experiment 2. There was an observable difference in the RMS error scores of error and effort minimizing groups; however, this did not result in differences in the amount of attention we measured from either group. It is important to emphasize that Experiment 2 did not give subjects full view of the entire roadway, but rather we limited preview to a slit region centered at 0.3 s into the future. If we assume a feedforward time delay in our subjects, the preview region around 0.15 s into the future in Figure 28 provides an idea of the difference we should have expected to find between the two groups if attentional strategy generalized from full view to slit view. It is possible the use of the slit changed the nature of how attention was being used in the task. The implications of attentional allocation with the use of the slit will be discussed in a later section.

In Experiment 2 we tried to manipulate subjects' effort directly, but a task can be made more effortful with other manipulations. Jagacinski et al. (2017) changed the difficulty of their tracking task in two other ways. They tested the effect of roadway bandwidth by having one set of subjects track a 3 rad/s roadway (as in our present experiments) and another set tracked a less challenging 1 rad/s roadway. A higher bandwidth roadway would require more effortful steering to navigate (e.g., speeding down a curving mountain road). Yet, they found that the bandwidth of the road did not affect the signal-to-noise distributions of their subjects. Similarly, they tested whether including a secondary memory task would shape subjects' attentional distributions. They found that the more challenging task of tracking while memorizing and reciting a sequence of 7 numbers did not affect subjects' attention either. These findings reinforce that different degrees of effort do not alter how attention is used during preview tracking.

Effects of Dynamics on Feedforward and Performance

We used the $\frac{q}{r}$ ratio derived from the previous section to make predictions on how preview weighting would change with different system dynamics. In this section we discuss our empirical findings for the relationship between attention and control dynamics.

Experiment 3 conducted a within-subject comparison between lag dynamics and rate control and failed to find evidence that the attentional allocation of our subjects was shaped by the tracking task's control dynamic. Subjects in both rate and lag dynamic conditions showed similar patterns of attention to the roadway when full view was available. For both groups, higher attentional signal-to-noise ratios were measured in closer preview regions between 0.1 s and 0.3 s (Figure 24). This is similar to the pattern of preview weightings predicted by Miller's model (Figure 20), and differs only in that both lag and rate control subjects look nearly identical.

If we only considered the results from Experiment 3, we would argue that Miller's model incorrectly predicted the effects of control dynamics on attentional allocation. Comparing our attentional allocation results to Jagacinski, Hammond, and Rizzi (2017) revealed a more nuanced finding. In their experiments subjects also tracked a roadway with a 3 rad/s bandwidth using a joystick controller. For their experiments the joystick had a position control dynamic in which joystick movements directly controlled the position of subjects' cursor on the display. They measured attentional allocation using the same techniques utilized throughout our experiments; consequently, we can compare their results to our findings and Miller's model.

We analyzed the data from their Experiment 1 with the data from our Experiments 1 and 3 where Full View conditions were used. We only included 3 rad/s roadway bandwidth conditions with descending frequency label ordering and no secondary task. This insured the experimental conditions being compared were as similar as possible, with the only exception being the differences in control dynamics. A 3 x 10 analysis of variance was conducted on the signal-to-noise ratios (Control Dynamics: Position, Lag, Rate; Preview Positions: 0.1 s to 1.0 s into the future). A main effect of Preview Position was found reflecting the consistent finding that subjects had higher attentional signal-to-noise ratios in preview regions 0.1 s – 0.3 s into the future [$F(9, 306) = 9.96$, $p < 0.01$]. Additionally, a main effect of Control Dynamics was found [$F(2, 34) = 14.38$, $p < 0.01$, $\bar{x}_{Position\ Control} = 2.20$, $\bar{x}_{Rate\ Control} = 1.69$, $\bar{x}_{Lag\ Control} = 1.43$]; subjects using position control showed higher attentional signal-to-noise ratios (Figure 29, bottom). However, the interaction of Control Dynamics and Preview Position was not significant.

Figure 29 also shows the preview weightings Miller would have predicted for various control dynamics we analyzed. To generate the curve for each dynamic, a $\frac{q}{r}$ ratio was calculated for each one from our collection of data. Using the equation we established in the previous section, a $\frac{q}{r}$ ratio of 5.7 was used for rate control subjects; that ratio was calculated from error minimizing rate control subjects in both Experiments

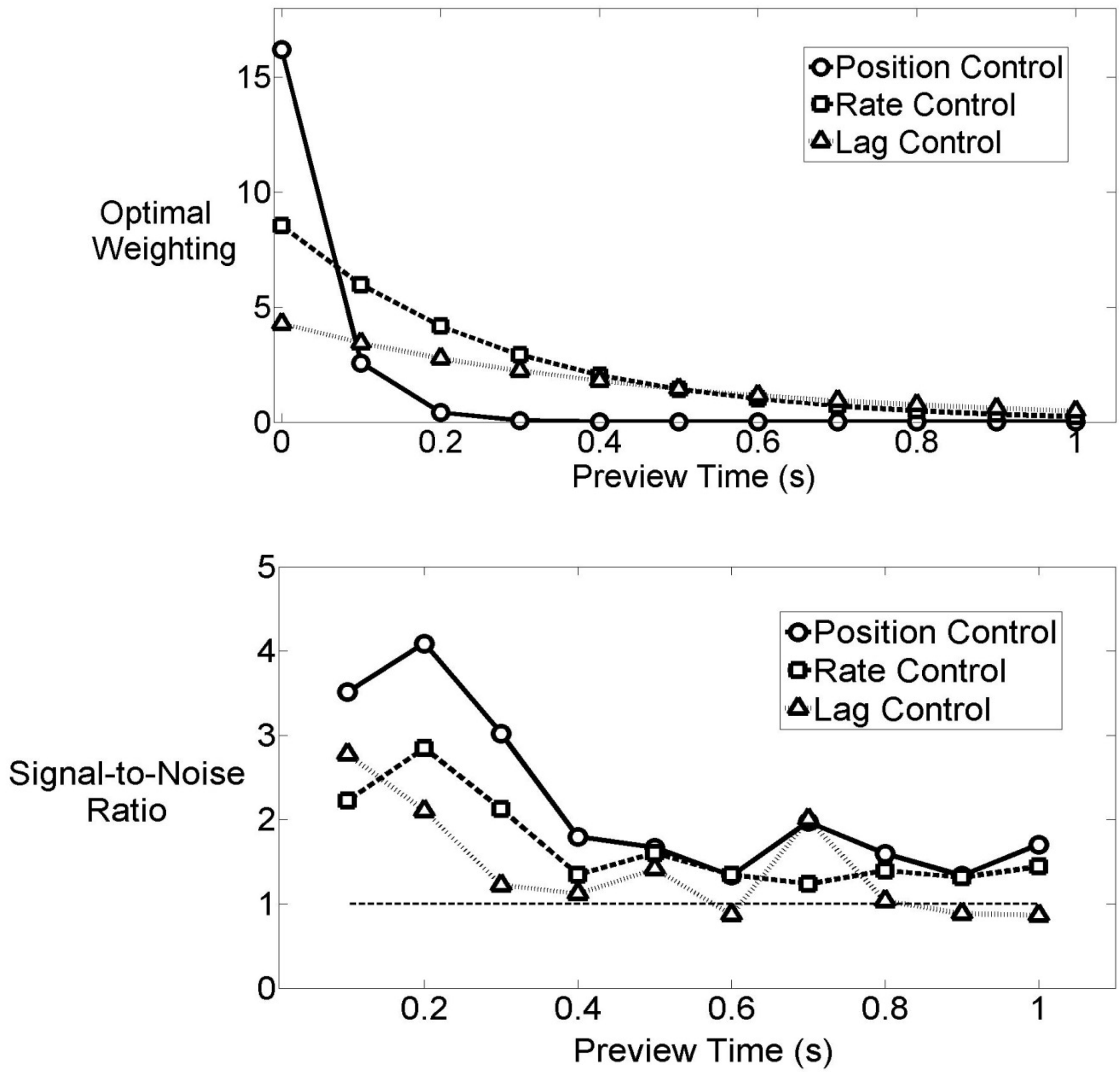


Figure 29. The top graph shows weightings for roadway preview for three difference control dynamics based on Miller's (1976) model. The bottom graph shows the empirical findings of attentional allocation to roadway preview from five tracking experiments. The position control data are from Jagacinski, Hammond, and Rizzi (2017), and the rate and lag control results are based on Experiments 1 and 3; all three curves are from Full View, Descending, 3 rad/s bandwidth roadway conditions.

2 and 3 (n = 18). The same equation was used for lag control subjects in Experiment 3 because we failed to find an empirical difference in the attentional measure of these two groups; using their gains in the $\frac{q}{r}$ equation, we established a ratio of 4.3 for them. We used the same approach to determine the $\frac{q}{r}$ ratio for subjects in Jagacinski et al.'s (2017) study. However, we calculated a new equation for $\frac{q}{r}$ as a function of gain based on the 6 subjects in Jagacinski et al.'s (2017) Experiment 1 and estimated these subjects had a $\frac{q}{r}$ of 1.4. With these ratio values we generated preview weightings using Miller's model (Figure 29, top). The key qualitative similarity between the preview weightings from Miller's model and the attentional distributions from our meta-analysis is that subjects using a position control demonstrated more attentional signal, especially concentrated to nearer preview regions, compared to rate and lag control dynamics. This suggests there is some effect of the dynamics of a control on the way attention is implemented in a tracking task.

Our analysis in Experiment 3 failed to find an effect between rate and lag control, perhaps indicting these two dynamics were very similar and we did not have enough power to capture this difference in attentional distributions. We investigated this possibility by conducting a post-hoc power analysis using the Miller weighting curves in top half of Figure 29. The predicted attentional distribution for each dynamic was estimated by taking the integral under the exponential curve around each of the 10 preview positions used in these experiments. We then calculated a ratio of the expected rate and lag control signal-to-noise measures to generate effect size estimates for the

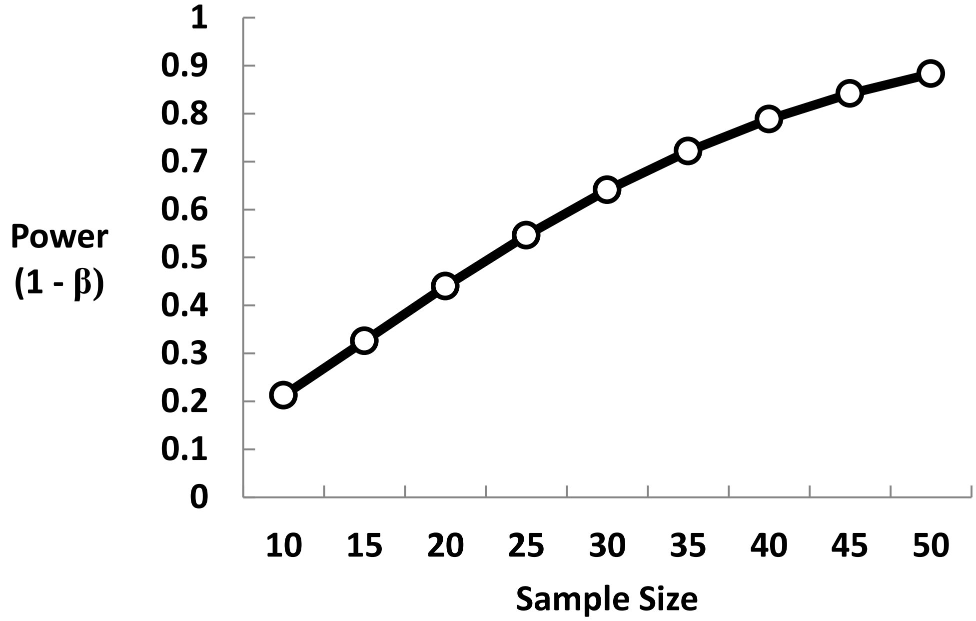


Figure 30. Graph shows the post-hoc power for detecting the interaction between Control Dynamics and Preview Position in Experiment 3 as a function of the sample size. The predicted effect size of the interaction (d = 0.23) was estimated from Miller preview weighting functions.

main effect and interaction of Control Dynamics and Preview Position. These values were used along with GPower 3.1 statistical software to calculate how much power Experiment 3 had to detect these effects.

This analysis determined that the predicted main effect size for the difference between rate and lag control was only d = 0.09, which aligned with our results showing no main effect of Control Dynamics. The predicted effect size for the interaction was approximately *d* = 0.23. Given that effect size, Experiment 3 had a power of 26% to detect the interaction that would have resulted from the difference in the attentional signal between rate and lag control at the first 4 preview positions. We only used 12 subjects total for Experiment 3, and Figure 30 shows how power for the interaction would have changed with larger sample sizes. It would have taken around 40 subjects for that experiment to have a good chance to detect the interaction, which would not have been easily feasible given that each subject's data take about 3 hours to collect.

Dynamics also affected tracking performance. In all these studies we measured root-mean-squared error (RMS error) and root-mean-squared joystick (RMS joystick), a measure of effort during the task, and found dynamics had an effect on both of these performance metrics. To compare these effects across experiments we used the control condition error and effort scores for all the subjects in both experiments in Jagacinski et al. (2017) in combination with the full view control condition error and effort scores from Experiments 1 and 3.

A one-way analysis of variance on RMS error (Control Dynamic: Position, Rate, Lag) revealed a main effect [$F(2, 45) = 25.36$, $p < 0.01$, $\bar{x}_{Position\ Control} = 0.305$, $\bar{x}_{Rate\ Control} = 0.582$, $\bar{x}_{Lag\ Control} = 0.572$]; a post hoc Tukey test replicated the finding from Experiment 3 that rate and lag error scores were not different, but subjects tracked considerably better with a position control compared to the other two dynamics ($p < 0.01$). Similarly, a one-way analysis of variance on RMS joystick (Control Dynamic: Position, Rate, Lag) found a main effect [$F(2, 45) = 515.04$, $p < 0.01$,

Performance Measure	**F statistic**	**Significance**	**Means**
Root-mean-squared Error *Control Dynamic*	$F(2, 45) = 25.36$	$p < 0.01$	$\bar{x}_{Position} = 0.305$, $\bar{x}_{Rate} = 0.581$, $\bar{x}_{Lag} = 0.571$
Position Error *Control Dynamic*	$F(2, 45) = 21.83$	$p < 0.01$	$\bar{x}_{Position} = 0.021$, $\bar{x}_{Rate} = 0.039$, $\bar{x}_{Lag} = 0.040$
Velocity Error *Control Dynamic*	$F(2, 45) = 26.92$	$p < 0.01$	$\bar{x}_{Position} = 0.151$, $\bar{x}_{Rate} = 0.235$, $\bar{x}_{Lag} = 0.223$
Acceleration Error *Control Dynamic*	$F(2, 45) = 22.63$	$p < 0.01$	$\bar{x}_{Position} = 1.406$, $\bar{x}_{Rate} = 2.061$, $\bar{x}_{Lag} = 1.924$
Root-mean-squared Joystick *Control Dynamic*	$F(2, 45) = 222.99$	$p < 0.01$	$\bar{x}_{Position} = 1.685$, $\bar{x}_{Rate} = 2.120$, $\bar{x}_{Lag} = 3.084$

Table 6. Results of meta-analysis on performance measures across multiple tracking studies

$\bar{x}_{Position\ Control} = 1.69$, $\bar{x}_{Rate\ Control} = 3.18$, $\bar{x}_{Lag\ Control} = 4.63$]. A post hoc Tukey test revealed that lag control subjects made the most joystick movements while tracking, followed by rate control subjects, and position control subjects made the least.

We also looked at higher derivatives of subjects' error scores using Position, Velocity, and Acceleration error to test the Progression-Regression hypothesis that as subjects become more proficient at a task they can track higher derivatives of the input signal relevant to their performance (Fitts, Bahrick, Briggs, & Noble, 1959; Fuchs, 1962).

We expected with easier dynamics subjects would generate smoother joystick movements. A one-way analysis of variance on Position, Velocity, and Acceleration error (Control Dynamic: Position, Rate, Lag) revealed significant results for all three of those performance measures. A Tukey post hoc comparison found that across all three measures [$p < 0.01$ for all comparisons] subjects tracking with a position control showed lower error, and therefore, smoother tracking movements (Table 6).

Effects of Restricted Preview on Feedforward

We failed to find an effect of performance style (error-versus-effort) on attentional allocation, and were only able to find evidence for dynamics' effect on attention when analyzing it across multiple studies. However, we may have evidence that attention adapts to other aspects of task demand. Here we discuss on how subjects performed in response to the slits conditions we used.

In Experiment 1A we hypothesized that attentional signal-to-noise ratios would be higher than with full view if subjects' roadway preview was restricted to 0.6 s into the future, because they would have nowhere else to allocate their attention to acquire anticipatory information. Other roadway regions were completely occluded except for the start of the roadway where the center-cross was located (see Figure 2). However, instead we measured lower maxima signal-to-noise ratios to the 0.6 s slit region compared to the maxima that occurred in full view conditions between 0.1 s – 0.3 s regions. This result appeared to be consistent with predictions that further preview would be weighted less heavily in a rate control system with full view (Miller, 1976). Therefore, we decided to investigate if moving the slit to a nearer roadway region, 0.3 s into the future would result in higher attentional signal-to-noise ratios. We found evidence for this effect in Experiment 1B, and furthermore, comparing 1A to 1B, we found more attention to the 0.3 s preview region than the 0.6 s.

When making that comparison, we failed to take into account that the roadway perturbations, i.e., frequency labels, were confounded with the preview regions in the slits. This meant we could not compare the amount of attention measured at 0.3 s to 0.6 s because any measured effect could be due to the frequency labels at those locations instead of the locations themselves. Experiment 1C corrected for this by assigning the same set of frequency labels to the visible portion of the slit at 0.3 s and 0.6 s, and using a within-subject design comparing the two regions. With this correction we were surprised to find there was no difference in the amount of attention subjects allocated to either of the slit preview regions. When restricting preview to a slit, subjects are equally able to attend to near or far regions.

From those results we were able to conclude that subjects adapt their attention to the available preview information even if it was a preview region they did not attend to when full view was available. At first this may seem in contradiction to the expectations from Miller's model, but his model is more applicable to full view conditions. Restricting preview as we did in Experiment 1 changed the pattern of attentional allocation.

Subjects were able to shift their attention to the slit region in both Experiments 1A and 1B, but performance was different between full view and slit conditions. We can make within-experiment comparisons in 1A and 1B because we used control blocks which did not have frequency perturbations to calculate subjects' error scores. This avoided the confound caused by the frequency label issue. In Experiment 1A subjects showed higher RMS, Velocity, and Acceleration error in the slit condition than in the full view condition. This suggested that they performed worse and tracked less smoothly when less preview was available. This was replicated in Experiment 1B where subjects scored worse on all error measures (RMS, Position, Velocity, and Acceleration error) in the slit condition than in the full view condition. Subjects could shift their attention to the preview region available from the slit, but their performance suffered relative to fuller preview from lack of matching higher derivatives of the roadway signal (Fitts, Bahrick, Briggs, & Noble, 1959).

Analyses of Experiments 1A and 1B compared whether performance was different between focused attention to the 0.6 s preview region and the 0.3 s preview region, respectively. Our data suggested that there was a difference in how smoothly subjects tracked depending on whether preview was limited to 0.3 s or 0.6 s into the future. The effect was replicated in Experiment 1C where the comparison was within-subject. Subjects tracked more smoothly when preview was centered on 0.3 s compared to 0.6 s into the future (Acceleration error is higher for subjects that had the 0.6 s slit). This suggests there is a negative effect of looking too far down the roadway. This seems to contrast with findings from driving simulators in which subjects' steering movements were smoother when their view of the road was limited to farther roadway regions compared to closer ones (Land & Horwood, 1995). However, it should be noted those simulations used more realistic car dynamics in an immersive environment, which is quite different from the velocity control and two dimensional display used in the present experiments.

Unexpected Effects on Attention during Tracking

Experiment 1 revealed that the frequency labels we used to measure attention had an unintended effect on the signal-to-noise ratios. Jagacinski et al. (2017) tested this effect in their study by comparing signal-to-noise ratios when frequency labels were in descending order (highest frequency at 0.1 s and lowest frequency at 1.0 s into the future) to when they were in ascending order (lowest frequency at 0.1 s and highest at 1.0 s). They found that descending frequency labels gave them higher signal-to-noise ratios, but did not change the overall pattern of attention to the roadway preview.

The results from Experiment 1 motivated us to also investigate the Frequency Label Ordering (ascending versus descending) effect. In Experiment 2 we tested Frequency Label Orderings using a slit which restricted the roadway preview to the 0.3 s region on the roadway. We measured higher signal-to-noise ratios with descending order than with ascending. Even though subjects were concentrating all their attention to a restricted region of preview, the frequency of the perturbation used to measure attention had a significant effect on how much attention we measured. Because we were using movement to infer attention, it is possible the lower frequency perturbations were not as pronounced in subjects' joystick movements as the higher frequency perturbations. However, we took signal-to-noise ratio between subjects' Control and Perturbation blocks. This meant any movement frequency that might have resonated in their joystick control would have affected both the Control and Perturbation block and the resonance would have effectively been canceled out. We suspected that attention was being shaped by the frequency labels we used, a hypothesis we resolved in the findings of Experiment 3 discussed below. It should be noted that regardless of whether subjects had an ascending or descending frequency label order, we were still able to measure subjects' attention in the slit region.

In Experiment 3 we tested the Frequency Label Ordering effect when roadway preview was not restricted. According to Jagacinski, Hammond, and Rizzi (2017) only the magnitude of the measured attentional pattern should change rather than the attentional allocation pattern itself. Experiment 3 instead found the Frequency Label Ordering did not have a main effect on the overall amount of attentional signal measured. The interaction in Experiment 3 instead suggested that the actual pattern of attention had been altered. For descending conditions we found the typical higher concentration of attention to near preview, but ascending conditions showed a flatter distribution of attention with a slight rise in attentional signal at the furthest preview regions (Figure 22). It does not look like an exact inversion of the descending attentional distribution, which suggests two forces are likely at play. Subjects had a tendency to focus on closer preview, but their attention seemed to get pulled away when the higher frequency perturbation

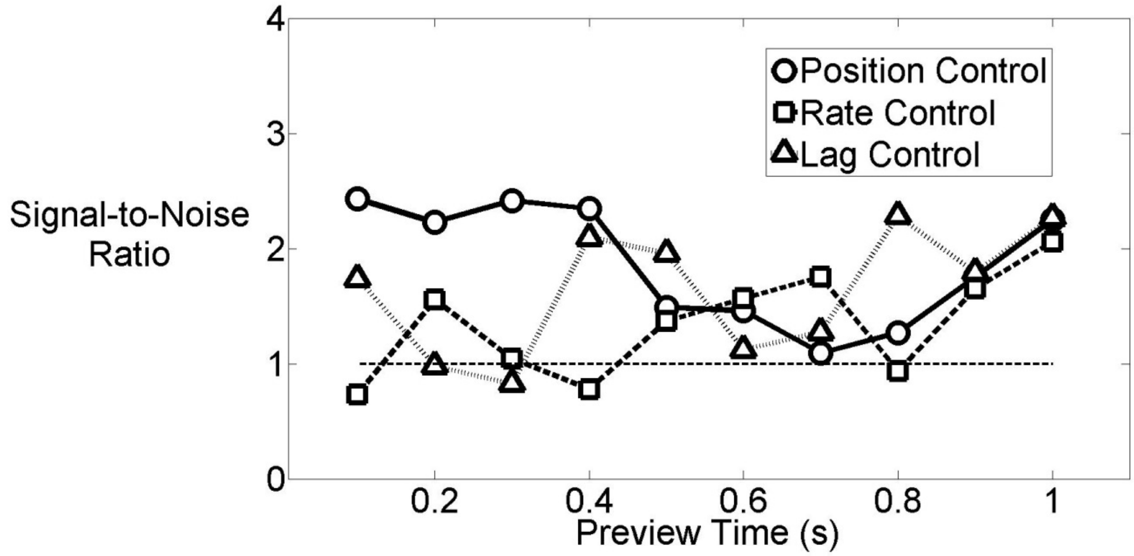


Figure 31. The average signal-to-noise ratios for Ascending conditions averaged for each dynamic across several experiments. All curves show attention being shifted to further preview by the ascending Frequency Label Ordering; however, the position control dynamics retained more of it original attentional allocation structure. The position control curve is based on Jagacinski, Hammond, and Rizzi (2017), and the Rate and Lag control results are based on Experiments 1 and 3.

occurred far from where they were focusing. The higher frequency perturbations shifted their attention further down the roadway, spreading it across more roadway regions than they typically focused on. The top half of Figure 22 shows how the attentional distribution of ascending frequency label subjects looks flatter and more spread out over more distant preview regions. Even in Jagacinski et al.'s (2017) experiments, subjects' attention seemed to be pulled to further preview regions by the ascending frequency label order, but their subjects were more able to maintain their attention to the closer regions (Figure 31).

Our findings in Experiment 3 differed from Jagacinski, Hammond, and Rizzi's (2017) results. This suggested that attentional capture during tracking varied for different control dynamics. A possible explanation was that subjects were more susceptible to distraction when using higher-order or more complex control systems. These distracting effects can persist even if attention is concentrated to a restricted region in the preview, as it was during slit experiments. These studies demonstrated that other aspects of the visual environment can have unintended effects on the allocation of attention during a perceptual-motor task. To subjects the frequency perturbations on the roadway seemed highly relevant to task performance even though they were irrelevant to their actual tracking error; subjects would have performed better if they had ignored them. This is consistent with other studies that suggest we discriminate information in the visual environment based on whether it is relevant to the action we plan to take (Welsh & Pratt, 2008; Pratt, Taylor, & Gozli, 2015) and that our vision may be sensitive to high frequency visual information (Waldin, Waldner, & Viola, 2017).

Though Frequency Label Ordering did have an effect on attention during tracking, it did not affect subjects' performance. When comparing performance scores (RMS, Position, Velocity, and Acceleration error) during perturbation blocks, there was no difference between ascending and descending error scores. The frequency label ordering shifted attention, but this shift in attention did not degrade performance during perturbation blocks. This finding was somewhat puzzling because we would expect good performance required good feedforward information. It might suggest that the attentional shift caused by the frequency label ordering was not enough to degrade the quality of the feedforward information subjects used to track.

Feedback Control's Sensitivity to Task Manipulations

Unlike feedforward control, people's sensitivity to error nulling, i.e., feedback control, was much more susceptible to task manipulations. In this section we present how feedback control was affected in the current and previous tracking experiments.

Feedback control corresponded to the system's responsiveness to error signals. In the case of tracking this control represented the subjects' ability to correct lateral deviations of their cursor's position from the center of the moving roadway. The effectiveness of these lane correcting joystick movements was measured by introducing unpreviewable "wind gust" disturbances during tracking. These disturbances pushed the cursor laterally as if a wind gust had unexpectedly occurred. Because subjects could not anticipate these wind gusts, their effectiveness in counteracting them measured the sensitivity of their feedback control to correcting these errors in roadway position. We characterized this sensitivity with a McRuer Crossover Model. A gain parameter determined the bandwidth of frequencies for which the system was effective at error nulling. A time delay that represented the human's processing time for translating error into appropriate corrective movements (McRuer & Jex, 1967). According to the crossover model, higher gains and shorter time delays result in more effective tracking, though oscillatory tracking behavior can occur if gains are set too high in a system with a time delay.

In Experiment 2 we demonstrated that gains were sensitive to the performance style subjects adopted. Subjects who were instructed to keep error below a particular threshold (Error Minimizers) had significantly higher gains than subjects who instead focused on maintaining RMS joystick scores below a particular value (Effort Minimizers). In Miller's (1976) model the $\frac{q}{r}$ ratio determined this tradeoff relationship between error and effort. In Experiment 2 we showed that gains were highly correlated with both error and effort measures in the task. Our finding suggests that subjects can adjust their tracking gains to adopt different $\frac{q}{r}$ ratios while tracking, resulting in different performance style emphases.

We were surprised to find that differences in performance style resulted in a statistically significant difference in time delay values. Time delays represent the time it takes roadway error signals to be processed and translated into control movements; they are analogous to a reaction time in this context. Reaction times are not considered to be under the subjects' control, so adopting different error versus effort emphases should not have affected the amount of time it took for subjects to process roadway information. However, this relationship did appear in our results. Other researchers have found that time delays could change in response to the task environment. For example, if the input bandwidth of a task is fairly high, a controller can decrease their response processing time (i.e., time delay) by reducing neuromuscular lags (McRuer & Jex, 1967). It might be possible that Effort Minimizing subjects had a more relaxed motor execution which resulted in a slight increase in their overall time delays. However, D.C. Miller (1978) also conducted a study where a trained subject adopted different error versus effort emphases. His study showed different emphases resulted in different gain values, but did not find any changes in time delays as we did in Experiment 2.

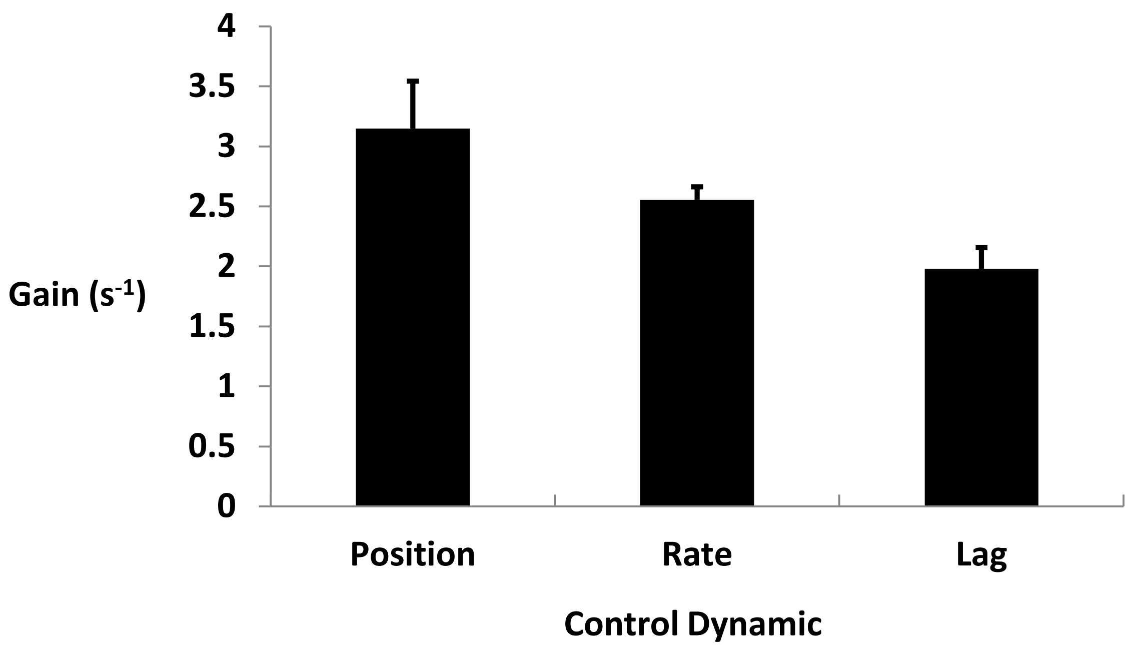


Figure 32. Graph of the different feedback gain averages for each control dynamic. Based on a meta-analysis of Jagacinski, Hammond, and Rizzi (2017) and the rate and lag control results from Experiments 3.

In contrast, Control Dynamics had a clear effect on Feedback gains, but not time delays in this case. A one-way analysis of variance on Time Delays (Control Dynamic: Position, Rate, Lag) found no significant difference in processing time between different Control Dynamics [$F(2, 29) = 0.98$, $p > 0.05$, $\bar{x}_{Position\ Control} = 0.18$, $\bar{x}_{Rate\ Control} = 0.20$, $\bar{x}_{Lag\ Control} = 0.20$]. However, a one-way analysis of variance on Gains (Control Dynamic: Position, Rate, Lag) found a main effect of Control Dynamics [$F(2, 29) = 5.98$, $p < 0.01$, $\bar{x}_{Position\ Control} = 3.15$, $\bar{x}_{Rate\ Control} = 2.55$, $\bar{x}_{Lag\ Control} = 1.99$]. A post hoc Tukey analysis found that position control subjects had a higher gain than lag control subjects ($p < 0.01$); however, rate control was not significantly different from either (Figure 32). Experiment 3 by itself managed to find significant evidence for a difference between lag and rate control, so it is unclear why we failed to find this effect in a post hoc Tukey meta-analysis across the different studies. It is likely that if this study was replicated with a position, rate, and lag control condition results would indicate that gains are different among all these systems.

Chapter 8: Final Discussion and Future Directions

This series of experiments modeled how subjects completed a tracking task that required the use of a joystick to navigate a winding roadway. This model looked at tracking behavior as being comprised of a Feedforward anticipatory system and a Feedback lane correcting system. These two processes simultaneously contribute to the model's behavior, so we used different perturbation techniques to measure and distinguish these components. We demonstrated it is possible to measure both of these systems by looking at the Fourier spectrum of subjects' joystick movements. This gave us an effective method for inferring cognition from action in this task.

Feedforward control represents a subjects' ability to look down the roadway in order to plan anticipatory steering actions. One might expect that the best place to focus on a roadway would be roughly one reaction time away so that steering responses made would match in time to incoming roadway maneuvers. We instead found subjects tended to focus on near roadway preview over further preview, which was not necessarily located close to their measured time delays, i.e., reaction times. This pattern of attentional allocation qualitatively matched aspects of Miller's (1976) optimal distribution of weights on preview for various control dynamics. Empirically, the attention pattern could also be altered by restricting the amount of preview available in the roadway environment. By occluding parts of the roadway we managed to shift subjects' attention to visible regions further down the roadway. This demonstrated that attention allocation was flexible and can be adapted to the task demands.

Combining our results with those of Jagacinski, Hammond, and Rizzi (2017) we found evidence for Miller's prediction that the dynamics of the system being controlled affected the pattern of attention to preview; simpler control dynamics require less anticipatory roadway information for effective control. However, other predictions from Miller's optimal control calculations did not match our empirical results. Different emphases on how subjects could prioritize error-versus-effort during tracking were expected to shape the pattern of attention (Miller, 1976). We tested this hypothesis by having subjects adopt different performance styles. We created two performance style groups by emphasizing either the error or effort scores in their tracking performance, but failed to find a difference in the magnitude of measured attention between the two groups. However, in that experiment we restricted roadway preview to a single region in order to improve the sensitivity of our attentional measure. This may have fundamentally changed the way subjects engaged attention in the task, which could explain why we failed to find evidence for Miller's prediction. A future replication of this study should look at whether these performance style emphases would change attentional allocation when full view of the roadway is available.

An aspect of our measurement technique also had an unexpected effect on subjects' attentional allocation. We visually perturbed the roadway at 10 different frequencies at successive 0.1 s preview intervals. The visual perturbations functioned as frequency labels at 10 preview locations. By looking at the Fourier spectrum of subjects' joystick movements at these frequency labels we determined which regions of the preview subjects had attended. We compared the effects of having these labels in either ascending or descending order on the previewed roadway and found that the ascending frequency label order pulled subjects attention to more distant preview regions compared to descending. There was no overall difference between the amounts of attention measured in the two frequency label orderings. This suggested that the ascending ordering was spreading attention across more preview regions than the descending ordering in which attention was mostly concentrated to regions between 0.1 s and 0.3 s into the future. It is likely that when the higher frequency perturbations were further away (as they were for ascending ordering), they captured attention because it appeared more unnatural. In our visual environment far away moving objects appear to move more slowly than closer objects (e.g., a plane in the sky appears to move slowly across our visual field, but a car may appear to zoom past us on the street). Another explanation for this effect may be that subjects' visual systems were more sensitive to the high frequency perturbations on the display (Waldin, Waldner, & Viola, 2017).

A suggestion to combat this measurement artifact might be to randomize the locations of the frequency labels on the roadway preview, but doing so may actually create more issues. If any subject received a trial in which a very low frequency label was assigned right next to a much higher one, it would create a more glaring contrast between the two that may capture attention even more. The use of the descending frequency label order in future experiments is still a better choice because it is more ecologically valid. We expect closer objects to appear to move faster than more distant ones. To lessen the effect of the contrast between the lower and higher frequency labels at the two ends of the roadway, it is recommended to restrict the range of frequencies used to identify the preview being attended. This would reduce the discrepancy between the closest and furthest frequency labels. However, one might still argue that using descending frequency label ordering biases subjects' attention to the closer preview regions. Jagacinski et al. (2017) showed that the pattern of attentional allocation they measured did not change based on the order of the frequency labels used. Rather, they found the magnitude of the attentional signal was lower when they gave subjects ascending ordering versus descending. In their study subjects tracked with a position control, a simpler dynamic than the rate control and lag control our subjects utilized. If we combine our results with theirs, it suggests that subjects' attentions might be more susceptible to capture or distraction when using a more complex control dynamics. Therefore, one needs to consider the control dynamics a study will implement when planning to use visual frequency perturbations to measure attention.

Feedback control is a subjects' ability to correct for lane deviations between their cursor and the center of the roadway. To measure feedback in our subjects we used a model with two parameters, a time delay and a gain (McRuer & Jex, 1967). Time delays represent the processing time it takes for roadway information to generate steering movements, and they were generally unchanged by different tracking conditions; the only exception to this was in Experiment 2. However, gains in feedback control were very sensitive to all the task manipulations we implemented across the studies. Different control dynamics resulted in different values of gain in our subjects. Subjects using a position control had higher gains than subjects using a rate control, who in turn had a higher gain than subjects using lag control. Gains were also sensitive to the performance style subjects adopted. Subjects who emphasized reducing error had higher gains than those who emphasized reducing effort. This suggests that the way subjects adopt different error-versus-effort emphases is by adjusting their feedback gains during performance.

Miller (1976) predicted that manipulating the emphasis of error-versus-effort would result in similar changes in patterns of feedforward and feedback control; his model suggested that an optimal solution for the preview weightings would depend on a combination of feedforward and feedback with matching time constants. However, we only found evidence of error-versus-effort affecting feedback. Our data suggests that these two systems may actually be independent. Similar findings occurred with other manipulations of effort. Jagacinski et al.'s (2017) study compared subjects' attentional distributions while tracking two different roadway bandwidths (1 rad/s versus 3 rad/s) and while tracking with a secondary memory task. Both manipulations would have likely made tracking more effortful. However, neither manipulation changed the attentional distribution of subjects.

Understanding the role of preview in the tracking model we present here gives us a clearer picture of which information is relevant to tracking performance. Different aspects of performance were also susceptible to many of the task manipulations we used. For example, different dynamics resulted in different degrees of effort, i.e., joystick displacement. Subjects with position control exhibited the least of amount effort to track a moving roadway, while subjects with lag control exhibited the most. By looking at higher derivatives of their control movements we also found that position control subjects were smoother trackers than rate and lag control subjects. This agrees with the Progression-Regression hypothesis that predicts that as subjects become more skilled at a task, they attune to higher derivatives of the input signal (Fitts, Bahrick, Briggs, & Noble, 1959; Fuchs, 1962). This would also be true if the control task is easier, such as it would be tracking with a position control. Using these higher derivatives of the roadway could also be hindered by limitations on the amount of preview available to subjects. Subjects performed much better with full view of the preview versus restricted view, likely because they were better able to map higher derivatives of performance to visual representations. For example, subjects could respond to the velocity of the input by responding to the slope of the previewed roadway angle. This would be a mapping of the visual roadway geometry to cursor velocity.

Skilled tracking, and by extension any skilled performance, involves subjects attending to task relevant information, but the relevance of the information in the environment may depend on the action being performed (Lohse, Jones, Healy, & Sherwood, 2014). A long history of attentional research has investigated the conditions under which the attentional system effectively discerns relevant information from the visual environment. Typically this has been studied by examining how susceptible participants are to distractors during visual search tasks in which they are attempting to locate a target among an array of distractors. The usual finding in these search paradigms is that the relative salience of objects in the visual field pulls attention, i.e., captures it; examples of such characteristics would include objects' luminance, color, size, or other feature distinctiveness (Folk, 2015). These studies have also found that participants' search goals affect the capturing ability these distractors. Evidence suggests that when a distractor's features do not match the target's key search feature or participants' search strategies, the distractors do not influence the reaction times of finding the search targets (Folk & Remington, 2008; Folk 2015). In other words, the attentional system may be attuned to objects in the visual environment that are relevant to its goals, and perhaps by extension, actions.

In our model of tracking, attention forms part of a larger dynamic system with feedback loops and feedforward elements that are shaped in response to input and task demands. Our subjects' primary goal was to track a moving roadway, making attention to the roadway an indirect aspect of successful performance. In the Full View conditions, they were not instructed to focus attention to different roadway regions, but instead attention was distributed in response to performance demands, motivation, and task-relevant distractors. This differs from experiments where subjects may be instructed to direct their attention, consciously avoid distractors, or find targets. In such studies the task itself is attentional control. We suggest that attention may behave differently in the context of sensorimotor control, and subjects may actually have less control of attention when it is in the service of action. Furthermore, real-world environments are more dynamic than the environments in visual search studies, so it might be difficult to generalize such findings to more practical contexts. For example, studies have found that during search tasks the attentional system is almost always sensitive to the sudden appearance of new objects, as well as novel motion of distractors in the visual field (Yantis & Hillstrom, 1994; Al-Aidroos, Guo, & Pratt, 2010). However, these studies' visual environments tend to have mostly static objects, which may result in any motion feature becoming salient, whereas in a real-world visual field there are probably both moving and static objects. It might be important for experimenters to consider how the sensorimotor responses of their subjects and the dynamics of the visual environment are shaping the attention they are measuring in their studies.

These tracking experiments have much potential for further investigation as some questions still remain, such as clarifying if error-versus-effort emphases might shape attentional allocation when more preview is available. Another potential goal would be to investigate whether our attentional measurement technique can be implemented in a more real-time way, so that we can see the signal-to-noise ratios changing through an extended tracking period. Eventually, we would like to apply our attentional measure to more complex control dynamics that better approximate realistic vehicular control. With more realistic dynamics we expect to find evidence that attention will shift further down the previewed roadway. Our simulation was also quite simplistic in its two dimensional representation of driving, so we might pose the question of how more immersive three dimensional simulations might change attentional allocation. Finally, we want to investigate the question of what effect experience has on attention as subjects become more familiar with performing the task. Some studies have found that more experienced drivers show different eye movement patterns scanning their driving environment compared to novices (Underwood, G., Chapman, Brocklehurst, Underwood, J., & Crundall, 2003; Konstantopoulos, Chapman, & Crundall, 2010). Might this suggest more experienced subjects have a more defined attentional distribution pattern; would they show a consistent attentional distribution pattern across multiple trials, blocks, or days?

What this series of experiments accomplished is the introduction of a different approach to measuring cognition and behavior. Here we modeled the cognition within a perceptual-motor task as forming part of a larger control loop that incorporates both the task environment and the human. Cognition is embedded within this loop, and by tapping into the appropriate psychometrics we can infer more about its dynamic role shaping the actions affecting the task environment, which in turn shape the individual's response further. This allows us to use action to measure cognitive mechanisms beyond a simpler stimulus-response paradigm.

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