THE EFFECT OF A SECONDARY TASK’S LOCATION ON LANE POSITION

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Abstract

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While driving the use of a driver’s cognitive and visual perception of heading combine to affect how drivers adjust their heading in relation to the road. The current experiments examined how using a secondary task to orient the cognitive and visual attention of drivers towards locations to the left of, in front of, or to the right of the driver affected their ability to keep a car in the middle of their lane on straight and curved sections of roads. Experiment 1 used a two lane road in a virtual environment that was relatively visually impoverished, and Experiment 2 added objects to the side of the road to increase the amount of optic flow present in the environment. Across both experiments, the average lane position of drivers was biased away from the location of the secondary task on straight and curved sections of roads, and the additional objects in Experiment 2 magnified this effect. These results replicated findings in the literature showing that moving the attention of drivers impairs their ability to maintain a car in desired position and that features along the side of the road have the potential to influence the errors that occur. These results suggest that drivers may try to compensate for the fact that their attention is distracted by steering away from where their attention is focused.
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THE EFFECT OF SECONDARY TASK’S LOCATION ON LANE POSITION

In addition to being aware of their surroundings (e.g. the flow of traffic and stoplights), drivers also need to have the correct perception of heading relative to the path of the road and to be able to correct their heading to match the path as needed. Warren, Kay, Zosh, & Sahuc (2001) propose two components of heading: a cognitive perception of heading based on where drivers think they are heading relative to their desired path, and a visual perception of heading that corresponds to how the visual information related to a driver’s movement is perceived. Ideally, drivers have an accurate cognitive and visual perception of heading relative to a goal which requires few adjustments and produces a heading that is close to the center of the goal path.

However, in scenarios where attention is oriented away from the goal path, drivers may erroneously perceive heading, resulting in incorrect adjustments. Based on the model proposed by Warren et al. (2001), two predictions arise when a driver’s attention is drawn away from the road in front of the driver. If a driver is relying on their visual perception of heading and not cognitively monitoring their heading, they would turn towards where their attention is focused. In contrast, if they are relying on their cognitive perception of heading, then they may think that they are heading towards where their attention is focused, and consequently turn away from it. The current experiments assessed the impact of the type of road and type of environment on these types of
deviations, using the Warren et al. (2001) model to predict the relative impact of the cognitive and visual components.

1.1 How Do We Perceive and Adjust Heading?

More formally, Warren, et al. (2001) proposed that the adjustment of heading \((d\phi/dt)\) is influenced by a constant \((k)\), the perceived location of the goal in relation to current heading from an egocentric reference frame \((\beta)\), retinal flow \((w)\), speed \((v)\), and the difference in visual angle of the focus of expansion and the goal \((\alpha)\); the location where motion appears to originate from, relative to where the goal of locomotion is). The, model can be expressed as:

\[
(1): \frac{d\phi}{dt} = -k(\beta +(w \alpha))
\]

The cognitive perception of heading is represented by the egocentric perception of heading in relation to the goal \((\beta)\), and the visual perception of heading is related to the motion \((w \alpha)\). Several predictions about the relative importance of the cognitive and visual components can be derived from this model across different settings, based on the values of \(\beta\), \(\alpha\), \(w\), and \(v\). For example, if visual attention is in the direction of the goal location then turning rate will be fairly low because \(\alpha\) is low, resulting in smaller deviations to either side of the road. As visual attention is drawn away from the goal location the turning rate would increase, and one would observe deviations away from the center of the lane. In situations with less visual information \((\alpha\), \(w\), or \(v\)), heading is influenced more heavily by \(\beta\). If drivers perceive their heading to be in the direction of the goal, then turning rate will be fairly low. However, when drivers perceive their
heading to be misaligned with the goal location, they should increase turning rate away from where they perceive their heading to be.

Evidence that supports this model comes from studies that have examined natural eye-gaze behavior while driving. Across multiple studies researchers have found that drivers look at specific areas of the road (Kandil, Rotter, & Lappe, 2009; Land & Lee, 1994; Lappi, 2013). On straight sections of roads, the eye-gaze of drivers tends to be oriented towards the center of the lane on a point that is about 2 seconds ahead of the car. This behavior matches the model discussed above, because while drivers are looking at a point along a straight stretch of road in front of them there would be no difference in the visual angle of the focus of expansion and the goal (α), resulting in a decreased turning rate and matching the straight path of the road. Eye-gaze studies that have examined where drivers look while going around curves found that drivers look towards the inside edge of the road (Kandil, Rotter, & Lappe, 2009; Land & Lee, 1994; Lappi, 2013). In the model studied by Warren et al. (2001) this eye-gaze pattern would result in an increased turning rate in the direction of where eye-gaze is oriented. This is because shifting eye-gaze left or right changes the retinal flow portion of the model (w), the visual angle of the focus of expansion of the goal (α), and because drivers perceive their egocentric heading (β) to be misaligned with the goal location while going around a curve.

1.2 What Affects Lane Position?

Based on the model discussed above, drawing a driver’s cognitive or visual attention towards a task not related to driving could result in erroneous heading adjustments. This is because these extraneous tasks may cause drivers to lose track of
their cognitive perception of heading or may result in drivers visually misperceiving their heading. An example of a situation that may cause simultaneous errors in both cognitive and visual perception of heading is using a windshield mounted GPS unit. Checking to see the current instructions requires drivers to think about how to accomplish the instruction and draws their eye-gaze towards where the GPS is mounted. Moving cognitive and visual attention towards the GPS could affect the values of $\alpha$, $w$, and $\beta$ resulting in inaccurate heading adjustments.

1.2.1 Cognitive Manipulations

One approach to examine the influence of the cognitive component of heading employs the dual-task paradigm (Horrey, Lesch, & Garabet, 2009; Hurwitz & Wheatley, 2002; Strayer & Johnston, 2001). Most research using this paradigm has shown that performing two tasks simultaneously interferes with the ability to perform either task as accurately or efficiently as performing each task separately (Pashler, 1994; Wickens, 2002). This decrease in performance is typically explained using theories that focus on the idea that there is a limited amount of processing capacity that can be allocated to complete all available tasks. As more tasks are added, the workload increases and the processing capacity is spread more thinly across all tasks (Pashler, 1994; Wickens, 2002). This interference when performing multiple tasks simultaneously has been shown when completing tasks involving working memory including driving (Baddeley & Hitch, 1974; Gardony, Brunyé, & Taylor, 2015; Pashler, 1994; Strayer & Johnston, 2001). When performing a secondary task in addition to driving, drivers must move cognitive processing power that would normally be devoted to keeping track of the flow of traffic, traffic signals, or perception of heading into the secondary task. This decreases the
driver’s ability to perform tasks involved with driving as accurately, such as maintaining heading.

The dual-task paradigm has been used to extensively show the effects of conversation on driving performance. These experiments typically involve having drivers talk on a cellphone (Drews, Pasupathi, & Strayer, 2008; Strayer, Drews, & Crouch, 2006) or having drivers talk to a passenger who is co-present (Drews, et al., 2008), while driving a car in a virtual environment. Across these studies researchers found that drivers who are engaged in conversation on a cell phone tend to have a higher variability in lane position (Drews, et al., 2008), are less successful at navigational tasks (Drews, et al., 2008), have slower braking reaction times (Strayer, et al., 2006), and have higher variability in following distance (Strayer, et al., 2006) when compared to drivers who have conversations with a passenger or drive without having a conversation.

Secondary tasks have also been used to examine how the amount of cognitive demand needed to perform the secondary task affected a driver’s ability to monitor their performance. Horrey et al., (2009) had participants drive on a closed track while they performed tasks normally associated with driving, such as responding to traffic signals, maintaining a specific pace, and keeping their car in the center of their lane. Participants completed five blocks of tasks. Two blocks were completed outside of the car and the remaining three blocks were completed while driving the car. The two out of vehicle blocks involved completing a Paced Auditory Serial Addition Task (PASAT), considered to be a low cognitive demand task, and the Twenty Questions Test (TQT), considered to be a high cognitive demand task. For the three driving blocks, participants drove with no secondary task, while performing the PASAT, or while performing the TQT. At the end
of the five blocks participants filled out a questionnaire that asked about their perception of their driving performance and the demand of the secondary tasks they completed.

The results showed that performing either of the secondary tasks while driving caused drivers to have slower reaction times, more variability in lane position, and decreased their ability to regulate pace. The results also showed that in the condition with the high cognitive demand secondary task drivers had slower reaction times, more lane position variability, and more trouble regulating pace than in the low cognitive demand condition. These results indicate an overall effect of dual-tasks on driving performance. Another important finding was that when performing the high cognitive demand task while driving, participants tended to rate their driving performance more positively than when they performed the high cognitive demand task. However, the participants had the worst performance during the high cognitive demand block (Horrey, et al., 2009). This finding is important because it suggests that driving performance may decrease with the addition of secondary tasks partially because drivers are not able to monitor their performance accurately.

These dual-task studies involving driving show that secondary tasks have an effect on a driver’s ability to maintain a position in the center of a lane, though they generally focus on lane variability rather than lane position. The current experiments used the measure of lane position to examine whether performing a secondary task results in a systematic bias in heading that is related to the physical location of the secondary task.

1.2.2 Visual Manipulations

Previous research has approached manipulating the visual information that drivers use while driving in several ways. Two of these approaches have focused on removing
visual information that is available to drivers, which changes how reliant drivers are on their visual perception of heading, or manipulating where visual attention is focused, which is designed to manipulate how drivers visually perceive their heading. In an experiment by Frissen and Mars (2014) drivers navigated along curved stretches of road while portions of their visual field were masked with static at varying opacities, resulting in drivers only being able to use environmental visual cues that were either close (top half of the visual field masked) or far (bottom half of the visual field masked) from their current location. The researchers found that when the top half of the drivers’ visual fields were masked they deviated towards the inside edge of the curve. This deviation was significantly different from conditions in which there was no mask present. In contrast, masking the bottom half of the driver’s visual field did not have any effect on their lane position (Frissen & Mars, 2014). This result is interesting because the visual degradation of the top half of the drivers’ visual field hinders how effectively drivers can relate their current heading to the goal location that they are navigating towards, decreasing the ability to use their cognitive perception of heading ($\beta$) from the model proposed by Warren et al. (2001). Degrading the visual information from the bottom portion of the screen does not cause the same result because drivers can see the goal relative to their position, allowing them to use their cognitive perception of heading.

Alternatively, dual-task studies have been used to examine the effect that manipulating the focus of visual attention has on driving performance (Hurwitz & Wheatley, 2002; Readinger, Chatziastros, Cunningham, Bülthoff, & Cutting, 2002; Yager, Cooper, & Chrysler, 2012). Secondary tasks requiring the visual attention of the driver have the potential to affect perceived heading by changing the focus of expansion
in relation to the goal (α). Hurwitz and Wheatley (2002) examined this by having drivers complete a letter-monitoring task that involved pressing a button on the steering-wheel when they heard (non-visual) or saw (visual) a letter “P” while driving in a virtual world. The letter-monitoring task was presented using speakers (non-visual) or using a dialog box on the simulator screen (visual) at certain points along the track. When a secondary task was present the change in the angle of the steering wheel was greater and drivers had more variability in lane position as compared to conditions with no secondary task. This indicates poorer driving performance in the presence of a secondary task in general. Additionally, trials with the visual secondary task had larger changes in steering wheel angle and higher variability in lane position as compared to trials with the auditory secondary task (Hurwitz & Wheatley, 2002). These results demonstrate that a secondary task that requires visual and cognitive attention can affect the precision of heading perception and may be more detrimental to driving performance than a secondary task that requires non-visual and cognitive attention. This supports the idea that the effect of a visual secondary task is not just related to the cognitive demand of the task but also has an impact on the visual perception of heading.

To examine how the placement of a visual secondary task affects the perception of heading Readinger et al. (2002) had participants attend and respond to a visual secondary task placed in various locations in the visual field while they drove down a straight section of road in a virtual environment. During each trial the stimuli were located at different visual angles along a horizontal axis ranging from 45° to the left of the driver to 45° right to the right of the driver. As participants drove along the road, the distance that the car deviated from the center of the road was measured. Experiments 1, 3,
4, 5, and 6 found that when a visual secondary task was located to the left or right side, drivers tended to steer toward the stimuli as long as the speed of the car was greater than 10 m/s (v in Warren et al.’s (2001) equation). The results from these experiments demonstrate how moving the eye-gaze of drivers to the left or right of the goal of the path resulted in drivers deviating in the direction of their eye gaze. In contrast, in their Experiment 2, drivers turned away from the direction of their eye gaze. In this experiment, there was no forward translation of the car along the road, removing visual cues about heading. Within the model proposed by Warren et al. (2001) this manipulation would reduce $\alpha$ (focus of expansion) and $v$ (velocity) to zero, making the visual perception of heading ($wv\alpha$) less informative, and resulting in drivers relying on their cognitive perception of heading ($\beta$).

1.3 Current Experiments

The current experiments examined how orienting the cognitive and visual attention of drivers to specific locations affects the perception of heading on straight and curved roads and how the visual information available in the environment affects the perception of heading, using a paradigm similar to Readinger et al.’s (2002). Two experiments were performed in virtual environments that featured straight and curved sections of two lane roads. The effects of manipulating eye-gaze on curved sections of road was not studied by Readinger et al. (2002) and is an important addition because the natural eye-gaze patterns of drivers differ on straight and curved sections of roads. Specifically, drivers focus at a point directly in front of the car on straight sections of road, whereas eye-gaze is focused on locations toward the inside edge of the road when
going around curves. Therefore, manipulating the visual attention of drivers on these sections of road may lead to differences in how well they adjust and maintain their heading (Kandil et al., 2009; Land & Lee, 1994; Lappi, 2013). The path structure of curved sections of road also means that drivers have to adjust their heading in a moment to moment fashion in order to match the path of the road, whereas on straight sections of road drivers do not need to adjust their heading as frequently in order to match the path of the road. In other words, drivers do not need to monitor their heading in relation to the path of straight sections of the road as closely as they do for curved sections of road.

Because of these differences in where the visual attention of drivers is focused, different patterns of bias could be observed based on the model proposed by Warren et al. (2001) for the different types of roads.

We predict that on straight sections of road the location of the secondary task in the driver’s visual field changes the visual information about heading (α) resulting in heading adjustments that are in the direction of the secondary task. On curved sections of road, a similar effect of secondary task location could occur. For conditions with the secondary task towards the inside edge of the curve drivers would maintain a position close to the center of the lane. This is because shifting eye-gaze to this location would increase the turning rate in the direction of the curve and is where drivers normally look while navigating curves (Kandil et al., 2009; Land & Lee, 1994; Lappi, 2013). When the secondary task is toward the outside edge of the curve, drivers should maintain a lane position closer to the outside edge of the lane because this should decrease the turning rate of drivers because it changes the angle of focus of expansion relative to the goal (α). In Experiment 2, we manipulated the influence of the visual perception of heading by
adding objects to the side of the road; this change increased the amount of optic flow (w) available for the perception of heading. According to the model studied by Warren et al. (2001) this change should impact the visual perception of heading and change the effect of the of secondary task location on lane position.

1.4 Experiment 1

Experiment 1 used Readinger et al.’s (2002) paradigm to test the effect of secondary task location on lane position for straight and curved sections of road. During each trial participants were told to drive the car down the center of the road while their visual attention was focused on a stimulus to their left, in front of them, or to their right. For straight sections of road, when visual attention is focused on a secondary task in front of a driver, there should be no bias to adjust heading toward either side of the center of the lane; in contrast, when attention is drawn towards the left or right side of the driver, the change in the value of $\alpha$ should result in lateral deviations that are biased in the direction of the secondary task, consistent with findings from several experiments by Readinger et al. (2002).

For curved sections of road on which drivers must turn the steering wheel of their vehicle to match the curve, turning rate should increase if visual attention is along the future path of the curve and decrease if visual attention is away from the future path of the curve. This should result in drivers having an average lane position close to the center of the lane when the secondary task is in front of the driver or toward the inside edge of the curve, and an average lane position close to the outside edge of the curve when the secondary task is in front of the car or along the outside edge of the curve.
1.4.1 Methods

1.4.1.1 Equipment

All subjects performed this experiment while wearing an Oculus Rift Development Kit Two (HMD) that displayed a virtual environment created for this experiment. The equipment set-up is shown in Figure 1. The HMD had a refresh rate of 75 Hz and took up 100° of the participants’ visual field. To control the car, participants used a Logitech Driving Force™ GT force-feedback steering wheel. The forced-feedback was disabled in all experiments because it had the potential to bias the direction of steering. Four buttons on the right spoke of the steering wheel were used for the secondary task, as described below. The location of these buttons is shown in the white square in the inset in the upper right corner of Figure 1. These buttons were selected because their location did not require participants to move their hand from the wheel while responding to the secondary task.

1.4.1.2 Stimuli

1.4.1.2.1 Environments

The environments for this experiment were four different sequences of straight and curved sections of road built using Google Sketchup™ and simulated in Vizard 5.0™. In the simulation distances map 1:1 (1 m in the Sketchup build = 1 m in the Vizard simulation). The environment featured a two lane road based on the Department of Transportation’s design standards (Stein & Neuman, 2007; American Association of State Highway and Transportation Officials, 1994). On this road, each lane was 2.85 m
wide and was separated by two parallel yellow lines that were 0.1 m wide with 0.1 m between them. The edge of the road was marked with a white line on each side. This line was 0.1 m thick; bordering this white line there was a 0.5 m shoulder that had the same texture as the road followed by ground textured to look like grass. These dimensions resulted in a road with a total width of 7.2 m.

For the practice trials in this experiment each road had three 120m long straights, one curved to the left, and one curved to the right. These curves had a minor arc of 46° and a radius of 122.49 m. For the experimental trials, each road had thirteen 120 m long straight sections and twelve curved sections (6 sections curved to the right and 6 curved to the left). Two degrees of curves were used in order to decrease the predictability of the road. Half of the curves in each direction had a minor arc of 46° with a radius of 122.49 m. The remaining curves had a minor arc of 68.6° with a radius of 78.37 m. The straight and curved sections were combined to create four roads by alternating straight sections and curved sections. A birds-eye view of these environments can be seen in Figure 2. The order of the curved sections was selected randomly and each road was used once per condition. The participants’ view of this environment can be seen in Figure 3.

1.4.1.2.2 Driving Task

Using a design similar to Readinger et al. (2002), participants were asked to drive the car down the center of the right lane of a two lane road while responding to a secondary task that manipulated visual attention (described below). Each trial lasted approximately 210 s, with a range of (200 s to 214 s). This variability occurred based on the participants driving performance, because the more participants weaved on the road
the farther they had to travel in order to reach the end of the road. For the first 10 s of each trial the car accelerated to 19 m/s; it maintained this speed for the duration of the trial.

1.4.1.2.3 Secondary Task

A secondary task was used to manipulate the cognitive and visual attention of participants while driving. Specifically, during each trial a rotating letter “C”, also known as a Landolt-C, appeared directly in front of the driver, 12° to their left, or 12° to their right (Readinger, et al., 2002). Throughout each trial the Landolt-C rotated in random 90° intervals about the roll axis every second. Participants were instructed to press a button on the steering wheel to indicate the orientation of the opening of the Landolt-C. For example, if the Landolt-C was oriented with the gap pointing left ( Crud), the participant would press the left button.

1.4.1.3 Participants

Thirty-five undergraduate students from the University of Notre Dame participated in the experiment (22 females, 12 males). All participants had a driver’s license at the time of the experiment. Additionally, all participants had normal vision or used contacts to achieve corrected-to-normal vision. Of the 35 participants the data from 6 were excluded from analyses (4 females and 1 male participant ended participation before completing all trials due to motion sickness associated with using the HMD and 1 participant experienced technical difficulties).
Figure 1. The virtual reality system used in all of the experiments. Participants wore the head mounted display for immersion into the virtual environment and drove the car using the steering wheel that was in front of them. In order to complete the secondary task, participants pressed the buttons on the steering wheel are shown in the white box in the upper right hand inset.
Figure 2. A birds-eye view of the environments from Experiments 1 and 2. All four of these environments were used in Experiment 1 and environments A-C were used in Experiment 2.
Figure 3. The participant’s perspective of the environment and secondary task in Experiment 1. For straight sections, the secondary task was located 12° to the left, in front of, or 12° to the right of the car. On curved sections of road, the secondary task was located: along the inside edge of the curve, straight in front of the car, or beyond the outside edge of the curve. The size of the secondary task is compressed in this photo due to translation between the Oculus Display and Monitor display that the image was taken on.
1.4.1.4 Procedure

1.4.1.4.1 Instructions.

Participants were seated in front of the steering wheel and were instructed to put the HMD on and adjust it to fit securely on their head. Before performing any trials, the participants were instructed to keep the center of the car in the center of the right lane throughout each trial, while responding to the secondary task as quickly and accurately as possible.

1.4.1.4.2 Practice Trials

Participants became familiar with how the car handled and how to respond to the orientation detection task in six practice trials. During the first two practice trials participants were told to practice driving and were given a chance to look around the practice environment. During the third practice trial participants were instructed to practice keeping the center of the car in the center of the right lane, without the orientation detection task present. For the last three practice trials participants were instructed to drive the car down the center of the right lane, while responding to the orientation detection task as quickly and accurately as possible.

1.4.1.4.3 Experimental Trials

Participants performed 12 experimental trials that lasted approximately 200 s each. On straight sections of road, the secondary task appeared equally often at location in front of the car, 12° to the left of the driver, or 12° to the right of the driver. On curved sections of road, the secondary task appeared equally often at locations along the inside.
edge of the curve of trials (12° towards the inside edge of the lane), in front of the car, and beyond the outside edge of the curve (12° towards the outside edge of the lane). Originally a placement of 20° to either side of the driver was planned, however, due to limitations in the HMD’s display this had to be decreased to a smaller angle. This smaller angle was still larger than the minimum angle that had yielded significant results in experiments by Readinger et al. (2002).

1.4.1.5 Measures

The simulation software tracked the position of the car on the road at a rate of 100 Hz. On straight sections of road, the initial 20 m was not included in data analysis because this data may have been influenced by performance along the preceding curved section of road. The software gave a readout of (x, y) coordinates based on the location of the driver in the environment. These coordinates were used to calculate the drivers’ distance away from the center of the lane. For straight sections of road, lane position was calculated, with zero indicating the center of the right lane, positive values indicating locations to the right of the center of the right lane, and negative values indicating location to the left of the center of the right lane. On curved sections of road, zero indicated the center of the right lane, positive values indicated positions toward the outside edge of the right lane, and negative values indicated positions towards the inside edge of the lane. Using the recorded position of the car, an average deviation away from the center of the right lane was calculated. Deviations were calculated separately for when participants correctly responded to the secondary task, indicating a successful manipulation of their attention toward the secondary task. On average participants
responded to 79.9% trials correctly in Experiment 1 and 80.8% in Experiment 2. When participants did not respond or incorrectly responded to the secondary task the lane position at those time points were excluded from analyses, because their attention may not have been allocated to the secondary task. This is an improvement in methodology over Readinger et al. (2002) who did not examine deviations as a function of accuracy in the secondary task.

1.4.2 Experiment 1 Results and Discussion

The analyses of results for straight and curved sections are presented separately because the location of the secondary task differed in relation to the structure of the road and the directions of deviation were defined differently.

1.4.2.1 Straight Sections

In order to assess whether the location of the secondary task affected lane position a one-way ANOVA was performed to compare the average deviation away from the center of the lane. There was a main effect of stimulus location, $F(2,56) = 18.227, p < .001$. When the secondary task was on the left side of the driver, deviations were farther toward the right side of the lane ($M = 16.1$ cm, $SD = 43.2$ cm) when compared to conditions with the secondary task in front of the driver ($M = -0.2$ cm, $SD = 29.3$ cm) on the right side of the driver ($M = -32.5$ cm, $SD = 24.7$ cm), $ps \leq .004$, $ds \geq 0.44$. There is also a significant difference between conditions with the secondary task in front of the car and conditions with the secondary task to the right of the driver, $p = .002$, $d = 1.19$. These differences were analyzed using paired comparisons with a Bonferroni correction. The differences between these conditions can be seen in Figure 4. The lane position when the
secondary task was to the right of the driver was significantly different from zero
\( (t(28) = -7.073, p < .001) \) meaning the average lane position was significantly biased
toward the left side of the lane, and when the secondary task was to the left of the driver
the average lane position was marginally different when compared to zero \( (t(28) = 2.000, p = .055) \) meaning that the average lane position was biased toward the right side of the
lane.

The results from this experiment indicated that drivers adjusted their heading
away from where their attention is focused rather than towards where attention was
focused. Even though these results do not match the predicted results, they match the
results from Readinger et al.’s (2002) Experiment 2, which removed optic flow where
drivers performed the same task on straight sections of road. This suggests that one
explanation for the results of Experiment 1 was that, because the environments didn’t
contain cues about, the influence of visual perception of heading (vwα) was minimal, and
that drivers’ reliance on the cognitive perception of heading led to drivers turning away
from where their attention was focused.
Figure 4. The average deviation away from the center of the lane for straight sections of road in Experiment 1. The green line in the center of the lane represents the center of the lane while the red line represents the average deviation away from the center of the lane and the standard error. Conditions with significant deviations away from the center of the lane are marked with “S.”, non-significant deviations are marked with “N.S.”, and marginally significant deviations are marked with an “M.S.”.
1.4.2.2 Curved Sections

A 3 (secondary task location: inside edge of curve, center of curve, outside edge of curve) X 2 (curve direction: left, right) repeated measures ANOVA was conducted on the deviations in lane position as measured from the center of the right lane. There was a main effect was of secondary task location ($F(2,56) = 27.034, p < .001$) and curve direction ($F(1,28) = 26.554, p < .001$). There was no interaction between the two factors, $F(2,56) = 2.188, p > .05$. The average deviation away from the center of the lane for all conditions can be seen in Figure 5. A Pairwise comparison was used to examine the effect of secondary task location found, significant differences among all three conditions, $ps \leq .001, ds > 0.63$. Finally, the average lane position was biased significantly toward the inside edge of the curve for all secondary task locations except for right turns with the secondary task towards the inside edge of the curve, $ps < .001$.

On curved sections of road drivers maintained a lane position that was biased based on the location of the secondary task. Drivers maintained a position that was close to the center of the lane when the secondary task was toward the inside edge of the road and as the task moved toward the outside edge of the road the average deviation away from the center of the lane became more biased towards the inside edge of the lane. These results were unexpected based on the model proposed by Warren et al. (2001), where moving the attention of the driver away from the inside edge of the road should decrease the turning rate of drivers, resulting in deviations in lane position towards the outside edge of the road for conditions with the secondary task in front of the driver and towards the outside edge of the road.
Overall the results from the straight and curved sections of road in this experiment show that the location of a secondary task had an effect on the lane position of drivers. However, for both straight and curved sections of road the results do not match those predicted based on the findings by Readinger et al. (2002) and Warren et al. (2001). One potential explanation for this is that because the object in the environment were sparse, there may have not been enough visual information to provide a strong sense of optic flow, resulting in drivers not being able to use their visual perception of heading to adjust their position on the road. Evidence in support of this idea comes from Readinger et al.’s (2002) Experiment 2, where a similar pattern of deviations away from the secondary tasks on straight sections of road occurred with low optic flow present.
Figure 5. The average deviation away from the center of the lane for curved sections of road in Experiment 1. The green line in the center of the lane represents the center of the lane while the red line represents the average deviation away from the center of the lane and the standard error. Conditions with significant deviations away from the center of the lane are marked with “S.” non-significant deviations are marked.
1.5 Experiment 2

This experiment investigated whether adding visual information to the environment affected how drivers adjusted heading. One explanation for the pattern of results in Experiment 1 was that because there was little visual information available in the environment there was a low amount of optic flow, leading to drivers weighing their cognitive perception of heading more heavily (Warren et al., 2001). Experiment 2 tested this by increasing the amount of optic flow available from the environment, which should increase the reliance on visual perception. The increased reliance on visual perception should lead to a greater influence of the manipulation of visual attention, leading to drivers turning in the direction of where their visual attention is focused on straight and curved sections of road and result in greater deviations away from the center of the lane on curved sections of road in Experiment 2.

1.5.1 Method

1.5.1.1 Equipment

The equipment in Experiment 2 was identical to the equipment in Experiment 1.

1.5.1.2 Stimuli

1.5.1.2.1 Environments

Three of the four environments used in Experiment 1 were used in Experiment 2 to reduce the number of trials per participant in hopes of reducing the number of drivers who dropped out due to motion sickness or eye strain. These three environments used the
same sequence of straights and curves as they did in Experiment 1. However, trees were added to both sides of the road in order to increase the amount of optic flow. These trees were 6.89 m tall and 5.77 m wide and were positioned 1m away from the edges of the road in parallel pairs along the straight and curved sections of the road, as shown in Figure 6A. On straight sections of road, the trees were placed on each side of the road 30 m apart, resulting in 4 pairs of trees along each straight section of road (as shown in Figure 6B). On curved sections of road five pairs of trees were placed in parallel and an equal distance from each other (Figure 6C).

1.5.1.3 Participants

Thirty-five undergraduate students from the University of Notre Dame participated in the experiment. All participants had a driver’s license at the time of the experiment and normal vision or used contacts to achieve corrected-to-normal vision. Data from 8 participants was excluded from analyses due to stopping before the end of the experiment due to motion sickness, resulting in a total of 27 participants.

1.5.1.4 Procedure

The procedure from Experiment 1 was used for the instructions and practice trials. One change was made to the procedure for the experimental trials; participants completed nine trials instead of twelve.

1.5.1.5 Measures

As in Experiment 1, the key dependent variable was the measure of lane deviation relative to the center of the right lane.
Figure 6. The placement of trees along the a section of road from Experiment 2. Panel A provides a birds eye view of two curved and two straight sections of road. Panel B provides an elevated close up of a straight section of road leading into a curved section of road. Panel C provides a elevated close up view of a curved section of road.
1.6 Experiment 2 Results and Discussion

1.6.1 Straight Sections

In order to assess whether the location of the secondary task affected lane position a one-way ANOVA was performed to compare the average deviation away from the center of the lane. There was a main effect of secondary task location, $F(2, 54) = 49.125$, $p < .001$. These results can be seen in Figure 7. Pairwise comparisons with a Bonferroni correction indicated a significant difference between conditions with the secondary task on the left side of the driver ($M = 0.004$ cm, $SD = 16.1$ cm) when compared to conditions with the secondary task was in front of the driver ($M = -15.6$, $SD = 23.4$) and when compared to conditions with the secondary task on the right side of the driver ($M = -48.1$ cm, $SD = 27.5$ cm), $ps < .001$, $ds \geq 0.78$. There is also a significant difference between conditions with the secondary task in front of the car and conditions with the secondary task to the right of the driver, $p < .001$, $d = 1.27$. These differences can be seen in figure 7. When the secondary task was in front of or to the right of the driver, deviations were significantly different from zero, $t(27) \geq 3.514$, $ps \leq .002$.

The pattern of lane bias was similar to Experiment 1, with a bias away from the secondary task rather than toward it. If the results from Experiment 1 were caused by low optic flow, then the addition of objects to the environment should have reversed the deviation pattern toward where attention was located. This suggests that optic flow was not the explanation for the differences in the results from the current Experiment 1 and the experiments performed by Readinger et al. (2002).

An additional 3 (secondary task location: inside edge of curve, center of curve, outside edge of curve) X 2(experiment) ANOVA was used to examine the effects of
adding visual information to the environment. There was a main effect of secondary task location, $F(2,110) = 52.510$, $p < .001$, with drivers maintaining a lane position that was biased away from the secondary task location. There was also a significant difference in lane position between Experiments 1 and 2, $F(1,55) = 8.293$, $p = .006$, such that participants in Experiment 1 maintained a position to the right side lane ($M = -6.2$ cm, $SD = 32.4$ cm) whereas participants in Experiment 2 maintained a position farther to the left side of the lane ($M = -21.1$ cm, $SD = 22.34$ cm). There was no interaction between stimulus location and experiment, $F(2,110) = 0.035$, $p > .05$. This is interesting because it demonstrates that on straight sections of road increasing optic flow by adding objects to the environment had an effect on overall lane position but not on the size of the effect, supporting the idea that low optic flow does not explain the results in Experiment 1.

1.6.2 Curved Sections

A 3 (secondary task location: inside edge of curve, center of curve, outside edge of curve) X 2 (curve direction: left, right) repeated measures ANOVA was used to examine the bias in lane position for curved sections of road. There was a main effect of secondary task location, $F(2,46) = 31.335$, $p < .001$. Pairwise comparisons with a Bonferroni correction showed difference between all stimulus location conditions ($ps < .019$, $ds > 0.27$). The largest difference occurred between the condition with the secondary task towards the inside edge of the road ($M = -20.9$ cm, $SD = 25.767$ cm) and the condition with the secondary task towards the outside edge of the road ($M = -52.2$ cm, $SD = 26.973$ cm), these differences can be seen in Figure 8. The average lane position was biased significantly toward the inside edge of the curve for all secondary task
locations except for right turns with the secondary task towards the inside edge of the curve ($p < .003$).

There was also a main effect of curve direction, $F(1,23) = 57.551$, $p < .001$. On sections of road that curved to the left drivers had an average lane position that was $-68.9$ cm ($SD = 24.7$ cm) towards the inside edge of the road, and an average lane position $-10.0$ cm ($SD = 30.0$ cm) towards the inside edge of the road when the curve was to the right. This can be seen in Figure 8. Additionally, there was an interaction between curve direction and secondary task location, $F(2,46) = 17.021$, $p < .001$. This indicates that the location of the secondary task had a stronger effect on sections of road that curved to the left than to the right.

These results for the curved sections of road replicated the pattern observed in Experiment 1. There was no difference in lane position between Experiments 1 and 2, $F(1,51) = 0.098$, $p = .755$. There were also interactions between curve direction and experiment, $F(1,51) = 9.160$, $p = .004$, and curve direction, secondary task location, and experiment, $F(2,102) = 5.460$, $p = .006$. These interactions suggest that the addition of objects to the side of the road had a stronger effect on lane position for left curves when compared to right curves. This pattern can be seen in by comparing Figures 5 and 8.
Figure 7. The average deviation away from the center of the lane for straight sections of road in Experiment 2. The green line in the center of the lane represents the center of the lane while the red line represents the average deviation away from the center of the lane and the standard error. Conditions with significant deviations away from the center of the lane are marked with “S.” and non-significant deviations are marked with “N.S.”.
<table>
<thead>
<tr>
<th></th>
<th>Inside Edge of Curve</th>
<th>In Front of Car</th>
<th>Outside Edge of Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Left Curve</strong></td>
<td><img src="image1" alt="Image" /></td>
<td><img src="image2" alt="Image" /></td>
<td>68.9 cm towards the inside edge of the curve</td>
</tr>
<tr>
<td></td>
<td><img src="image3" alt="Image" /></td>
<td><img src="image4" alt="Image" /></td>
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<tr>
<td><strong>Right Curve</strong></td>
<td><img src="image5" alt="Image" /></td>
<td><img src="image6" alt="Image" /></td>
<td>10.0 cm towards the inside edge of the curve</td>
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<td><img src="image7" alt="Image" /></td>
<td><img src="image8" alt="Image" /></td>
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<tr>
<td></td>
<td><strong>20.9 cm toward the inside edge of the curve</strong></td>
<td><strong>49.9 cm toward the inside edge of the curve</strong></td>
<td><strong>52.7 cm toward the inside edge of the curve</strong></td>
</tr>
</tbody>
</table>

*Figure 8.* The average deviation away from the center of the lane for curved sections of road in Experiment 2. The green line in the center of the lane represents the center of the lane while the red line represents the average deviation away from the center of the lane and the standard error. Conditions with significant deviations away from the center of the lane are marked with “S.” non-significant deviations are marked with “N.S.”.
1.7 General Discussion

The goal of the current studies was to examine how the model of heading adjustment proposed by Warren et al. (2001) related to driving on straight and curved sections of road. The results from two experiments show that on straight sections of road drivers had a pattern of lane position bias away from where the secondary task was located. While on curved sections of road drivers maintained a lane position closer toward the inside edge of the curve as the visual attention of the drivers oriented away from the inside edge of the lane. Additionally, on both straight and curved sections of road, this bias was affected by the addition of visual information to the environment in Experiment 2, suggesting that visual information in the environment has an impact on how drivers adjust their heading.

The finding that drivers adjust their heading away from where their attention is focused can be explained in relation to Warren et al.’s (2001) model. For curved roads when the secondary task was located at the inside edge of the curve there were smaller deviations toward the inside edge of the road, because this is where drivers typically work well driving manipulating attention toward this location almost no effect on the driver’s ability to accurately maintain lane position, as predicted (Kandil, Rotter, & Lappe, 2009; Land & Lee, 1994; Lappi, 2013). When attention was moved away from the inside edge of the road drivers were not able to keep track of the goal location (path of the road), and were adjusting heading based on where they thought they were in relation to the path of the curve. This is similar to the effect of Frissen and Mars’ (2014) manipulation where they reduced the driver’s ability to see the future path of the road while driving around curves by adding static to the top or bottom half of the screen.
Though we did not replicate Readinger et al.’s (2002) results for straight sections of road in the current experiments one possible explanations for our pattern of results may be that drivers are more aware of distracted driving and experiments about distracted driving now, as compared to when Readinger and colleagues performed their studies in 2001. Evidence that supports this idea can be seen in the panels of Figure 9. Both panels show that both the portion of Google searches that feature the phrase “distracted driving” have increased since 2004 and the frequency of the same phrase appearing in books scanned by Google has increased since 2000. Both of these trends suggest that people are more aware of distracted driving and its potential consequences of distracted driving.

Because of this increased awareness, participants may have thought that their heading would be biased in the direction of the secondary task, and attempted to correct it by adjusting their heading away from where their attention was focused. This caused a bias in lane positions that was away from where attention was focused on straight sections of road, and a bias in lane position closer to the inside edge of curves when attention was focused towards the outside edge of the curve. Additionally, the difference in lane position for straight sections of road and left curves for Experiments 1 and 2 provides some support for this explanation. On these sections of road drivers may have thought of the trees on the side of the road and then tried to avoid these obstacles (Fajen & Warren, 2003), resulting in drivers shifting their lane position farther away from the edge of the road.

To test whether the effects that occurred in both experiments could be a result of drivers thinking about the effect of distracted driving a follow up study could be performed that manipulates the cognitive demand of the secondary task. This
manipulation should further affect the ability of drivers to cognitively monitor their heading (Horrey, et al., 2009) resulting in an increased reliance on visual perception of heading and a decreased ability to devote cognitive processing to keep track of their heading. This may change the pattern of lane position bias so that it would be in the direction of the secondary task for straight and curved sections of road. If this does not occur, it suggests that the effect seen in Experiments 1 and 2 were different from the results of Readinger et al.’s (2002) experiments due to other differences in methodologies (e.g. simulator differences or structure of the car in the environment).

The results from these two studies provide valuable insights into how people drive every day. Over the last ten years cellphone usage has increased (Pickrell & KC, 2015) and more interactive in-vehicle infotainment systems (e.g. video players, Wi-Fi, and touch screen maps) have been featured in cars, both of which can draw a driver’s visual or cognitive attention away from the task of driving. Based on the current studies and previous studies about secondary tasks while driving (e.g. Drews et al., 2008; Horrey, et al., 2009; Readinger et al., 2002; Strayer & Johnson, 2001) there is ample evidence that the inclusion of these features can impair how drivers effectively drivers perform tasks related to driving. One of the effects that consistently occurs when performing a secondary task is that the lane position of drivers becomes more variable (Drews, et al., 2008; Strayer & Johnson, 2001), and the amount of cognitive demand associated with the secondary task can increase this effect (Horrey, et al. 2009). These findings suggest the need for a close analysis of driving behavior and the maintenance of heading when new features are added to cars, with a particular focus on the visual and cognitive demands of these features. Additionally, because drivers seem to be aware of the fact that they are
distracted but are still unable to adequately correct their performance; these results support the development and implementation of Driver Monitoring Systems that can alert drivers when their visual attention is drawn away from the road and guide it back to where they normally look while driving.
Figure 9. Panel A shows the relative frequency of google searches for “distracted driving” relative to other searches from the year 2004 to 2015. Higher numbers on the y-axis signify more a higher number of Google searches in relation to the total number of Google searches performed that year. Panel B is a graph of the percentage of phrase “distracted driving” used in the Google English 2-gram corpus from the Google Books Ngram Viewer utility between the years of 2000 and 2008.
REFERENCES


