

## Gaze-Eccentricity Effects on Road Position and Steering

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The effects of gaze eccentricity on the steering of an automobile were studied. Drivers performed an attention task while attempting to drive down the middle of a straight road in a simulation. Steering was biased in the direction of fixation, and deviation from the center of the road was proportional to the gaze direction until saturation at approximately 15° gaze-angle from straight ahead. This effect remains when the position of the head was controlled and a reverse-steering task was used. Furthermore, the effect was not dependent on speed but reversed when the forward movement of the driver was removed from the simulation. Thus, small deviations in a driver's gaze can lead to significant impairments of the ability to drive a straight course.

Human beings who are active in the environment need to know where they are headed, accurately judge their progress toward a goal, and adapt to unexpected changes in the environment to reach that goal. When one considers tasks of applied navigation such as driving, however, one may be struck by the remarkable automaticity with which such behaviors are performed. Because of the confidence many people have in their ability to navigate effectively, other tasks are undertaken simultaneously. As a result, the issue of steering has recently become a topic of interest as the use of in-vehicle navigation systems and cellular telephones while driving is being reevaluated in light of safety issues involving these devices (e.g., National Highway Traffic Safety Administration, 1997). Of primary concern is the allocation of both attentional and perceptual resources involved in additional tasks, and how they may interfere with safe driving (e.g., Strayer & Johnston, 2001). Furthermore, drivers are often required to direct their attention to instruments inside the car or to objects outside of the vehicle while maintaining a consistently safe road position. What are the attentional and perceptual resources involved in this re-

markable ability, and how can we use an understanding of these factors to increase safety? In this article, we sought to study one common behavior that is often discussed but rarely formally considered in empirical research on steering or control of locomotion: the eccentricity of an operator's gaze as it relates to the ability to control road-holding and steering of an automobile.

The execution of navigational tasks is, under the majority of circumstances, not dependent on perfect, continuous visual feedback. That is, we can walk through the world while not looking precisely in the direction in which we are heading without any significant detriment to the behavior (see Cutting, Springer, Braren, & Johnson, 1992). Occasionally, we need to attend to objects away from the most informative areas of the environment (in terms of judging direction of travel), and we nonetheless are able to function sufficiently; how we manage to do this has been a question of interest at several different levels of analysis for some time now (e.g., Regan & Beverley, 1982; Wann, Rushton, & Lee, 1995). In fact, data from Wagner, Baird, and Barbaresi (1980) suggest that, during walking, humans spend very little time looking precisely in their heading direction (but see Hollands, Patla, & Vickers, 2002). Naturally, as speed of travel increases, so too does the possibility for errors to accumulate before corrective action is taken, and one would expect that gaze would be more frequently directed toward the direction of travel, as Calvert (1954) showed was the case for drivers nearly 50 years ago. Even at highway speeds, though, looking as much as 45° from the current focus of expansion to attend to a road sign, adjusting the radio, or checking the blind spot before changing lanes are common behaviors.

Of course, there is a history of research investigating the relationship between gaze and the driving task, as well as the necessary and sufficient conditions for proper (or arbitrarily defined "safe") driving practices. Land and colleagues (e.g., Land, 1998; Land & Horwood, 1995; Land & Lee, 1994) have shown the importance of the road's tangent point for controlling steering around a curve, and have further shown that drivers do, in fact,

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look at this as a source of information to guide behavior. Furthermore, the (usually very tight) coupling of gaze direction and steering wheel adjustments has been made clear through some of the analyses resulting from these studies. In these cases, however, gaze was not meant to be experimentally controlled for the benefit of the analyses, and therefore it is not clear what specific causal effects gaze deviation has on the control of steering. We aim to expand on these earlier findings and provide a link between this previous work on road-holding and other driving-related actions that could affect the task in as yet undefined ways.

In the cases of such over-learned tasks as driving or walking toward a destination, one would certainly expect that common (in some cases, apparently trivial) deviations in gaze can be dealt with by the perception–motor system without any important effects on behavior. However, Cutting, Readinger, and Wang (2002) have recently found evidence that walkers do tend to move in the direction of their fixation under conditions of both normal lighting and darkness. Participants in these experiments took seven or eight steps while fixating objects initially only 5° from straight ahead, and it was found that their walking paths demonstrated modest (but significant) degrees of curvature. Equally interesting, though, is the more general finding that, even under naturalistic environmental circumstances (i.e., small gaze-movement angles, relatively slow eye- or head-rotation rates, normal lighting in a large room) and a small number of steps, participants in these experiments showed significant movement toward the direction of their fixations. Although, to our knowledge, this is the only empirical evidence of this phenomenon, phenomenological support for the existence of this effect can be seen if we consider several other related anecdotal examples from three different practical navigational tasks.

1. In a manual describing methods for hunting game from horseback, Morris (1990) suggested that a horse would respond to subtle changes in the body position of a rider. That is, movement of the reins may provide a direct signal to the horse about the direction in which the rider wishes to travel, but an experienced horse can be “primed,” in a sense, by changes in the contraction and expansion of leg muscles that result from even a small shift in body position. As a result, Morris recommended that a rider should orient himself or herself and look in the direction in which he or she wishes the horse to go. Looking behaviors such as head turning can lead to natural changes in body position which affect guidance of the horse, and it is these consequential behaviors to which the horse, presumably, has learned to respond.
2. Many motorcycle drivers may have experienced a very similar effect of body position on their ability to steer. In a manual designed for training course instructors, the Motorcycle Safety Foundation (1992) claims that riders steer in the direction of their gaze. As in the case of horse riding, the direction of travel is extremely dependent on the posture and changes in weight distribution of the rider; these factors are, in turn, affected directly by the movement of the head and shoulders that is often associated with simple changes in looking behavior. In fact, reports from this document recalled instances where riders were unable to avoid hitting obstacles in the road

because they looked at them. The result of the orienting behavior in a case such as this seems to be an inability to separate (within the context of the perception–action relationship) gaze direction from direction of travel.

3. Finally, former racecar driver Bob Bondurant (Bondurant & Blakemore, 1998) provided a somewhat different sort of example. In the case of driving an automobile, it seems that there is also some anecdotal evidence for the tendency of operators to drive in the directions of their gaze. The recommendation made to students in this situation is quite to the point: “Look where you want to go.” This case is, in some ways, different from the others mentioned in that it is not quite as obvious how changes in posture or body position might influence the steering of an automobile. The sort of control inherent in steering a car is a further step removed from riding a horse or motorcycle in that merely leaning the body to the side will not in itself lead directly to a change in the attitude of the car. Although there is evidence that changes in head position can systematically affect hand position while using handlebars (Heuer & Klein, 2001), whether this effect generates experimentally to a steering wheel remains to be determined. Nonetheless, we see here some support for the notion that the eccentricity of a driver’s gaze can also have meaningful effects on the performance of the steering task in an automobile.

With these examples in mind, one may be led to believe that humans are poor at (or at least, capable of only insufficiently) compensating for head or eye movements during the course of translations and rotations. If one considers research on perception of heading, however, this appears certainly not to be the case. Banks, Ehrlich, Backus, and Crowell (1996), for example, provided evidence that observers are able to accurately perceive their heading direction during pursuit eye movements and simultaneous translation; this information even appears not only to be available, but necessary under certain experimental conditions (Li & Warren, 2000). Furthermore, when the simulated path of the observer is a curved one and the potential mathematical decomposition of the retinal flow information is more complex, performance on absolute-heading detection tasks often remains quite good, particularly when the rate of (real or simulated) rotation of the eye is less than about 1°/s, (see Warren, 1998, for a thorough review).

Similarly, although observers are able to make accurate decisions about heading from visual information alone in naturalistic environments (Cutting et al., 2002; W. H. Warren & Hannon, 1988), compensation for head turns also seems to be a well-developed routine in the process of heading perception. To this end, there exists evidence supporting the claim that neck position and head movements not only play significant roles in the handling of retinal flow, but that the information from these efferent signals is useful (and used) in making judgments of where one is going (Crowell, Banks, Shenoy, & Anderson, 1998). Finally, returning to the notion of gaze eccentricity in general, the stimulated area of the retina does not appear to be an important factor in the effectiveness of heading perception under laboratory conditions (Crowell & Banks, 1993; but see also Atchley & Andersen, 1998), thereby implying that this perceptual capacity is not impaired directly through presentation of stimuli away from the fovea.

These contrasting results may lead one to wonder if the perception of heading is really a meaningful comparison to the actual, closed-loop control of locomotion that is being discussed in the earlier examples mentioned here. Indeed, some researchers have convincingly argued (Wann & Land, 2000) that accurate heading judgments are not necessary for the degree of steering control required to safely and effectively operate an automobile. As a result, information about a target in the environment (and progress toward it, based on other properties of the environment) may be of more value than optic flow per se (e.g., Rushton, Harris, Lloyd, & Wann, 1998). Researchers have proposed models of driving performance based on this information (or, more notably, produced without the calculation of heading on the basis of characteristics of the optic flow field), which appear to fit human behavioral data reasonably well (e.g., Model 2 of Hildreth, Beusmans, Boer, & Royden, 2000). However, considering that drivers certainly do not have to be engaged in constant tracking of any goal objects or environmental landmarks, plausible explanations of meaningful effects of gaze deviation remain equally puzzling for this account of steering control.

The possibility of a discrepancy between the performance of human actors on a locomotion task and performance of observers in a heading-judgment task should, however, not be troubling given the increasing acceptance of findings relating to multiple streams for visual processing (e.g., Goodale & Humphrey, 1998; Goodale & Milner, 1992). It is possible that very similar visual information may be used in dissimilar ways for two different processes, specifically for active control of movement through an environment (which often is not under conscious control), and deliberate judgments of simulated heading direction (see Owens & Tyrrell, 1999, for further discussion of this distinction in a similar context). For example, researchers have claimed that depth information (especially from height in the visual field, or retinal disparity) is used in the robust perception of heading (e.g., van den Berg, 1992; van den Berg & Brenner, 1994). However, in experiments where participants were actively controlling their locomotion toward a goal under otherwise similar experimental conditions, Rushton, Harris, and Wann (1999) found that these factors were not at all important in the task. Obviously, knowing where one is going at the present moment is an important aspect of actually controlling the movement toward that point, but the same processes may not be at work in both cases. Thus, being able to report where one is headed might not entail use of the same information required in the act of actually getting there. How, then, is perception actually related to the guidance of locomotion? Much work has been done on relating looking behavior and eye movements to perceiving and reporting heading (e.g., Cutting, Alliprandini, & Wang, 2000; Kim, Turvey, & Growney, 1996). Considerably less is known, however, about the corresponding question of looking behavior and actual control of human movement.

In this article, we initially present the first empirical evidence for the existence of the phenomenon of steering in the direction of fixation. The guiding question throughout the series of experiments that follow is: What perceptual sources of information are involved in the production of this behavior? To this end, we remove as possible explanations effects of head position and simple tonic reflexes that could result from changes in body position ordinarily associated with gaze deviation (i.e., changes in shoulder or trunk position). Finally, through a series of conditions in which speed of the simulated vehicle and the type of retinal flow

information available are controlled, we suggest that this effect is not a direct product of the physical movement of the body, but results from the visual stimulus environment of the driver and, as such, may represent a problem for operators in certain types of driving situations.

## Experiment 1

### Method

*Participants.* Every participant in each of the experiments reported here was naïve to the purposes of the experiment being conducted at the time of testing. Before the experiment, all participants gave informed consent and were made aware of their rights as experimental participants, consistent with American Psychological Association guidelines and German law. All were right-handed, between the ages of 16 and 35 ( $M = 23.9$ ), and paid for their participation. All participants had normal or corrected-to-normal vision. For each experiment reported here, participants were recruited from a list of individuals who had expressed interest in volunteering for psychology experiments and lived in the area of Tübingen, Germany. No participant was involved in more than one condition of the experiments presented in this article, except where noted.

Eight participants completed Experiment 1. An experimental session consisted of 4 training trials, followed by 49 experimental trials (seven repetitions of each eccentricity listed below), and finally a debriefing. A typical session lasted approximately 45 min.

*Materials and apparatus.* All experiments reported here were conducted in a large-scale simulation environment specifically designed for the development and execution of driving and navigation experiments. A three-pipe Silicon Graphics Onyx2 InfiniteReality II (Silicon Graphics Inc., Mountain View, CA) was used to compute the stimulus images that were then front-projected onto a large half-cylindrical projection screen (diameter: 7 m; height: 3.15 m) by means of three CRT projectors (Electrohome Marquee 8000; Electrohome Limited, Kitchener, Ontario, Canada). Video blending hardware (Panorama Panomaker II; Panoram Technologies Inc., Sun Valley, CA) was used to obtain a smooth transition between the three images. The participants were seated in the center of the half cylinder, and the projected image subtended an angle of  $180^\circ \times 50^\circ$  in the observer's field of view. The frame rate of the projectors and the update rate of the simulation was 72 Hz.

The participants controlled their position in the driving simulation with a custom-designed, forced-feedback steering wheel. The feedback delay between the steering wheel and the visual projection had been minimized, and was estimated to be approximately 28 ms for this simulator. The steering wheel was fitted with a mouse-button attachment (mounted directly on the right side of the device), which allowed participants to respond comfortably to stimuli while not removing their hands from the wheel (see Figure 1). Steering-wheel angle and lateral position on the road were stored at a rate of 36 Hz for the purpose of later analysis.

*Stimuli.* The environment consisted of a textured ground plane and a plain blue sky. Drivers began each trial in the center of a perfectly straight road, which was also richly textured. The road was 7.5 m wide, and white demarcating lines indicated the left- and right-side boundaries. The road did not contain any distinctive features that indicated its center.

*Driving task.* Initial heading angles were randomly assigned to be very slightly left or right of straight ahead to ensure an initial correction in heading from the participants during the beginning of each trial. Each trial lasted 30 s, and there was a break between trials in case the participant reported fatigue or wanted a brief pause. Trials began and ended with a short period (approximately 1 s) during which the virtual car accelerated and decelerated, respectively. This has been found to reduce the likelihood of simulator sickness and, indeed, no participants reported any discomfort with the simulation.

*Orientation-detection task.* To ensure fixation at a desired location, a Landolt-C figure was generated and appeared just above the horizon

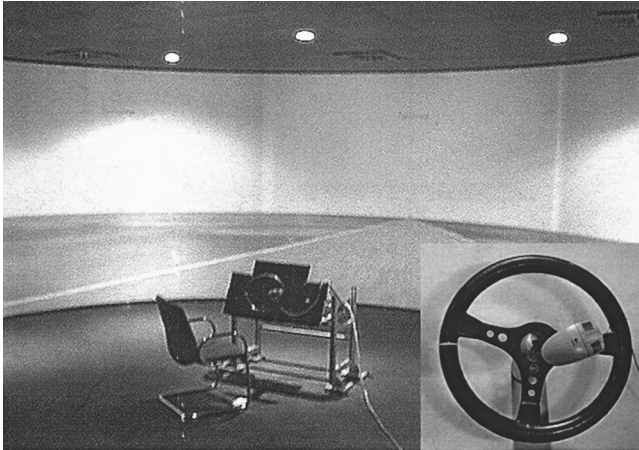


Figure 1. Virtual reality theater used in the presentation of the experiments. The panel represents a close-up photograph of the steering wheel and button devices.

throughout each trial. Traditionally, a Landolt-C figure can be used to determine visual acuity by asking observers to determine the orientation of the figure (see Vasa, 1960, for an early discussion of this technique as a measure of acuity). More precisely, the figure may be rotated in  $90^\circ$  intervals, and acuity is determined by asking an observer to report the orientation of a single gap in a ring, resembling the letter “C”, when the stimulus is presented at differing sizes. The Landolt-C figure in these experiments subtended a constant visual angle of  $0.66^\circ$  vertically and horizontally, and the “gap” in the letter was approximately one fifth of this, or  $0.13^\circ$ . For the first 5 s of each trial, the figure appeared at the center of the screen, that is, directly ahead of the driver. After this period, the figure was assigned a random location on the screen:  $-45^\circ$ ,  $-30^\circ$ ,  $-15^\circ$ ,  $0^\circ$ ,  $15^\circ$ ,  $30^\circ$ , or  $45^\circ$  from center (with negative eccentricities henceforth representing left of center screen). The Landolt-C figure then began to rotate in random intervals of  $90^\circ$  about the roll axis, such that the gap between the ends of the letter could be construed as “pointing” up, down, left, or right, as in the typical Landolt-C clinical task. The orientation of the figure was selected over a random time interval varying between every 0.5 and 1.5 s, yielding an average of one change in orientation per second. Thus, given its size, the figure needed to be viewed in the fovea in order for participants to determine its orientation and respond appropriately.

It should be noted that the fixation figure was not “planted” in the environment in these experiments. Rather, the figure was assigned screen coordinates and remained in the same position on the screen regardless of the driving behavior of the participant. Phenomenally, this would be similar to fixating a bug on the windshield of an automobile. To be more specific, though, consider an example of the alternative. If the figure were located as part of the environment on the left side of the screen, and the participant drove toward the figure (i.e., steered left), the projection of the figure would move toward the center of the screen. This process would effectively destroy the notion of eccentric fixation which we sought to study in these experiments. Therefore, by assigning the figure screen coordinates, as opposed to a fixed position in the environment, we were able to maintain a constant and controlled eccentricity of gaze for each driver.

*Design and procedure.* Experiment 1 consisted of two separate, between-subjects conditions. In the first condition, there were no control or external restrictions placed on the head or body positions of the drivers. In this condition, participants simply assumed a comfortable position behind the steering wheel and viewed the fixation figure via eye movements, head movements, body position changes, or any combination of these. In the second (between-subjects) condition, we sought to determine the influence of only eccentric eye gaze on the results obtained. To accomplish this,

position behind the wheel was restricted, and a chinrest and headstrap were used. Participants in this condition experienced an experimental session identical to the “unrestricted” drivers, except that each participant was instructed to keep his or her head forward (in the chinrest) and aligned with his or her body. The chinrest was adjusted such that it provided no hindrance to the view of any part of the projection screen or the steering abilities of the driver. Although no participants reported any difficulty in performing the driving task or actually seeing the Landolt-C figure, during debriefing 2 participants in this condition reported a small degree of discomfort in fixating  $45^\circ$  from center using only eye movements. The speed and accuracy of the button-press responses of drivers in this condition, nonetheless, are consistent with those in all other conditions, suggesting no residual, undesired effects (other than mild discomfort) of this manipulation.

Participants were instructed to fixate the Landolt-C figure throughout the duration of each trial. They were asked to press the button on the steering wheel whenever the figure was in a particular orientation (when the gap in the figure was on the bottom, for example). The goal of their task was to respond to the figure as quickly as possible while driving as close as possible to the center of the street. Participants were given four practice trials to familiarize themselves with the task and the simulation environment.

## Results and Conclusions

The dependent measure of interest in these experiments was the extent of lateral displacement (from the center of the street) on differing trial types. This measure was preferred both because it is an ecologically valid one (driving behavior depends, of course, a great deal on lateral control of one’s automobile) and for the representativeness of this measure for the behavior we aim to examine. Instantaneous heading and steering wheel position, for instance, can be used to assess performance, but road position is more reflective of the behavioral consequences of the manipulations associated with these experiments. It may be possible that the center of the street was not always accurately perceived, and this could make lateral position a less meaningful measure. However, in this experiment and those that follow, participants had little trouble driving near the center of the street in conditions in which their gaze was directed straight ahead. Also, even if the center of the street were somewhat ambiguous, this ambiguity ought to be constant throughout the experiment and therefore not jeopardize any conclusions based on differences between conditions of gaze eccentricity.

The results from the unrestricted-movement condition are represented in Figure 2. Furthermore, mean position data and standard error scores for this and all forthcoming experiments appear in Table 1. For analysis of these data, we used a one-factor analysis of variance (ANOVA) with repeated measurements to compare means of the different eccentricities. We calculated a “mean path,” in which all data for a particular eccentricity were averaged to determine the average position across drivers and trials at each given point in time. These data were drawn from a 25-s interval that began 5 s after the start of the trial and continued until the end. The average lateral deviation value across time for each of these paths was used in ANOVAs to compare the effect of different gaze eccentricities on the lateral position on the road. In some cases, when noted, all eccentricities to the left (i.e.,  $-45^\circ$ ,  $-30^\circ$ ,  $-15^\circ$ ) and all to the right of center were collapsed and compared with one another or with the “control” condition of  $0^\circ$ . Of primary interest was the finding that fixation has a significant effect on road position,  $F(6, 42) = 10.73$ ,  $p < .01$ . Using the unbiased estimator

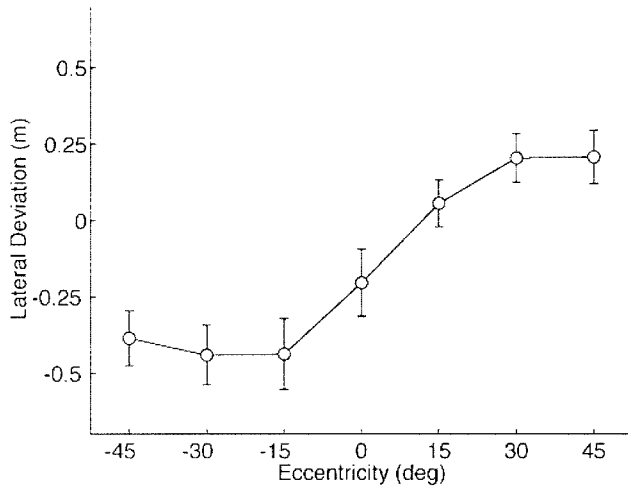


Figure 2. Results from the free-movement condition of Experiment 1. Points represent mean lateral deviation from the center of the street for all drivers at each of the seven different eccentricities; bars are standard error of the mean. In this condition of Experiment 1, no restrictions were placed on the head or body position of the drivers.

$\omega^2$  for the strength of association (Keppel, 1991), the resulting effect size was  $f = 1.02$ , which is considered to be a large effect (Cohen, 1988, p. 287). Contributing ANOVA characteristics for this and forthcoming conditions appear in Table 2. Generally, looking to the left of center leads to a leftward bias when compared with center, and similarly there were rightward biases in each of the right-fixation eccentricities.

It can be seen that, at least at these relatively large differences in eccentricity from center screen, the behavioral effect was not dependent on the extent of gaze eccentricity; the resultant displacement of lateral position on the road, and indeed the steering behavior of the participants, was similar in all cases. It should be noted that there was a strong tendency to steer to the left of the road in the beginning of these trials. To foreshadow a bit, this is a pattern that appears in most conditions discussed later. It is be-

Table 1  
Means and Standard Error Results for Lateral Deviation as a Function of Condition and Experiment

Condition	Mean			Standard error		
	Left	Straight	Right	Left	Straight	Right
Experiment 1						
Unrestricted	-0.44	-0.21	0.16	0.25	0.27	0.18
Chinrest	-0.20	-0.12	0.36	0.13	0.18	0.14
Experiment 2	0.05	0.05	-0.12	0.06	0.07	0.05
Experiment 3	-0.28	-0.27	0.14	0.12	0.14	0.15
Experiment 4	-0.15	0.07	0.24	0.15	0.14	0.21
Experiment 5	-0.15	0.05	0.33	0.17	0.17	0.17
Experiment 6	-0.31	-0.04	0.19	0.10	0.12	0.14

Note. All values are in meters from center. Negative mean values indicate position to the left of the street's center. Experiment 6 is included for illustration purposes, although it should be noted that this experiment contained eccentricities of fixation that were different from those used in all other experiments, and significant differences were found between eccentricities on each side of 0°.

Table 2  
Analysis of Variance Characteristics for Effects of Gaze-Eccentricity Condition as a Function of Experiment

Condition	MS <sup>a</sup>	MSE <sup>b</sup>	df <sup>c</sup>	F	f
Experiment 1					
Unrestricted	0.69	0.10	6,42	10.72	1.02
Chinrest	0.68	0.06	6,42	6.56	0.77
Experiment 2	0.10	0.02	6,42	4.12	0.56
Experiment 3	0.43	0.05	6,42	9.15	0.93
Experiment 4	0.28	0.05	6,36	5.40	0.73
Experiment 5	0.49	0.08	6,42	5.88	0.72
Experiment 6	0.56	0.08	4,28	7.32	0.79

Note. All  $ps < .01$ .

<sup>a</sup> Mean square of factor "eccentricity of fixation." <sup>b</sup> Mean square of error term. <sup>c</sup> Degrees of freedom of MS and MSE.

lieved that this is a reflection of the methods used in these experiments, more precisely, the lack of a visible model of a car in the simulation. When drivers are instructed to drive in the center of the street, it seems natural for Germans (who have learned to drive on the right side of the street) to position their (virtual) car in the center of the street which was simulated. This entails, of course, putting their bodies to the left of center on the road, and this is the trend we see in the data. In support of this claim, researchers have found that with drivers in Australia, where left-side driving is the law, simulations similar to the one used in these experiments lead to a similar trend in the opposite direction. Drivers move their bodies to the right of the road's center in order to place the virtual car in the middle of the street (G. Wallis, personal communication, August 2001).

Results of the chinrest condition appear in Figure 3. In this condition, on trials where fixation was anywhere to the left of 0°, participants reliably drove further on the left side of the street, when compared with 0°, and to the right of 0° when fixating anywhere to the right side of the screen. An ANOVA confirmed these observations with a significant main effect of eccentricity on lateral deviation from center,  $F(6, 42) = 6.56, p < .01, f = 0.77$ ; once again, a large-sized effect.

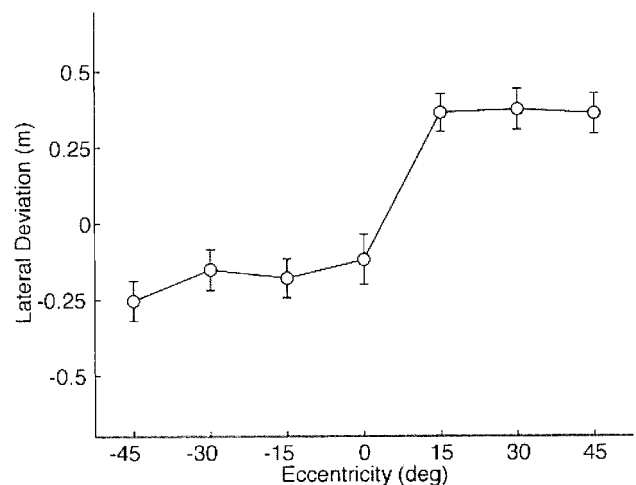


Figure 3. Mean and standard error of the mean results for participants in the chinrest condition of Experiment 1.

The data from these two conditions, taken together, can be seen as evidence for two points on which the following manipulations are based: First, the effect of gaze eccentricity on control of locomotion that was mentioned by several experts on riding and driving were, in fact, confirmed here. The differences between looking to one side of the direction of travel as opposed to the other leads to statistically significant and sizable changes in the pattern of steering behavior of the operator. Second, this effect is not a result of the hands of the driver simply “following” the direction of movement of the head. Eccentric eye position relative to the center of the simulation is sufficient to lead to similar patterns of results when head position is controlled and when free head movements were allowed. Thus, although it remains necessary to examine the possibility that the hands follow not the head but the eyes, as it were, one potential explanation based on body position has been accounted for.

At this point, it also seems prudent to point out an anecdotal observation made for drivers in these conditions. Although the actual mean lateral displacement of the virtual car in all these cases was perhaps fairly modest (at its most extreme, approximately 50 cm), it is still sufficient to represent some practical significance to actual driving. Every participant on nearly every trial with eccentric gaze showed a striking pattern of behavior. Specifically, participants tended to drive in a sinusoidal pattern toward the fixation point for several seconds, followed by a correction toward the center of the street, and finally a second (and occasionally third or fourth) repetition of this cyclical pattern. Because of the difference between trials and certainly between participants in the frequency and amplitude of these sinusoids, the average of lateral displacement from the road’s center at any given time point is, of course, smaller than the magnitude of typical displacements. Figure 4 shows examples of this pattern of driving behavior taken from three individual trials, each performed by 2 participants.

Given this pattern, however, we performed a further analysis to determine the actual extent of the change in position of the street at some point during the trial. When the most extreme point left or right of center during each trial for each driver in this condition was determined, the average of these points was 1.33 m ( $SD = 0.80$ ) for left-looking fixations (i.e., 15°, 30°, and 45° to the left) and 1.18 m ( $SD = 0.66$ ) for right-looking fixations (15°, 30°, and 45° to the right). Considering the magnitude of these averages, there should remain little doubt that the effects reported here constitute a meaningful factor with the potential to affect driver safety in certain realistic environments.

## Experiment 2

Experiment 2 is designed as a first step toward resolving the question of speed and its role in the findings presented in Experiment 1. Specifically, is forward translation necessary for the production of this effect, or would a similar effect be seen in terms of purely lateral displacement? Does merely looking to one side of the simulated environment lead one to turn a steering wheel in that direction, or is some aspect of the forward movement of the driver important? In this experiment, these issues are addressed.

### Method

**Participants.** Eight participants also took part in this condition. One participant was excluded for failure to learn the driving task during training

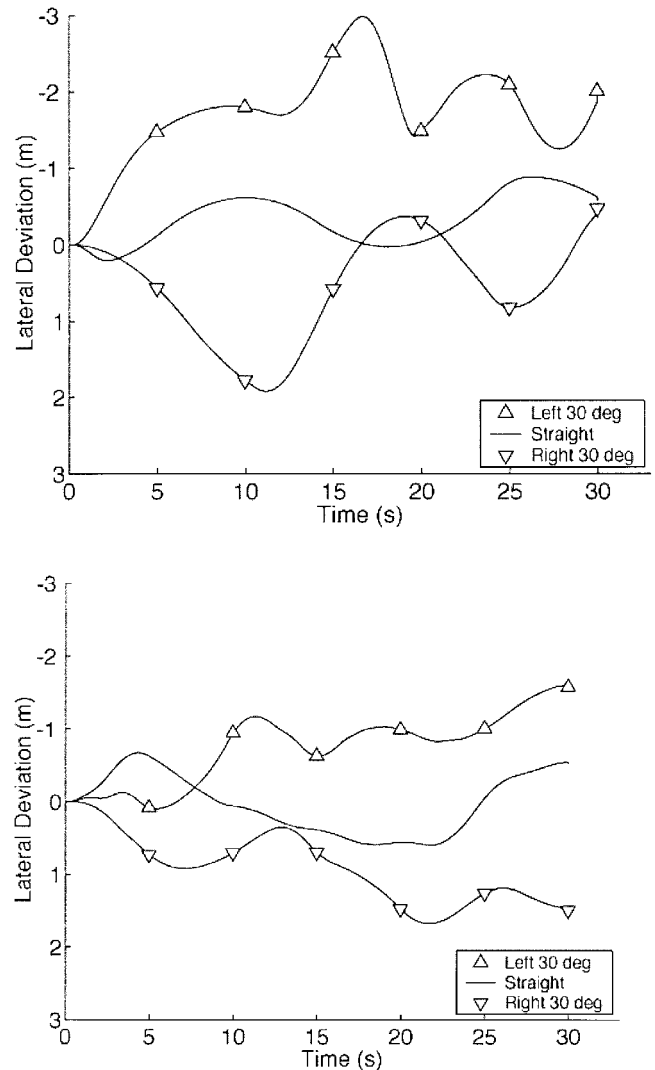


Figure 4. The top panel illustrates three example paths taken from a typical participant in Experiment 1 with fixation 30° to the left, 30° to the right, and straight ahead. The bottom panel illustrates three corresponding example paths from a different participant in Experiment 1.

trials. The typical experimental session lasted approximately 45 min, including debriefing.

**Design and procedure.** The procedure used in this experiment was similar to the procedure in Experiment 1, but forward movement was removed from the display. That is, the driver could control his or her position on the street in exactly the same fashion as in Experiment 1, but the forward position through the environment was not updated on the screen. As in normal driving, turning the steering wheel led to a change in heading for the virtual car, and therefore a change in position on the road, but no optical flow information from forward translation was present, only near-laminal flow from the changes in yaw. The phenomenological experience of participating in this condition was somewhat different than that of the other versions of the experiment reported here. Specifically, this task removed a prototypical element of the driving situation and, as such, represented a somewhat less ecologically valid driving experience, although the control devices and methods were identical to earlier conditions. The practical effect of this manipulation can be thought of as driving in an environment without texture, where the driver must use only splay angles

of the road outline, or color differences between the road surface and ground to control position on the street. With this in mind, we intended only to consider this condition as a perceptual control to potentially contrast the findings above.

### Results and Conclusions

As can be seen in Figure 5, the trend to drive in the direction of fixation disappeared when the element of forward translation was removed from the simulation. In fact, there was a significant difference between the eccentricity conditions,  $F(6, 42) = 4.12$ ,  $p < .01$ , and a large-sized effect of  $f = 0.56$ ; but it is in the direction opposite the one that has been observed earlier. That is, when looking to the left, participants tended to "drive" somewhat to the right of the street, and vice versa, in this condition. This difference is, however, modest; it amounts to approximately only 10 cm of deviation, on average, from the street's center. This is of a magnitude smaller than the results found in the earlier conditions, and the tendency of drivers to conform to the heretofore standard sinusoidal pattern of deviation and correction is not nearly so prevalent in the findings for this condition.

In this somewhat strange situation, it seems quite likely that participants may have made an effort to steer modestly away from the direction of fixation in order to bring the road toward the center of their field of view. Practically, this is somewhat of a futile strategy on the part of the participant, because even at the smallest eccentricity, the car would have moved considerably away from the center of the street (indeed, entirely off of the road) before the road was centered in the field of view. The findings still may reflect a tendency to explore this type of strategy, only with limited success. Nonetheless, it is clear that the earlier effects of gaze eccentricity were not present in this condition. Merely looking at a certain portion of the environment does not lead one to drive in the direction of this fixation in the absence of simulated forward translation.

### Experiment 3

Given the results of Experiment 2, one may question the importance of the speed of the simulated automobile in the effects

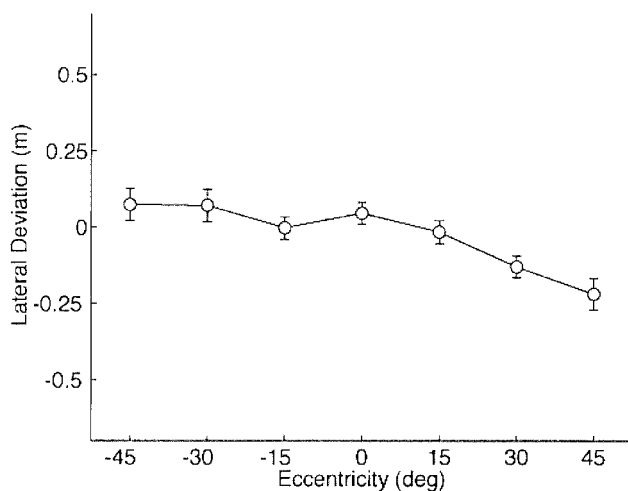


Figure 5. Results from Experiment 2 in which the simulation featured no forward movement. Mean and SEM data representing lateral position on the street are reported as a function of gaze eccentricity.

that have been observed so far. Attending to a point to the right of center led to rightward positional bias in the results of Experiment 1 at a speed of 20 m/s, but to a bias toward moving left when speed was 0 m/s. It may be reasonable to consider the possibility that at a speed between these two extremes, the effect of Experiment 1 would be seen to some lesser extent. For this reason, the present experiment has modified the forward velocity of the simulated car.

### Method

*Participants.* Eight participants were tested. Including instructions, practice trials, and debriefing, typical session lengths were once again approximately 45 min.

*Design and procedure.* The variable of interest in this variation of the experiment was the speed of the virtual car. We sought in this condition to determine if the results of the earlier conditions were based on the speed of the virtual automobile, or on the fact that there was forward movement at all. Thus, drivers in this experiment were assigned to perform a task identical to those described above, with the exception that speed of the car was now set to 10 m/s. An experimental session consisted of 49 trials.

### Results and Conclusions

Somewhat unexpectedly, the results of this experiment yielded a pattern of results that is consistent with the results from Experiment 1. Specifically, looking right led to significant road position changes in the same direction, and the case remained the same when drivers looked to the left,  $F(6, 42) = 9.15$ ,  $p < .01$ ; this was also a large effect, with an effect size of  $f = 0.93$ . (Please refer to Figure 6 for results from this condition.) Furthermore, although no quantitative measures were performed, one may notice the apparent similarity between the extent of average lateral deviation in this condition and the findings in other versions of the experiment (see Table 1).

### Experiment 4

It appears, considering the findings of Experiments 1 and 3, that the tendency for drivers to steer in their direction of gaze is robust. It occurs reliably at slow and moderate speeds of travel, but one may still wonder if the behavior could be further exaggerated by increasing the speed of the simulation. This was the question we sought to answer in Experiment 4.

### Method

*Participants.* Seven participants completed this experiment; data from 1 participant were excluded for failure to follow directions for completion of the experiment. Two of these participants also took part in Experiment 3, however, the order of presentation of the experiments was counterbalanced between these participants in an attempt to ensure against order effects. Considering instructions, practice trials, and debriefing, participation in Experiment 4 took approximately 45 min.

*Design and procedure.* As in Experiment 3, speed of the virtual car was the only change made to the design of the experiment. Drivers' tasks were identical to those described in earlier permutations of this experiment, and this condition once again consisted of 49 trials, this time at a forward speed of 30 m/s.

### Results and Conclusions

There was no clear evidence of increased speeds having a significant effect on road position under these conditions. As seen

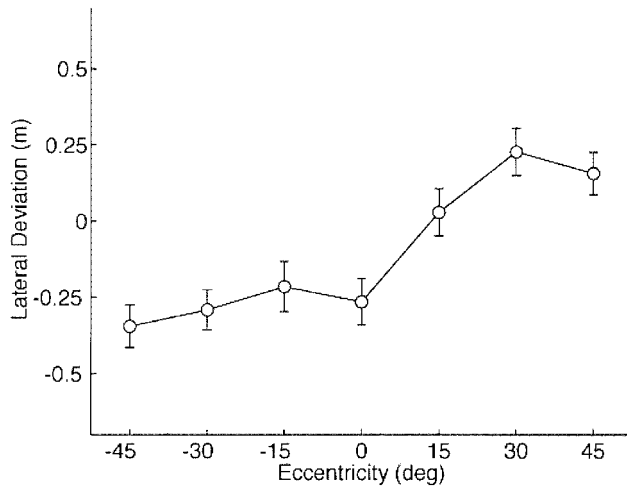


Figure 6. Average lateral position data from the 10 m/s condition of Experiment 3.

in Experiments 1 and 3, there was a significant effect of eccentricity of fixation on road position,  $F(6, 36) = 5.40, p < .01$ ; namely, looking left led to steering in that direction and vice versa. The effect size was  $f = 0.73$ , which is also considered a large effect. These results appear in Figure 7. At different speeds, the general effect of “steering where one looks” remained robust and was of similar magnitude (see Table 1 for a more detailed comparison of the mean and variability data and Table 2 for effect sizes).

### Experiment 5

In this experiment, we sought to separate the effects of perceptual tendency to drive toward fixation from the possibility of an effect of simple body position on the results from Experiment 1. Researchers have shown that, under most normal circumstances, the head tends to follow the eyes when gaze moves eccentrically (Corneil & Muñoz, 1999; Doherty & Anderson, 2001), and that this movement can lead to some meaningful changes in hand position that could affect steering (Heuer & Klein, 2001). Similarly, the argument could be made that in cases where fixation is sufficient to ordinarily require a head turn, the hands tend to follow the head (or perhaps themselves also follow the eyes), and this would account for the data presented above. This experimental manipulation should effectively remove the possibility of this explanation as an account of the pattern of data presented in Experiment 1.

### Method

**Participants.** A total of 8 participants were involved in this experiment, and one additional driver was excluded for failure to learn the reverse-steering task. The typical experimental session lasted approximately 90 min.

**Design and procedure.** The methods used in this experiment are identical to the methods used in Experiment 1, with the following exceptions: The steering control of the virtual car was reversed in this condition. That is, when the steering wheel was turned counterclockwise (normally initiating a left turn), a right turn was initiated, and vice versa. An invisible buffer was also added to the environment to ensure that, particularly during

the initial practice trials, drivers did not get too far from the road. The buffer was located 10 m from the edge of each side of the road (a location that would indicate an extremely errant steering behavior which was never reached by any driver in Experiment 1), and did not affect any of the experimental trials that are reported here.

Participants in this experiment were also provided with training to become accustomed to this unusual method of steering. Each driver was given 50 practice trials, each 30 s in length. In the first half of these trials, the drivers were asked only to practice staying as close to the middle of the street as possible and get accustomed to the steering method. During the second half of the training trials, the Landolt-C figure was added at  $0^\circ$ , and participants responded to a given orientation, as above. The training period lasted approximately 35 min, and following this, the details of the experimental session were again identical to Experiment 1, except for the reversal in steering control.

### Results and Conclusions

The general pattern of driving behavior in which leftward fixations led to leftward average lateral positions and vice versa continued in this experiment. Specifically, there were once again significant differences in average lateral position for all eccentricity conditions,  $F(6, 42) = 5.88, p < .01$ , and a large effect size of  $f = 0.72$ . These results are represented in Figure 8.

This finding is surprising in that, while driving toward their point of fixation, drivers are systematically steering in the opposite direction. Given the reverse-steering input with which the driver has been trained, in order to produce a pattern of results that is qualitatively similar to those of Experiment 1, as we see here, the steering behavior must also be reciprocated. If the results of Experiment 1 were the result of a simple tendency of the hands to follow the head or eyes, the virtual car would have been moved in the direction away from gaze in this condition and would have yielded a very different, in fact opposite, pattern of results. Thus, we can reasonably remove head turns and body position accounts as explanations of these data.

### Experiment 6

One aspect of the results reported here that has not been discussed in detail thus far is the perhaps surprising finding that the

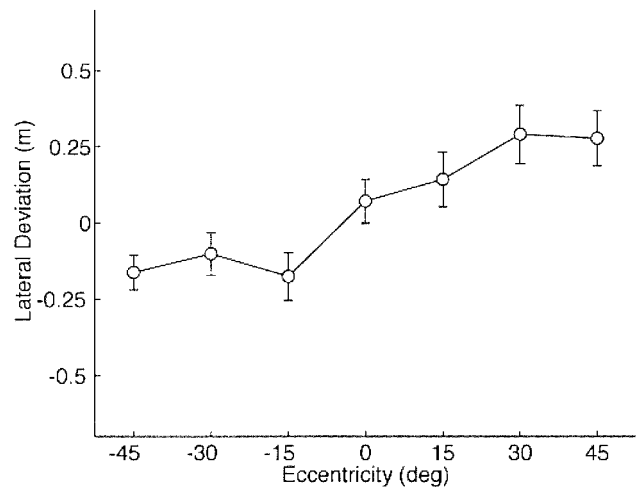


Figure 7. Results from the 30 m/s condition of Experiment 4. Once again, average lateral position on the simulated road is shown as a function of the eccentricity of gaze.

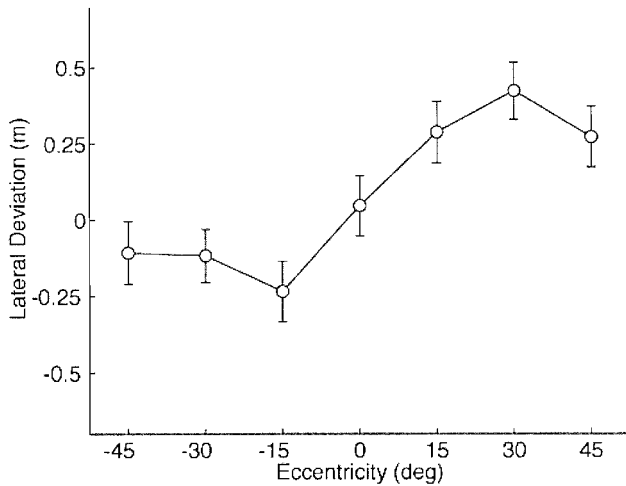


Figure 8. Results from the reverse-steering condition reported in Experiment 5. Values greater than 0 once again correspond to lateral position to the right of the street's center, but a leftward turn of the steering wheel was required to initiate movement in that direction.

extent of the deviation of gaze from the center of the display does not seem to have a meaningful impact on road position, on average. Relatively large eccentricities have been used in the experiments reported above, so the possibility of achieving the same pattern of effects was tested with smaller gaze eccentricities in this experimental manipulation.

### Method

**Participants.** Although there were fewer total trials per participant in this condition (now 35), each trial was longer, and this led to an experimental session lasting, once again, approximately 45 min. Once more, 8 participants were paid for their involvement, none of whom had been included in any of the previous conditions.

**Stimuli and task.** In this version of the experiment, we sought to determine the extent of gaze eccentricity necessary to produce results similar to those found thus far. To this end, the eccentricities of the fixation figure were reduced, such that there were now five possible locations of the Landolt-C figure: straight ahead, 5° to the left and right, and 10° to the left and right; each eccentricity was repeated 7 times per participant. The length of each trial was extended from the previous 30 s to 40 s for this condition, however each trial retained a 5-s initial period when the fixation figure was straight ahead of the driver (i.e., before it jumped to an eccentric position). All other details regarding the stimuli and task were consistent with the previous conditions reported here.

### Results and Conclusions

The results from this experiment are in contrast to the findings of the previous conditions in which the degree of eccentricity away from the center of the screen had no effect on the lateral position of the driver. Here, we found that the same general pattern of results appears in that looking to the left still led to leftward movement and vice versa, but in the cases of these smaller eccentricities, now there was a clear effect of the extent of gaze eccentricity. It can be seen in Figure 9 that there is again a significant main effect of the eccentricity of the fixation,  $F(4, 28) = 7.32, p < .01$ , which is a large-sized effect ( $f = 0.79$ ). However, in contrast

to earlier experiments, more eccentric gaze positions led to greater average lateral deviation from the center of the street.

Furthermore, the nature of the relationship between effects of differing eccentricities in this case appeared to be linear. This linearity was confirmed in the ANOVA by a significant linear trend for the factor eccentricity of fixation,  $F(1, 7) = 9.45, p < .05$ ; accounting for a proportion of  $\eta^2 = .57$  of the variance in the sample. Two points can be taken from this finding, in combination with the data that have been presented in earlier conditions. The first is that the effect of eccentric gaze appears to saturate at approximately 10–15° from center, yielding behavior that is similar as long as fixation is somewhere between this point and 45° from straight ahead. Given the pattern of results that have been found in earlier experiments reported here, the theoretical direction of prediction is clear for any pairwise comparison: Eccentric gaze to the right of fixation should lead to average road position that is to the right of the street's center, and vice versa. A one-tailed  $t$  test was performed to establish the second important point to take from this particular experiment. Deviations of gaze as small as 5° led to a systematic and statistically significant effect compared with 0°,  $t(7) = 2.07, p < .05$ , on driving behavior in this virtual environment.

### General Discussion

In this series of experiments, we have considered cases of extended fixation at varying eccentricities from straight ahead (and center screen) and the effects of these manipulations on the steering performance of drivers. At the most general level, one can conclude from the data presented here that there is a systematic and reliable tendency for operators to follow their direction of gaze with their direction of travel, in many cases without the conscious awareness of doing so at all. Further, we have shown that this effect (a) is not a result of tonic changes in body posture, (b) does not occur in situations where no forward translation is present, and (c) is of a magnitude that is sufficient to be meaningful for practical driving situations. Finally, we have shown that the effect occurs quickly after the gaze is directed away from the direction of

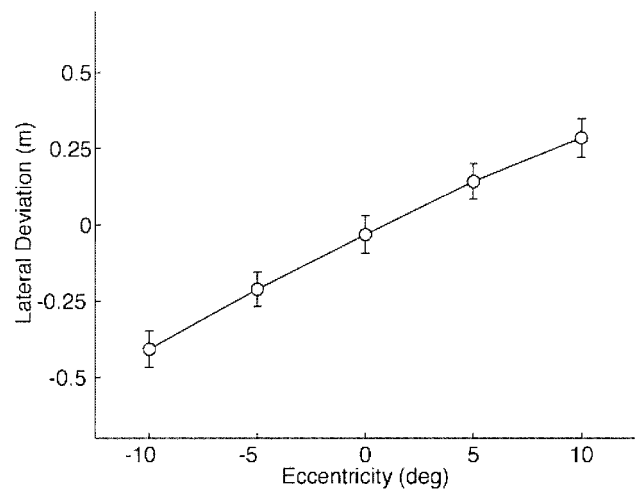


Figure 9. Results from the smaller eccentricity condition in Experiment 6. Smaller eccentricities were tested in this experiment, and the length of individual trials was increased.

travel and the trend remains despite changes in the speed of the virtual car in these experiments.

Why should it be the case that a sample of drivers with widely varying levels of experience tend to show a very similar and unnoticed pattern of behavior in these cases? One initially appealing possible account of these results may be based on a driver-safety explanation. That is, it might seem reasonable for drivers to drive in the direction of their fixation because they know what potential hazards exist there. If one is looking to the right, one can make use of the information available from this part of the visual field, especially compared with the relative dearth of information of this type from the left, or even straight ahead. This theory, however, cannot account for two important aspects of the data presented here. First, and most importantly, some observations suggest that when performing a similar task and looking at an oncoming car, drivers tend to display the same behavior; that is, they steer toward the oncoming car (Helander, 1978; but see Triggs, 1997). This seems to be a situation in which the information from the fixated field of view would lead the driver to prudently move away from fixation, but this does not appear to be the case in the experiments presented here. Second, the saturation effect of the varying eccentricities does not seem to be consistent with this account. More specifically, one would predict that in cases when a driver is looking  $45^\circ$  from center screen, he or she would steer more in that direction (and probably more quickly) than in a case when he or she is looking only  $15^\circ$  from center; this pattern of results was certainly not obtained.

### *On Driver Experience and Expertise*

The results may also seem fairly typical of drivers without a great deal of experience. During informal debriefing, it was found that very few drivers (6 of 53) noticed that they tended to drive in the direction they were looking. It may have been the case that novices at the driving task do not have the cognitive resources available to actively perceive the presence of this phenomenon, whereas experts fail to notice it because of the nearly automated nature of the task for them. So, along with experience may come confidence in driving abilities and also a failure to recognize situations in which their behavior is not consistent with their intentions or, in this experimental situation, the instructions they have been given. Consistent with the multiple modes of visual-processing discussion offered in the introduction, this frequent failure of experienced drivers to detect the patterns in their performance may constitute further evidence for the automaticity of behaviors associated with the guidance of locomotion, in contrast to tasks involving explicit judgments of passive translation and rotation through space.

Furthermore, differences between experts and novices at the driving task may be reflective of levels of control that typify drivers in these stages of proficiency. Rasmussen (1983) described three levels of control in a hierarchy of human performance. Presumably, drivers with a great deal of experience reside in Rasmussen's "skill-based" level, where the behavior is not under conscious supervision and proceeds automatically, unless there is some interruption in normal functioning that necessitates attention. However, relatively inexperienced drivers still perform at the lower level of "rule-based" control. Here, although the attentional demands are not overwhelming, behavior remains explicit, and the driver is often aware of component subprocesses associated with

the overarching task. Such a distinction would predict that in unusual cases, novices may be more likely than experts to recognize and attempt to correct for errant behaviors, because the driving task remains less automated and therefore more accessible to conscious corrections. These speculations are preliminary but certainly seem to support the great importance of proper driver training, including awareness of susceptibility to the tendency we discussed here, and deserve further attention.

### *The Roles of Attention, Fixation, and Saccadic Eye Movements*

The issue of attention is, of course, an important one here. One may be led to wonder about the results of another control experiment in which observers look straight ahead but are asked to simply attend away from their gaze direction. This is quite a valid concern, considering it is a very common behavior while driving; imagine tuning a radio while watching the road ahead. In a case such as this, certainly attention is directed for a few moments toward the console of the car, even though gaze may remain on the road. We propose that these experiments represent a solution to this concern as well. The driver need not fixate straight ahead to resolve the issue. Presumably in all the experiments presented here, the fixation of the driver is controlled while some degree of their attention is lying away from this fixation and on the road surface, the splay angle provided by the lines at the edge of the road, or some other feature of the simulation. For instance, in the case where the driver is fixating to the right of the road in these experiments, there is a tendency to drive to the right, although attention is, to some extent, directed relatively left of fixation (because the road itself is relatively left of fixation). If attention, relative to fixation, were the key factor in these findings, one would expect an opposite pattern of results (i.e., steering to the left while fixating right and attending relatively left of fixation) in the basic findings reported here.

Some mention should also be made of the nature of the fixation task drivers carried out in these experiments. On average, a driver had to respond to the assigned orientation of the fixation figure only once every 4 s. However, because the average time between changes in the orientation of the figure in general was only 1 s, it is certainly possible that participants were able to make saccades around the environment and still perform the attentional task of responding to the Landolt-C figure with high accuracy and speed. It was not uncommon for some participants to report occasional saccades on some trials; indeed, this might be expected considering that 30 s is a rather extended fixation on one solitary point. This serves only to reinforce the salience of the effects, though. Although saccades away from the fixation figure would lead to differences between drivers, which cannot be controlled, this also produces a task that is more ecologically valid and speaks more directly to the task of driving under realistic circumstances. The fact that the effects reported here were obtained despite likely saccades away from the fixation point should be seen as even more convincing evidence of the potency of this effect.

Lately there has been much debate relating to the use and physical positioning of cellular phones and in-vehicle navigation systems while driving, which has led to the beginnings of some very intense and extensive undertakings (e.g., Llaneras, 2000) on the part of automotive companies as well as regulatory agencies. One of the issues of primary concern is the detrimental effect of

looking from the road ahead to the console (or somewhere else within the car's interior) to use these devices. One of the clear differences, though, between this real-world example and the studies presented here is the length of the fixation involved. In cases of extended fixation such as those that were used in these experiments, results could be explained if we considered the relevant informational source not to be the actual position of the eye, in terms of eccentricity, but the movement of the eye to this point. A decay in the usefulness of the information about absolute position of the eye over time would lead to increases in errors over the course of fixation, perhaps until a saturation point is reached. Considering that we see effects of the eccentric looking very quickly after the behavior occurs (within about 2–3 s), this account could of course be only partial, but should be considered when addressing the human-factors problems in real automobiles.

### *A Partial Explanation, Unresolved Questions, and Future Directions*

We find it reasonable to conclude that, under a variety of different stimulus environments, it is indeed a combination of retinal flow and extra-retinal signals that contribute to the perception of heading direction and the control of steering (see W. H. Warren, Li, Ehrlich, Crowell, & Banks, 1996) and eye movements (Land & Furneaux, 1997). Of course, the nature of the information available would dictate which of these sources receives more weight in any behavioral process. With this in mind, one interesting possible account of a portion of these data comes from a recent article by W. H. Warren, Kay, Zosh, Duchon, and Sahuc (2001). They provided a novel explanation and justification for some results of human walking data with the following equation:

$$d\phi/dt = -k(\beta + wv\alpha)$$

In this equation,  $\phi$  = locomotor direction,  $t$  = time,  $\beta$  = goal direction,  $v$  = velocity, and  $\alpha$  = gaze-movement angle. However, the most interesting aspect of this account for the data presented here is the variable  $w$ , which represents the amount of optical flow information available in the environment. If the applicability of this formula may be stretched somewhat beyond that for which it was intended and extended to the active control of steering an automobile, the amount of flow information may lead to the basis of a reasonable explanation of the tendency participants have displayed to drive in the direction of their fixation.

In cases where the amount of flow available to the operator is relatively small ( $w$  approaching 0), the control of steering (the derivative on the left side of the equation) can lead to the goal-direction factor ( $\beta$ ) increasingly dominating the equation. In a case such as the one presented to drivers in these studies, the amount of retinal flow is certainly significant, but many indicators often available in normal environments are conspicuously absent. In particular, objects indicating relative depth information (such as trees) are not available to provide cues that are certainly used, especially in the nominal direction of heading (e.g., Cutting, Vish-ton, Flückiger, Baumberger, & Gerndt, 1997). Thus, this might represent a case of somewhat impoverished flow information, and therefore increase the significance of the goal-directional component. Once again to expand the scope of these variables, "goal direction" may be functionally equivalent to the fixation point in these experiments. If granted these extensions (as well as possible

asymptotes in the gaze-movement angle and velocity components), the equation can provide at least a qualitatively reliable account of these results.

However, such an account would be able to say nothing about the direction of the effect. That is, when it becomes possible to predict the magnitude of errors or deviations from the center of the street, as in the case of these results, we still have no explanation for why these deviations might be reliably distributed unequally toward the direction of fixation and this, of course, is the most meaningful aspect of these experiments. Instead, a more general consideration of the possible importance of optic flow may shed light on these results. W. H. Warren et al. (2001) showed that as increasing optic-flow sources were added to a display, this source of information dominated behavior, in contrast to an egocentric direction hypothesis (e.g., Rushton et al., 1998), which explained behavior when no optic flow was present. In general, it appears that walkers would attempt to use flow information to effectively move the focus of expansion of the visual array toward the target of their locomotion. If indeed drivers treated the fixation object as similar to a target of locomotion, the data we report here are consistent with this pattern of behavior found in the literature.

Certainly, these findings should be tested in the more robust environment associated with actual driving. Along with careful monitoring of eye gaze, the phenomena reported here should be examined in cases of fixation that do not extend to the extreme situations which were imposed upon drivers in these experiments. If these results are also found in cases of steering a real car in a closed circuit under similar experimental control conditions, the confirmation of anecdotal evidence mentioned earlier should be used to better prepare novices learning the driving task, and perhaps even to inform experts of their susceptibility to this tendency. As many inexperienced (as well as expert) drivers have undoubtedly heard the admonishment, "Look where you're going!" it seems also practically important for them to know, given these findings, that they may also tend to "go where they're looking."

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