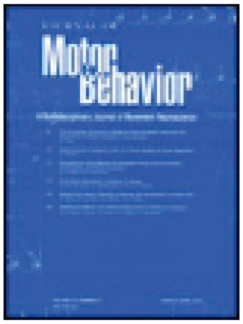

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RESEARCH ARTICLE

Spatio-Temporal Flexibility of Attention Inferred from Drivers' Steering Movements

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ABSTRACT. Participants attempted to center a cursor on a video display of a winding roadway with a rate control system. Fourier analysis of their steering movements in response to sinusoidal perturbations of the roadway revealed how much attention they allocated to different roadway preview locations. We compared a full 1.0 s of preview with preview restricted to a narrow slit around 0.3 s or 0.6 s. Participants were able to flexibly shift their attention to either slit. However, they performed better in terms of root-mean-squared error, velocity error, and acceleration error with the fuller view. They concentrated their attention over a range from 0.1 s to 0.3 s of preview in a manner qualitatively consistent with Miller's optimal control model.

Keywords: attention, driving, preview, control theory, perceptual-motor buffer

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 upcoming 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 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 various circumstances in vehicular control.

Dynamic models of steering control typically involve two components (e.g., Donges, 1978; McRuer et al., 1977; Figure 1). One is a feedback loop that maintains the vehicle in the center of the roadway by nulling lateral position error. The second is a feedforward component that responds to future roadway and allows the system to anticipate upcoming steering movements (e.g., Sheridan, 1966; Wierwille et al., 1967). The question we wish to investigate is how attention allocation by the human controller plays a role in effective feedforward control.

Previous researchers have theorized about what aspects of preview drivers might attend. One of the main debates is whether drivers focus on a single discrete future roadway location, multiple discrete future locations, or distribute their attention more continuously (Jagacinski et al., 2017). Some researchers have used classical control theory to argue for a single point of attentional allocation for both feedback and feedforward control (van der El et al., 2020). Another model proposes that drivers generate feedforward by focusing their attention one reaction time into the future so that their steering movements would appropriately coincide with the arrival of bends in the roadway (Hess, 1987).

Still others have argued for two discrete previewed locations (e.g., Hess & Chan, 1988 for helicopter control; Salvucci & Gray, 2004; Sentouh et al., 2009). For example, Land and Horwood (1995) tested participants in a simulated driving task where the view of the roadway could be unrestricted or restricted to one or two discrete locations on the display. They found driving performance with two discrete locations to be indistinguishable from driving with unrestricted view. They argued that drivers only require two regions of previewed roadway for successful driving. One location close to the vehicle informs the feedback loop by focusing on extrapolated lateral position error. This information is used by the system to nullify lane drifting. The second region of attention was found to be about 0.85 s further ahead on the road (Land, 1998). Curvature in this region was used for the feedforward control aspect of driving.

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 a continuous range of regions in the previewed roadway. The relative emphasis of these regions depended on the dynamic characteristics of the vehicle being controlled and on the driver's relative weighting of mean-squared lateral position error and mean-squared control movement (a measure of the driver's effort).

Psychological research on the spatial distribution of attention in other contexts (e.g., Folk, 2015) does not argue against the possibility of these various different strategies. One metaphor used to describe attention allocation is a movable spotlight (e.g., Posner, 1980; Wachtel, 1967) or zoom lens that has adjustable width

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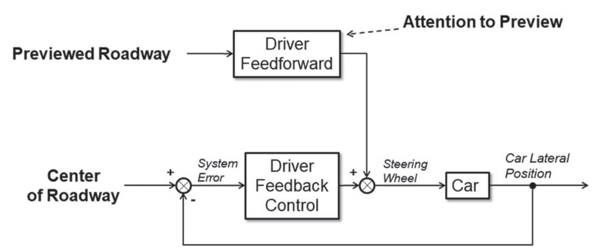

FIGURE 1. A typical control model of driving consisting of an error nulling feedback loop that responds to lateral position error and anticipatory feedforward control that responds to upcoming previewed roadway (after Jagacinski et al., "Measuring memory and attention to preview in motion," *Human Factors*, *59*(5), p. 797. Copyright © 2017, Human Factors and Ergonomics Society. DOI: 10.1177/0018720817695193).

(e.g., Eriksen & St. James, 1986; LaBerge, 1983). Other research suggests that spatial attention can be allocated to more than one location simultaneously (e.g., Bay & Wyble, 2014; McMains & Somers, 2005).

Using participants' steering responses to roadway display perturbations, we assessed the relative amount of attention devoted to various preview locations and distinguished among these different hypotheses about attention allocation while driving. Previous studies with this measurement technique (Jagacinski et al., 2017, 2019) have provided evidence for a continuous distribution of attention qualitatively consistent with the predictions of optimal control theory (Miller, 1976; Sharp, 2005). However, these studies leave open the possibility that drivers would do better if forced to attend to discrete preview locations rather than a contiguous range of locations. The present set of experiments compared these two strategies by using display perturbations to measure the spatial distribution of attention and forcing participants to attend to particular discrete locations (Land & Horwood, 1995). Experiments 1 and 2 compared a full view of the previewed roadway with restricted views 0.3 s and 0.6 s into the future. Experiment 3 compared the two restricted views more directly.

Experiment 1 – Testing Discrete vs. Continuous Distribution of Attention

Our goal in this experiment was to investigate drivers' attentional allocation to the roadway in a simplified simulated environment. Previous research has looked at attention in driving using measurements such as eye-tracking (Cooper et al., 2013; Land & Lee, 1994; Readinger et al., 2002). 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 used a relatively new measurement technique that perturbed the visual display of the roadway with different frequency sinusoids. The presence of those sinusoids in the Fourier spectrum of participants' steering movements then provided a measure of how attention was directed in the feedforward component of their driving.

If participants distribute their attention over a contiguous range of locations when full preview is available (e.g., Jagacinski et al., 2017), could participants successfully attend to preview if we restricted their view of the roadway to two widely separated locations? We compared a view of the present roadway position plus a full 1.0 s of preview with a view of the present roadway plus a narrow slit of preview relatively far down the roadway at 0.6 s. Given that attention is a limited cognitive resource (e.g., Kahneman, 1973), we expected that restricting the participants' attention to the slit location might result in a higher degree of attention at that location than in any particular location in the full view condition for which attention to preview is more dispersed. However, the wide spatial separation between the present roadway and slit might limit this effect.

We also 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 (e.g., 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.

Our evaluation of tracking performance was guided by the Progression-Regression Hypothesis of Fitts et al. (1959). It predicts that as individuals become more skilled at a task they attune to higher derivatives of the signals essential to their task performance, e.g., velocity and acceleration characteristics of the input signal. Velocity error in our tracking task is a measure of how well participants match the slope of the roadway, and acceleration error is a measure of to how well participants match the curvature of the roadway. 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 restricted slit of preview.

Method

Participants

Eight university students between the ages of 18 and 25 volunteered as part of an introductory psychology

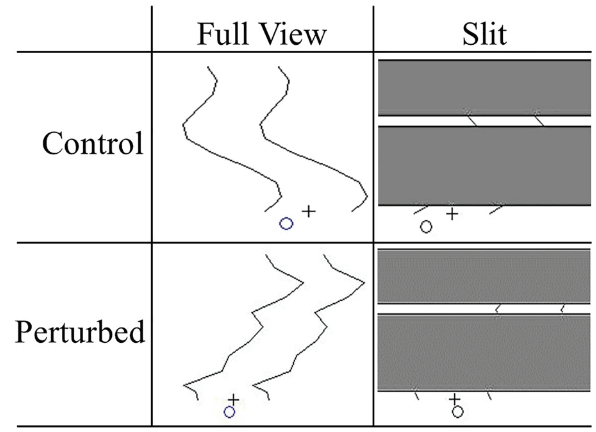

FIGURE 2. The four conditions that participants saw during the experiment. The circular cursor was controlled by participants' joystick movements; the cross indicated the center of the roadway display. The perturbation manipulation is shown in the bottom row. It creates the appearance of "elbows" at 10 specific future roadway positions. The center of the slit corresponds to 0.6 s into the future.

course research experience. 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.

Apparatus

Participants sat at a desk with a Measurement Systems 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, 0.10, 0.20, 0.30 … 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 et al., 2017). Participants could attend to the displayed roadway without shifting their 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 session 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 region of the roadway between 0.53 s and 0.67 s into the future, i.e., a small slit centered at 0.60 s. Participants could also see the present roadway position up to 0.05 s into the future, so they could perceive any deviations of the cursor from the center of the roadway. 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 condition first was also counterbalanced across participants. 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.

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 the circular cursor directly below a cross which indicated the center of a roadway. A block consisted of 4 trials with a 20 s 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 (see *Tracking Performance* in the Results section for details). Participants were told the lower their score, the better their performance. To keep participants motivated they were informed that the best performing participant would be rewarded a $20 bonus at the conclusion of the study. After each block, participants were then given a two-minute break before starting the next block.

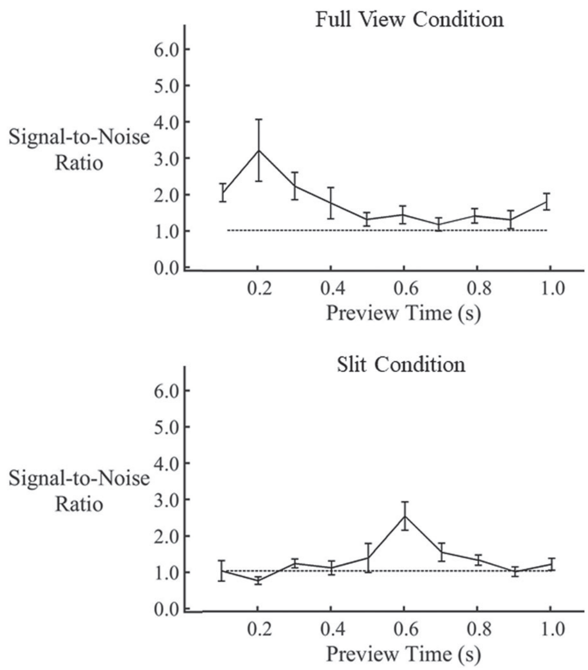

FIGURE 3. Average attentional allocation for 8 participants in the Full View and Slit conditions. In the Full View condition participants placed most of their attention at roadway regions around 0.1 s – 0.3 s into the future. In the Slit condition only preview around 0.6 s into the future was visible, and it has a high signal-to-noise ratio. The error bars represent ±1 standard error.

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 upcoming roadway preview. Ten roadway positions separated by 0.1 s into the future were each perturbed by a unique sinewave in the Perturbation conditions. In essence, each future position of the road oscillated with a unique frequency. The perturbation frequency used at each of the ten locations did not correspond to any of the sinewave frequencies used to generate the road's lateral movement; they functioned as observation noise that was unrelated to the actual movement of the road. They were interleaved among the roadway frequencies and had an amplitude that was 30% of the larger amplitudes used to generate the roadway. 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 the ratio of the Fourier amplitudes at the labeling frequencies 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 filtered white noise throughout the measured frequency spectrum (Allen & Jex, 1972; Jagacinski & Flach, 2003, p. 223). By measuring the remnant amplitude at the labeling frequencies we established a baseline. Each labeling frequency's baseline amplitude was compared to its amplitude during the Perturbation condition. If a participant was attending to a particular region of the display, the labeling frequency 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 at the labeling frequency during the Perturbation block to the amplitude at that same frequency during the Control block (baseline) to create a signal-to-noise ratio that reflected the degree to which each preview region was being attended.

Interleaved sinusoids have been used before to identify the perceptual cues guiding control behavior in simulated helicopter piloting (Johnson & Phatak, 1990). In our task, the perturbations allow us to specify attention to preview as a signal-to-noise ratio in participants' 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's remnant amplitude

Results

Attentional Distributions

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. If a participant was attending to a particular region in the display, then we expected that region, denoted by how many seconds 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. 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 2×10 analysis of variance of the signal-to-noise ratios (Condition: Full View, Slit; Preview Positions: 0.1 s to 1.0 s into the future). There was a main effect of condition [$F(1, 7) = 24.54$, $p < 0.01$; $\bar{x}_{Full\ View} = 1.75$, $\bar{x}_{Slit} = 1.28$] and an interaction [$F(9, 63) = 4.31$, $p < 0.01$]. Figure 3 shows how qualitatively different attentional allocation was in the Full View condition when compared to the Slit condition. If Full View represents what participants typically attend to when the entire roadway preview is visible, then Figure 3 demonstrates that the Slit condition was able to force participants to attend elsewhere.

Tracking Performance

We tested whether having full preview of the upcoming roadway was functionally significant to tracking performance. The root-mean-squared error of tracking performance was calculated for each trial. Error was equal to the difference between the cursor participants controlled and the center of the roadway at each instant of time over the 164 s trial. We calculated the median root-mean-squared error score for the four trials in a block and used that as the measure of overall error for that block/condition.

We conducted a 2×2 analysis of variance of the root-mean-squared 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 participants 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 participants 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 interaction was found. The results indicate there was a performance advantage for the Full View condition.

Performance was also analyzed 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 at the 10 frequencies that generated the roadway. At each roadway frequency, a median amplitude was calculated from the four trials in a block. The root-mean-square of the median magnitudes at each of these frequencies is a measure of Position error (Jagacinski et al., 2017). Position error showed a high correlation with the root-mean-squared error used in the previous analysis for both the Slit condition [$r(6) = 0.78$, $p < 0.03$] and the Full View condition [$r(6) = 0.92$, $p < 0.01$]. A 2×2 analysis of variance of Position error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) revealed no main effects or interaction, though both the Condition main effect and the interaction were close to significant [$F(1, 7)_{\mathrm{Condition}} = 4.88$, $p = 0.06$; $\bar{x}_{Full\ View} = 0.034$, $\bar{x}_{Slit} = 0.042$; $F(1, 7)_{\mathrm{Interaction}} = 5.16$, $p = 0.06$].

The Progression-Regression Hypothesis (Fitts et al., 1959) suggests participants 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 participants to capture slope and roadway curvature information. We calculated each participant's Velocity and Acceleration error in the frequency domain by taking the 10 median amplitudes of the Position error and generating their first and second derivatives. This was done by multiplying each of those 10 median amplitudes by their frequency for Velocity error, and frequency squared for Acceleration error, and then calculating the root-mean-squared value.

A 2×2 analysis of variance of Velocity error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) revealed a main effect of Condition [$F(1, 7) = 20.05$, $p < 0.01$; $\bar{x}_{Slit} = 0.265$, $\bar{x}_{Full\ View} = 0.220$], a main effect of 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 the Full View condition with Control trials had the lowest Velocity error of any Condition by Trial Type combination.

The 2×2 analysis of variance of Acceleration error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) similarly revealed a main effect of Condition [$F(1, 7) = 27.52$, $p < 0.01$; $\bar{x}_{Slit} = 2.352$, $\bar{x}_{Full\ View} = 1.984$], a main effect of 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.

Discussion

The data in Figure 3 showed strong evidence that the measurement system can capture how participants 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. Participants shifted their attention to the only future roadway information that was available. Even so, participants did not necessarily focus on the central portion of the slit region. Two participants showed peak attention at neighboring previewed locations. One participant seemed to be attending to the 0.5 s preview region, and the other participant was focused on both the 0.6 s and 0.7 s preview regions. This suggests that these participants 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.

In agreement with previous research, the upper part of Figure 3 provides evidence that when full preview was available participants distributed their attention in regions close to the cursor they were controlling (Jagacinski et al., 2017; Miller, 1976). While Miller's theory (1976) predicts a continuous decrease in attention with increasing preview time for a rate control system, he did not consider human time delays. The trend toward lesser attention at 0.1 s may reflect difficulty for participants to respond to the previewed roadway in that short a time. For example, Carlton (1981) estimated the time to amend an ongoing movement as about 135 ms.

We can also see that participants appeared to pay less attention to preview regions further away. The pattern of attention was qualitatively different in the Slit condition (lower part of Figure 3). The slit was therefore effective in making participants allocate attention to a region they normally did not attend.

Our manipulation was able to demonstrate the flexibility of participants' attentional allocation, but tracking performance in the Slit condition was not as accurate as in the Full View condition as assessed by the root-mean-squared error. Although Position error did not quite meet the criterion for statistical significance, participants 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 as 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.

Experiment 2 – Moving the Slit Location to a Closer Preview Position

In Experiment 1 it was unclear whether the performance differences in Velocity error and Acceleration error between the Full View and Slit conditions were due to the perceptual limitations of 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 relocated the slit to a preview region that participants might consider more informative. Figure 3 showed peak attention allocation occurred at about 0.1 s − 0.3 s into the future in the Full View condition. We tested a new set of participants with the slit centered at 0.3 s into the future to see if attention and performance changed when the slit is located in a region where participants 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.

Results

Attentional Distributions

Just as in Experiment 1, participants showed two qualitatively different attention allocation patterns. Figure 4 shows that in the Full View condition participants emphasized the first three preview positions much the same way they did in Experiment 1. The attentional allocation in the Full View condition also looks very different from the Slit condition. A 2×10 analysis of variance of 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 1 that participants were attending to roadway preview differently in the two conditions. A follow-up matched pairs t-test on the signal-to-noise ratios at 0.3 s of preview revealed that participants attended to this preview position much more in the Slit condition than in the Full View condition [$t(7) = 4.57$, $p < 0.01$; $\bar{x}_{Slit} = 4.916$, $\bar{x}_{Full\ View} = 2.023$].

Tracking Performance

We tested whether tracking performance was different for Slit and Full View conditions. A 2×2 analysis of variance of root-mean-squared error (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) revealed a main effect for Trial Type indicating again that the Perturbation trials resulted in poorer tracking [$F(1, 7) = 32.46$, $p < 0.01$; $\bar{x}_{Perturbed} = 0.785$, $\bar{x}_{Control} = 0.698$]. A main effect of Condition indicated less tracking error in the Full View condition [$F(1, 7) = 14.13$, $p < 0.01$; $\bar{x}_{Full\ View} = 0.666$, $\bar{x}_{Slit} = 0.817$]. There was no interaction.

We analyzed performance in the frequency domain by using Position error as in Experiment 1. A 2×2 analysis of variance (Condition: Slit, Full View; Trial Type: Control trials, Perturbation trials) found a main effect of Trial Type [$F(1, 7) = 9.37$, $p < 0.02$; $\bar{x}_{Perturbed} = 0.057$, $\bar{x}_{Control} = 0.050$], a main effect of 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 participants tracked better in the Full View condition.

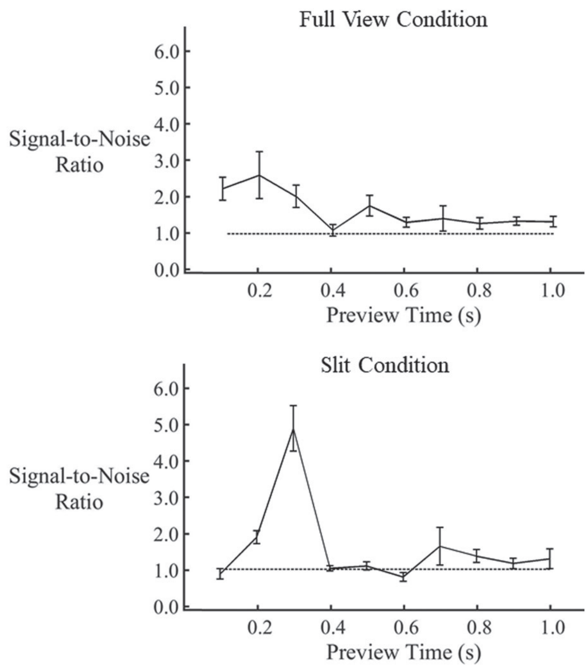

FIGURE 4. Average attentional allocation for 8 participants in Full View and Slit conditions. In the Full View condition participants distributed their attention across roadway regions from 0.1 s to 0.3 s into the future. In the Slit condition only preview around 0.3 s into the future was visible, and it has a high signal-to-noise ratio. The error bars represent ± 1 standard error.

The Progression Regression Hypothesis also appears to be well supported by analyses of Velocity and Acceleration error, higher derivatives of Position error reflecting participants' smoothness of tracking. A 2×2 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 of Trial Type [$F(1, 7) = 6.44$, $p < 0.04$; $\bar{x}_{Perturbed} = 0.269$, $\bar{x}_{Control} = 0.250$] and a main effect of Condition [$F(1, 7) = 16.36$, $p < 0.01$; $\bar{x}_{Full\ View} = 0.239$, $\bar{x}_{Slit} = 0.279$], while Acceleration error revealed a main effect only of Condition [$F(1, 7) = 7.81$, $p < 0.03$; $\bar{x}_{Full\ View} = 2.009$, $\bar{x}_{Slit} = 2.134$]. Both analyses showed no interaction. They both demonstrate smoother tracking in the Full View condition compared to the Slit condition.

Comparison of Attention to Slits in Experiments 1 and 2

As can be seen in Figures 3 and 4, participants attended to the Slit at the 0.3 s region in Experiment 2 with greater intensity than the 0.6 s region in Experiment 1. A t-test comparing the highest signal-to-noise ratio for each participant in each of the two slit regions confirmed this difference [$t(14) = 3.27$, $p < 0.01$; $\bar{x}_{0.3\ s\ in\ \mathrm{Exp.}\ 2} = 4.92$, $\bar{x}_{0.6\ s\ in\ \mathrm{Exp.}\ 1} = 2.50$].

Prevalence of Noise in the Attentional Measure

The Slit condition in Experiments 1 and 2 provided a method for estimating the prevalence of spuriously large attentional signal-to-noise ratios. Occasionally a participant'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 calculated the proportion of signal-to-noise ratios that were above 2.0, 2.5, or 3.0 in the concealed preview regions during Slit conditions across the two days of each experiment for all participants. The signal-to-noise ratios of concealed preview positions exceeded 2.0, 2.5, and 3.0 with relative frequencies 6.5%, 2.3%, and less than 1%, respectively. These low percentages indicate that most of the signal-to-noise ratios greater than 2.0 were reliable depictions of participants' attentional allocation.

Discussion

The purpose of Experiment 2 was to test whether the location of the slit on the previewed roadway had an effect on participants' ability to attend to it. Miller (1976) predicted that an optimal controller with Full View would emphasize closer regions of the preview. Experiments 1 and 2 both qualitatively corroborated this prediction; participants tended to place most of their attention at preview positions 0.1 s – 0.3 s into the future (Figures 3 and 4). These results motivated us to test whether centering the slit at the 0.3 s region in Experiment 2 would result in a stronger attentional signal for the Slit condition than we saw at 0.6 s in Experiment 1. Comparing Figures 3 and 4 it is evident that participants attended to the 0.3 s region much more effectively than they did to the 0.6 s region.

Even though participants were able to direct a lot of attention to the Slit region, their performance was worse than in the Full View condition, which was also the case in Experiment 1. Full View seems to allow participants 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 of our results. All measures of performance error including higher derivatives of Position error (i.e., Velocity and Acceleration error) were worse in the Slit condition in Experiment 2. The Slit condition limited participants' ability to anticipate roadway slope and curvature.

Experiment 3 – Revisiting the Comparison of Slit Regions at 0.3 s and 0.6 s

Our measurement technique revealed that participants could shift their attention to the roadway region in the slit, but they did so more effectively when the slit was located at the edge of the region they attended in the Full View condition. One possible interpretation is that when attending too far down the roadway, participants may have difficulty planning their steering actions so far in advance. Therefore, they devoted less attention to the slit in the 0.6 s region. Another possibility is that there were carryover effects from the Full View condition to the Slit condition given that the 0.6 s position was deemphasized under Full View.

Another possible contributor to the lower signal-to-noise ratio for the 0.6 s slit is that the 10 perturbation frequencies decreased with longer preview times. Jagacinski et al. (2017) found that ascending perturbation frequencies with longer preview times did not change the qualitative pattern of greater emphasis of closer preview locations with Full View, but that the magnitudes of the signal-to-noise ratios at closer preview locations were larger with descending frequencies. That is why descending perturbation frequencies were used in Experiments 1 and 2. While this procedure enhanced measurement of the Full View attentional distribution, the perturbation frequencies were higher for the 0.3 s region than the 0.6 s region in the Slit conditions. Stronger bottom-up attentional capture by the higher frequency perturbations at 0.3 s might contribute to the relatively lower signal-to-noise ratio with the 0.6 s slit.

To address these issues, Experiment 3 used the same frequency labels for the 0.3 s and 0.6 s slits. We compared attention and tracking error performance with a within-participants design. Additionally, exposure to the Full View condition was minimal to lessen the likelihood of carryover effects. These experimental design changes gave us a better understanding of what happens when participants are forced to look at very narrow preview regions that lay both closer and farther from the cursor they are controlling. Based on Experiments 1 and 2, we predicted participants might still show a higher signal-to-noise ratio when attending to the closer slit region at 0.3 s compared to the farther slit region at 0.6 s. We also predicted that attending to the 0.3 s slit might result in better tracking performance because this region is at the edge of the region where participants typically prefer to attend during Full View conditions.

Method

Participants

Thirteen university students between 18 and 30 years of age volunteered for this experiment as part of an introductory psychology course. One participant was excluded from the final data analysis because her error scores exceeded 3 standard deviations from the mean of the group. This left twelve counterbalanced participants for our analysis.

Procedure

The same control dynamics and slit procedure as in 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-participants so we could compare participants' attentional signal-to-noise ratios to themselves. All participants' first block was a two-trial Full-View condition to give them experience with the task without the observational constraint imposed by the slits. For the remaining blocks half of the participants started with the slit centered on 0.3 s and half started with the slit centered on 0.6 s into the future. Participants then performed both a Control and Perturbation block of tracking for their initial slit condition before moving on to the other slit condition. Whether they received a Control or Perturbation block first was counterbalanced across participants.

To control for the effect of frequency label on signal-to-noise ratios, we assigned the same three frequency perturbations 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 perturbation; the next closer preview position below it received an 8.94 rad/s perturbation; and the next farther preview position above it was assigned a 5.02 rad/s perturbation. These frequencies corresponded to the perturbations used at preview positions at 0.2, 0.3, and 0.4 s in Experiments 1 and 2, and therefore provided a replication of the 0.3 s Slit condition in Experiment 2. The surrounding frequencies influenced the slopes of the displayed lines extending from the center of the slit region (see Figure 2).

Results

Attentional Distributions

To determine the effects of the slit location on signal-to-noise ratios we analyzed the three preview locations 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 5 we can see participants attended to the 0.3 s and 0.6 s slit regions approximately equally. A 2×3 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, $p < 0.01$; $\bar{x}_{Bottom} = 2.43$, $\bar{x}_{Center} = 5.42$, $\bar{x}_{Top} = 1.26$]. Regardless of where the slit was positioned, participants showed the

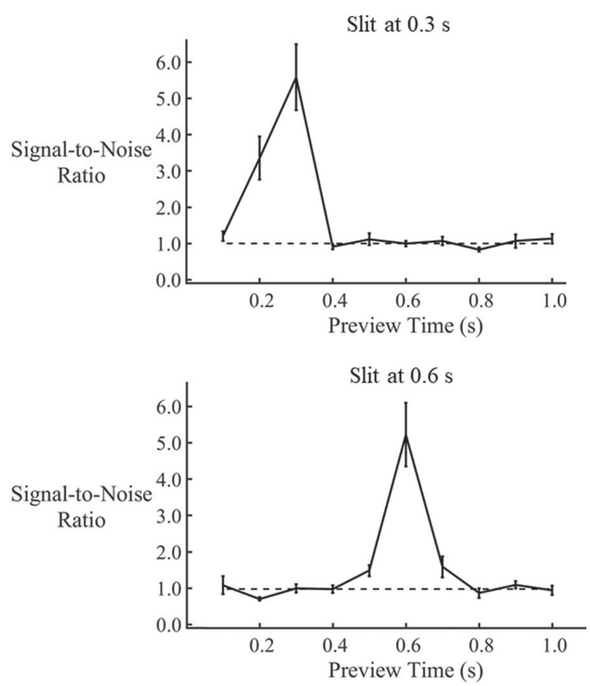

FIGURE 5. The attentional distributions of 12 participants when the slit was centered at 0.3 s and 0.6 s. There was no significant effect of the slit preview time on the magnitudes of participants' signal-to-noise ratios. The error bars represent ±1 standard error.

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 indicates that participants were approximately equally able 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 that the 0.3 s slit would receive greater attention. Figure 5 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.

Tracking Performance

We analyzed whether the location of the two slit regions had any effect on tracking performance. Paired samples *t*-tests indicated no significant effect of the slit location on root-mean-squared error, Position error, or Velocity error. However, Acceleration error was lower for the 0.3 s slit [$t\ (11) = -3.05$, $p < 0.02$; $\bar{x}_{Slit\ at\ 0.3\ s} = 1.98$, $\bar{x}_{Slit\ at\ 0.6\ s} = 2.37$].

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 found that participants were more effortful when the slit was centered at 0.3 s [$t\ (11) = 10.42$, $p < 0.01$; $\bar{x}_{Slit\ at\ 0.3\ s} = 3.63$, $\bar{x}_{Slit\ at\ 0.6\ s} = 3.10$].

Discussion

After equating the perturbation frequencies at the 0.3 s and 0.6 s slits and minimizing possible carryover effects from the Full View condition, we found that there was no effect of the slit location on attention allocation. Participants could redirect their attention to both close and far preview with approximately equal focus. The signal-to noise ratios were comparable to the high level found for the 0.3 s slit in Experiment 2. This result indicates that Miller's (1976) predictions that more distant roadway preview would be weighted significantly less when permitted Full View does not generalize to Slit conditions involving highly restricted view. The two slit regions were only 0.3 s apart, so it is still possible that there might be a preview region between 0.6 s and 1.0 s to which allocating attention becomes more difficult. Given that participants also had to attend to current position error relative to the center of the roadway, these results imply that participants were able to attend to two distinct loci of horizontal motion that were vertically separated by about 2° of visual angle in the 0.6 s slit condition. Land and Horwood (1995) found that simulator driving performance with two slits separated vertically by 7° of visual angle was equivalent to full view performance in terms of deviation from the roadway center.

Given that attention was approximately equally allocated to both near (0.3 s) and far (0.6 s) 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 participants were forced to attend. However, we did find an effect of the slit location on Acceleration error, which captured how smoothly participants were tracking the roadway. Participants were smoother in their tracking when focusing on the closer preview region. This is contrary to Land and Horwood (1995) study that found participants' tracking in a simulated vehicle environment was smoother when their 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. Miller's (1976) theory predicts that more distant preview will be used in controlling more complex dynamics, and this trend has been found empirically (e.g., Ito & Ito, 1975; Tatler & Land, 2015; van der El et al., 2018).

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, participants exhibited greater joystick movement than when it was further away. The higher effort measure is the result of participants 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 participants generated had to be differentiated twice to determine Acceleration error, so higher frequencies contributed more heavily to this measure of accuracy. The Fourier spectra of participants' 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 participants 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.

General Discussion

When measuring participants' attention to roadway preview in similar tracking studies, some researchers have used techniques such as eye tracking to determine which roadway preview regions are being emphasized (Cooper et al., 2013; Land & Lee, 1994; Readinger et al., 2002; Underwood et al., 2003). However, it is still possible for individuals to direct their gaze at something without actually attending to it, and there can be uncertainty as to what features are being attended within a gaze (Land, 1998). The measurement technique in the present experiments delivers a promising supplement to eye movement measurements. These experiments provide evidence that with the use of display perturbations participants' steering movements carry information about participants' attentional allocation. We can use their action response as a means to measure the distributed pattern of attention that shapes their motor execution. The display perturbation technique used in the present experiment might be usefully adapted to other perceptual-motor tasks to measure continuous regions of attention.

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

Even so, we were able to force participants to attend to specific roadway regions by making only a particular preview position visible during Slit conditions. We managed to shift participants' attention to the 0.6 s preview region they were not normally attending during the Full View condition; we also examined the 0.3 s region that was normally attended during the Full View condition. We found that these restricted viewing conditions were detrimental to their performance. Participants had lower root-mean-squared 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 participants also demonstrated lower Velocity and Acceleration error, meaning their tracking was a smoother approximation to the roadway. One of the benefits of fuller preview is that participants 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 in Experiment 3, we found that participants attended about equally well to the slits at 0.3 s or 0.6 s into the future. Moreover, participants demonstrated comparable Position error scores for 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 has been proposed is that participants' 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 vehicle reaching the previewed bends in the roadway. 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 participants attending to the 0.6 s preview region. This can be thought of as analogous to individuals retaining a sequence of discrete stimuli in working memory and constantly updating them such as in the n-back task (e.g., Wilhelm et al., 2013). The longer the sequence, the higher the cognitive load and the longer one has to retain each item in memory. This can lead to loss of certain details in the sequence and increases in errors. In this way, both the proposed tracking buffer and working memory updating more generally can be thought of as a type of low pass filter.

In summary, this study demonstrated that participants are able to adapt their attention to the available preview in order to track a winding roadway. One might expect that the best place to focus on a roadway would be roughly one reaction time away so that steering responses would coincide with upcoming roadway windings (Hess, 1987). We instead found that participants in the Full View condition tended to focus on a range of preview that extended beyond the range of typical reaction times in tracking tasks. This distributed attention led to better root-mean-squared error, Velocity error, and Acceleration error relative to the restricted attention to preview of the Slit conditions. The latter two measures reflected how smoothly tracking matched the higher derivatives of the roadway path. Miller's (1976) optimal control model qualitatively described the attentional distribution in the Full View condition. For the Slit conditions we may need to consider other behavioral mechanisms to describe participants' behavior. These observations reinforce the point that attention is flexible and that it is important to study it in the context of action.

A potential criticism of these results is that the experimental conditions do not accurately reflect real-world driving conditions. For one, the simplified display does not match the amount of visual information participants may need to attend to when driving an actual vehicle. Secondly, the visual information for most driving situations changes at a much lower bandwidth than the 3 rad/s participants experienced in our study. Finally, 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. This final point is particularly relevant because as we already mentioned systems with more complex dynamics require more anticipation for stable control.

Additional studies should therefore test this measure of attention in a moving base simulator with realistic handling characteristics, lower roadway bandwidth, and a more geometrically complex display of preview. A small step in that direction is a study by Morrison et al. (in press), which showed that with a position control a more realistic three-dimensional view of a 1 rad/s roadway did not change the pattern of attention relative to a two-dimensional top-down view. However, the three-dimensional display did result in higher attentional signal-to-noise ratios with more complex dynamics. These results and the distinct predictions from optimal control theory for higher order systems (Miller, 1976) provide additional motivation to test the present measurement technique with more realistic car simulations.

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REFERENCES

Allen, R. W. & Jex, H. R. (1972). A simple Fourier analysis technique for measuring the dynamic response of manual control systems. *IEEE Transactions on Systems, Man, and Cybernetics*, *SMC-2*, 630–643. https://doi.org/10.1109/TSMC.1972.4309192

Bay, M. & Wyble, B. (2014). The benefit of attention is not diminished when distributed over two simultaneous cues. *Attention, Perception, and Psychophysics*, *76*, 1287–1297. https://doi.org/10.3758/s13414-014-0645-z

Carlton, L. G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(5), 1019–1030. https://doi.org/10.1037/0096-1523.7.5.1019

Cooper, J. M., Medeiros-Ward, N., & Strayer, D. L. (2013). The impact of eye movements and cognitive workload on lateral position variability in driving. *Human Factors*, *55*, 1001–1014. https://doi.org/10.1177/0018720813480177

Donges, E. (1978). A two-level model of driver steering behavior. *Human Factors*, *20*, 692–707. https://doi.org/10.1177/001872087802000607

Eriksen, C. W. & St. James, J. D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40*(4), 225–240. https://doi.org/10.3758/bf03211502

Fitts, P. M., Bahrick, H. P., Noble, M. E., & Briggs, G. E. (1959). *Skilled performance* (Ohio State University Final Report for Contract AF 41[657]-70). Ohio State University.

Folk, C. L. (2015). Controlling spatial attention: Lessons from the lab and implications for everyday life. In J. M Fawcett, E. F.

Risko, & A. Kingstone (Eds.), *The handbook of attention* (pp. 3–25). MIT Press.

Hess, R. A. (1987). Feedback control models. In G. Salvendy (Ed.), *Handbook of human factors* (pp. 1212–1242). Wiley.

Hess, R. A. & Chan, K. K. (1988). Preview control pilot model for near-earth maneuvering helicopter flight. *Journal of Guidance, Control, and Dynamics*, *11*, 146–152. https://doi.org/10.2514/3.20284

Ito, K. & Ito, M. (1975). Tracking behavior of human operators in preview control systems. *Electrical Engineering of Japan*, *95*(1), 120–127. https://doi.org/10.1002/eej.4390950118

Jagacinski, R. J., & Flach, J. M. (2003). *Control theory for humans: Quantitative approaches to modeling performance*. Erlbaum.

Jagacinski, R. J., Hammond, G. M., & Rizzi, E. (2017). Measuring memory and attention to preview in motion. *Human Factors*, *59*, 796–810. https://doi.org/10.1177/0018720817695193

Jagacinski, R. J., Rizzi, E., Bloom, B. J., Turkkan, O. A., Morrison, T. N., Su, H., & Wang, J. (2019). Drivers' attentional instability on a winding roadway. *IEEE Transactions on Human-Machine Systems*, *49*(6), 498–507. https://doi.org/10.1109/THMS.2019.2906612

Johnson, W. W. & Phatak, A. V. (1990, August). Modeling the pilot in visually controlled flight. *IEEE Control Systems Magazine*, 24–26. https://doi.org/10.1109/37.60419

Kahneman, D. (1973). *Attention and effort*. Prentice-Hall Inc.

LaBerge, D. (1983). Spatial extent of attention to letters in words. *Journal of Experimental Psychology: Human Perception & Performance*, *9*(3), 371–379. https://doi.org/10.1037/0096-1523.9.3.371

Land, M. F. (1998). The visual control of steering. In L. R. Harris & M. Jenkin (Eds.), *Vision and action* (pp. 163–179). Cambridge University Press.

Land, M. F. & Horwood, J. (1995). Which parts of the road guide steering? *Nature*, *377*, 339–340. https://doi.org/10.1038/377339a0

Land, M. F. & Lee, D. N. (1994). Where we look when we steer. *Nature*, *369*, 742–744. https://doi.org/10.1038/369742a0

Levison, W. H. (1979). A model for mental workload in tasks requiring continuous information processing. In N. Moray (Ed.), *Mental workload: Its theory and measurement* (pp. 189–218). Plenum. https://doi.org/10.1007/978-1-4757-0884-4_11

McMains, S. A. & Somers, D. C. (2005). Processing efficiency of divided spatial attention mechanisms in human visual cortex. *Journal of Neuroscience*, *23*, 9444–9448. https://doi.org/10.1523/JNEUROSCI.2647-05.2005

McRuer, D. T., Allen, R. W., Weir, D. H., & Klein, R. H. (1977). New results in driver steering control models. *Human Factors*, *19*, 381–397. https://doi.org/10.1177/001872087701900406

Miller, R. A. (1976). On the finite preview problem in manual control. *International Journal of Systems Science*, *7*, 667–672. https://doi.org/10.1080/00207727608941951

Morrison, T. N., Rizzi, E., Turkkan, O. A., Jagacinski, R. J., Su, H. & Wang, J. (in press). Drivers' spatio-temporal attentional distributions are influenced by vehicle dynamics and displayed point of view. *Human Factors*. https://doi.org/10.1177/0018720820902879

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

Readinger, W. O., Chatziastros, A., Cunningham, D. W., Bülthoff, H. H., & Cutting, J. E. (2002). Gaze-eccentricity effects on road position and steering. *Journal of Experimental Psychology: Applied*, *8*, 247–258. https://doi.org/10.1037/1076-898X.8.4.247

Rizzi, E. (2018). *The relationship between attention to preview and action during roadway tracking* [Unpublished doctoral dissertation]. Department of Psychology, Ohio State University. http://rave.ohiolink.edu/etdc/view?acc_num=osu153331644665238

Salvucci, D. D. & Gray, R. (2004). A two-point visual control model of steering. *Perception*, *33*, 1233–1248. https://doi.org/10.1068/p5343

Sentouh, C., Chevrel, P., Mars, F., & Claveau, F. (2009). A sensorimotor driver model for steering control. In *Proceedings of the 2009 IEEE International Conference on Systems, Man, and Cybernetics* (pp. 2462–2467). IEEE. https://doi.org/10.1109/ICSMC.2009.5346350

Sharp, R. S. (2005). Driver steering control and a new perspective on car handling qualities. *Proceedings of the Institution of Mechanical Engineers: Part C: Journal of Mechanical Engineering Science*, *219*, 1041–1051. https://doi.org/10.1243/095440605X31896

Sheridan, T. B. (1966). Three models of preview control. *IEEE Transactions on Human Factors in Electronics*, *7*(2), 91–102. https://doi.org/10.1109/THFE.1966.232329

Tatler, B. W. & Land, M. F. (2015). Everyday visual attention. In J. M Fawcett, E. F. Risko, & A. Kingstone (Eds.), *The handbook of attention* (pp. 391–421). MIT Press.

Underwood, G., Chapman, P., Brocklehurst, N., Underwood, J., & Crundall, D. (2003). Visual attention while driving: Sequences of eye fixations made by experienced and novice drivers. *Ergonomics*, *46*, 629–646. https://doi.org/10.1080/0014013031000090116

van der El, K., Padmos, S., Pool, D. M., van Paassen, M. M., & Mulder, M. (2018). Effects of preview time in manual tracking tasks. *IEEE Transactions on Human-Machine Systems*, *48*, 486–495. https://doi.org/10.1080/0014013031000090116

van der El, K., Pool, D. M., van Paassen, M. R. M., & Mulder, M. (2020). A unifying theory of driver perception and steering control on straight and winding roads. *IEEE Transactions on Human-Machine Systems*, *50*, 165–175. https://doi.org/10.1109/THMS.2019.2947551

Wachtel, P. L. (1967). Conceptions of broad and narrow attention. *Psychological Bulletin*, *68*(6), 417–429. https://doi.org/10.1037/h0025186

Wierwille, W.W., Gagné, G.A., & Knight, J.R. (1967). An experimental study of human operator models and closed-loop analysis methods for high-speed automobile driving. *IEEE Transactions on Human Factors in Electronics*, *8*, 187–201. https://doi.org/10.1109/THFE.1967.233968

Wilhelm, O., Hildebrandt, A., & Oberauer, K. (2013). What is working memory capacity, and how can we measure it? *Frontiers in Psychology*, *4*, 433. https://doi.org/10.3389/fpsyg.2013.00433

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