Effects of Edge Rate on Perceived Egomotion in a Driving Environment

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ABSTRACT

Automobile drivers have a tendency to make judgments of their perceived rate of travel, or egospeed, that are slower than the speed they are actually traveling. This often leads them to drive at faster speeds, which results in increased crash risk for themselves and other vehicles. A driver's egospeed can be affected by visual cues in the environment including Edge Rate (ER) optical effects. The purpose of this research was to examine how speed production would be affected by (1) the presence and distance of roadside (geographic) ER cues; (2) proximal ER cues such as traffic moving at faster, similar, or slower speeds than the driver; and (3) the combined presence of geographic and traffic ER cues. A novel methodology had participants drive at comfortable and ratio speeds while experiencing 10 continuous minutes of each ER condition. Performance was examined in terms of: mean speed choice; ratio speed-production performance (target ratio); speed consistency (speed drift ratio, reliability ratio); and judgments of task difficulty (ease rating). Data suggested that certain cues reduced a driver's comfortable speed of travel: the presence of geographic ER cues; closer-distance geographic ER cues; slower-speed-traffic ER cues; and the pairing of geographic ER with slower-speed-traffic ER cues. Data showed that a reduction in traffic speeds may be produced by increasing the saliency of ER cues in the environment regardless of traffic conditions.

Keywords: Drivers, Speed production, Edge rate, Traffic, Visual perception

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INTRODUCTION

Driving at an excessive speed is a prevalent and costly driving behavior that can be directly related to crash risk. During 2008 speeding was found to be a contributing factor in 31 percent of all fatal crashes, accounting for 11,674 fatalities (National Highway Traffic Safety Administration [NHTSA], 2009). NHTSA also estimated the economic cost of speeding-related crashes to be more than US $40.4 billion each year. Although the number of annual traffic fatalities has been decreasing steadily from 2005 to 2008, the proportion of crashes where speed was a contributing factor has remained at or above 30 percent since at least 1996 (NHTSA, 2007, 2008a, 2008b, 2009). This suggests that the recent fatality-reduction trend was due to other factors while speeding remains a prevalent contributing factor to traffic crashes.

Recent meta-analyses performed on speed and crash risk literature (Elvik, 2005; Aarts & van Schagen, 2006) agree there are strong, positive relationships between increased vehicle speed and the likelihood and severity of crashes. Higher speeds are directly related to crash severity in that they increase the kinetic energy of the moving vehicle (energy being equal to vehicle mass times the square of its velocity). When considering that traffic may be moving at different speeds, especially when it is traveling in opposite directions, Aarts and van Schagen (2006) found that the crash rate was elevated in cases where vehicles drove faster than surrounding traffic. Bowie and Walz (1994) examined tow-away crash data (i.e., when a crash resulted in one of more vehicles being unable to drive away on its own) and found that the likelihood of a severe injury is

2.6 percent when these “speed differentials” are between 11 and 20 mph. However, this likelihood increases to 11 percent when differentials are 21-30 mph, and the rate jumps to 29 percent when differentials are 31-40 mph. Aarts and van Schagen propose a rule of thumb for this relationship between speed and crash risk: when speed of travel increases by one percent, the injury crash rate increases by two percent, the serious injury crash rate increases by three percent, and the fatal crash rate increases by four percent. Conversely, the evidence is less conclusive but suggests that the reverse relationship holds true when speed decreases.

Driving through scenes that provide a greater amount of optic flow information may help drivers to regulate their speed (Andersen, Sauer, & Saidpour, 2004; Chihak, 2007). One implication from these findings is that a driver’s speed performance may be assisted by increasing the salience of these cues. The absence of roadside objects may lead drivers to perceive there is a lower level of crash risk, resulting in faster speeds. If this is the case, one way to promote safer speed behavior would be to design roads with more apparent risk. In a review of how the built environment is related to traffic safety, Ewing and Dumbaugh (2009) argue that less-forgiving designs (e.g., narrow lanes, traffic calming measures) improve safety performance because they provide a driver with clear information on safe and appropriate operating speeds. For example, recent European trends for road design have used visual features to give roads the appearance of demanding more attention and forgiving fewer driver errors (Shared-Space, 2007; Theeuwes & Godthelp, 1995). In effect, these designs tend to increase the *perception* of ambiguity and risk so that drivers believe they are entering a more demanding situation. The result of increasing ambiguity to the driving environment is typically that the driver maintains a reduced speed and pays more attention to resolve the ambiguity (Shared-Space, 2007). The driver also perceives greater consequences for making risky driving maneuvers, resulting in the adoption of more cautious attitudes and behaviors. This design philosophy has been applied to highway design where curves are added or lanes are reduced in width or number to give drivers the perception that slower speeds are necessary. There is still a need for research to examine the potential application of this type of design philosophy for less-frequently maintained roads or in areas where changing the road geography is not feasible.

“Egomotion” refers to the displacement of a perceiver with respect to the environment (Warren, 1990). In contrast with “locomotion” which implies the act of moving; “perceived egomotion” may be experienced while not moving (e.g., motion perception while immersed in a virtual environment), just as locomotion may be experienced without egomotion (e.g., rowing a boat against a current). In this context, “perceived egospeed” refers to the visual and proprioceptive cues that signal the speed of displacement in respect to the environment. In environments where there is weak optic flow information, safety interventions can be designed to increase the perception of egospeed by emphasizing visual cues inherent in the environment. The edge rate (ER) or “discontinuity rate” can improve a driver’s ability to differentiate between changes in velocity (Triggs, 1986) by providing repetitive cues that are viewed against static points within the optical field. Viewing ER cues are effective at increasing perceived egospeed and producing a reduction in speed both in simulated and real-world driving contexts (e.g., Denton, 1980). Drivers often believe they are driving at a slower speed than they are actually traveling after having adapted to expanding optic flow cues over a prolonged period of driving. Denton theorized that “speed illusions” using ER cues could be used to counteract the effect of negative speed adaptation. However, this same adaptation is the typical drawback of speed calming techniques (e.g., installing landscaping planters near the side of the road), in that prolonged exposure to these visual cues may overcome many of the beneficial effects (van der Horst & de Ridder, 2007). Therefore, it is important to examine the initial and prolonged effects of ER on speed perception so the mechanisms that allow these techniques to work are better understood and can be improved upon.

Interestingly, one of the conclusions of Aarts and van Schagen’s meta-analysis (2006) was that other factors, such as traffic characteristics and lane widths also affect the relationship between speed and crash frequency. So it seems that it is often a combination of speeding with dangerous situations (e.g., poorly lit roadways, high-speed differentials between traffic lanes) that lead to higher fatality rates (NHTSA, 2001). In addition, elevated workload and distraction further reduce the time available to initiate and complete a crash avoidance response, especially when drivers are traveling at faster speeds. Whereas factors such as weather and limited funding often present challenges to reducing the number of fatal crashes, an alternative method for discouraging dangerous behaviors may be to affect driver behavior through perceptual cues. Denton (1980) provides a viable example of this type of solution: painting transverse lines on the road approaching a roundabout reduced the drivers’ speeds when entering the roundabout and resulted in a net decline in crashes for that road. Examples of this effect have been reported in a range of circumstances, including approaches to curves in the real world (Shinar, Rockwell, & Malecki, 1980) as well as approaches to intersections in simulated environments (Godley et al., 2000). Thus, changes in speed behavior are possible when drivers increase the accuracy of their perception of egospeed while viewing ER cues.

Real-world driving environments contain numerous and potentially conflicting visual cues within the optic array that may interact with these speed-calming solutions. In an on-road experiment, Conchillo, Recarte, Nunes, and Ruiz (2006) found that passenger-observers made more errors in egospeed estimation during highway driving with "medium density" parallel-traveling traffic than when estimating the same egospeed with lower densities of traffic. Consistent with the framework for motion perception proposed by DeLucia (2008), observers may have been more sensitive to the proximal ER cues (i.e., vehicles) than any of the more-distant cues. Furthermore, they may have been using more direct perceptual mechanisms that emphasize immediate, unconscious (visceral) references. Therefore, traffic in surrounding lanes that is moving faster or slower than an observer not only contributes strong ER cues but may also occlude more distant cues from the driver, resulting in egospeed misperceptions.

It is unclear whether the presence of distant ER cues in the driving environment will interact with proximal ER cues to either increase or decrease perceptions of egospeed. Previous research has suggested that opposing optical flow and ER patterns in a laboratory setting may lead to an intermediate perception of egospeed (Johnson & Awe, 1994), although there is no previous evidence to support this claim within a driving context. For example, it is unknown whether passing a row of nearby buildings will have more or less of an effect on perceptions of egospeed when the driver is also passing or being passed by traffic in nearby lanes—although it is expected that the proximity of the traffic (more proximal ER cues) will lead to stronger influence in egospeed in comparison to the buildings (more distant ER cues).

Drivers may have other influences that lead to speeding such as social motivation or the personal excitement and enjoyment of traveling at faster speeds. Designing speed countermeasures which directly address these types of motivation may be difficult due to the enormous range and scope of individual differences in these motivating factors. However, focused efforts for improving a driver's perception of egospeed offer the possibility of affecting a driver's perception regardless of underlying motivation. The objective of this research is to understand how ER cues normally experienced from the roadside environment and those that are experienced from surrounding traffic lanes may affect a driver's perceived egospeed and the resulting speed choice; such insight could suggest methods that may curb excessive and unsafe speeds and reduce dangerous speed differentials in traffic. These findings should provide recommendations for measures that may lead drivers to become more aware of their egospeed and to choose more appropriate speeds. Hopefully, the appropriate limits of applying these cues may be identified so that the potential for speed adaptation towards these countermeasures can be avoided.

This chapter begins with a description of how the perceptual phenomenon was defined, including differentiation between *optic flow rate* and *edge rate* cue types. Differences between passively estimating speeds are contrasted with the effects of actively producing target speeds. This also includes a discussion of how object movement estimations can be affected by a number of perceptual factors which often lead to inaccurate judgments of self-motion. Visual cues that affect the perception of speed are then reviewed, including characteristics of visual stimuli and overall field of view. Then this chapter reviews the relationship between different types of perceptual movement cues. First, evidence is presented suggesting that global optical flow rate from self-motion has a significant effect on speed estimation. This includes the recalibration effects of prolonged exposure to global optical flow rate wherein an observer's perception of speed may change over time. Next, evidence is presented suggesting that information from ER also has a significant effect on speed estimation. Then evidence is presented suggesting that ER is a more effective cue for enabling accurate speed estimation than is optic flow rate. The conclusions and resulting research questions are discussed, including considerations that acknowledge the advantages and disadvantages of the proposed methodology; This includes framing the results within DeLucia's framework for space perception based on distance, task, and motion characteristics. Conclusions from this review are presented along with proposed research questions which attempt to fill observed gaps in the field.

Perception of Speed

This section reviews previous findings and known issues relating to speed estimation: how an observer perceives movement in the environment in general and how speed during egomotion is perceived while driving a vehicle. Egomotion describes how observers perceive their own motion through the world, specifically in terms of the displacement of the observer with respect to the environment (Warren, 1976). Egomotion represents any active or passive environmental displacement of the observer. Similar patterns are created whether the observer is walking, if the observer is being transported through the environment, or if the visual array moves around the observer. Perceived egomotion may also occur when visual cues in the optic array mimic those viewed during actual movement, for example in a virtual environment or optokinetic drum.

Perceived egomotion can be described within the ecological perspective of visual perception, which is based on the following concepts outlined by Gibson (1966). An observer receives an array of emitted and reflected light energy from the physical environment onto the eye's retina. This energy is composed of the interactions between the light with the surfaces and contours of objects within the environment. The observer can use this *ambient optic array* at each point along the stream of motion to determine the relative arrangement of surfaces, contours, and light sources. The change in this energy information over time is detectable, and the observer can use this information to determine the relative velocity and direction of egomotion as well as the motion paths that other objects take through the environment. The ambient optic array may be composed of a number of localized flow fields, each of which provides *optic flow* cues based on the movement and characteristics of the viewed cue, relative to an observer. The subtended visual angle of an object's optic flow cues will increase in size as the object moves closer to the observer. The estimated velocity of an object is related to the change in this subtended visual angle over time. Similarly, the egospeed of the observer can be determined by the relative change in speed of all optic flow cues from objects within the visual array. For example, the retinal images of approached objects will dilate at an increasing rate as the observer closes the distance to those objects.

Gibson and Crooks (1938) used these concepts to conceptualize perceived motion while traveling in a vehicle. They proposed that an observer is attuned to information in the entire visual field that is thought to be relevant to locomotion. In the case of driving, the observer is centered in the visual field as the point of reference and perceives “fields of safe travel” through the environment. According to this theory, every object within view can be thought to have clearance lines radiating from it, creating a negative valence around that obstacle and leading the observer to avoid driving near those locations. Thus the observer perceives the potential for injury as directly related to an object’s salience for avoidance. This also allows the driver to use his or her own egospeed to envision a minimum stopping distance before colliding with any other object within the environment. The observer then uses these cues to continually modify what locations in their path are to be considered safe or unsafe, relative to the location of static objects and the predicted future location of moving objects. When a driver shortens the edge of her field of safe travel to a distance near her minimum stopping distance, the driver will perceive more danger in their current set of conditions. In response to this, the driver is likely to reduce the perceived danger by altering her field of travel by moving further from the halos of avoidance or by reducing their speed to shorten their minimum stopping distance.

Gibson and Crooks also speculated that drivers limit their field of safe travel based on potential unseen obstacles, such as when approaching a blind intersection where other approaching traffic may not be visible. In this instance, the driver’s field of travel will be cut off based on clearance-lines of where potential other vehicles may arrive and enter the intersection. These fields of travel for other vehicles (directly viewed or not) are considered obstacles from which the driver must react and continually adjust their own field of safe travel. It is helpful to describe the driver’s interaction with environmental stimuli in this manner because it explains how both observed and expected cues may govern a driver's speed behavior.

In terms of detecting one's own speed, Gibson and Crooks (1938) proposed that "global flow rates" are used to detect changes in ongoing velocity. It is thought that the observer may dynamically create a weighted average of all perceived global flow rates to gather a sense for egospeed. Warren (1982) defined global optical *flow rate* (FR) in the aviation context as

$$FR = V_g / h \qquad (1)$$

where V_g is the observer's ground speed and h is the observer's altitude or eye-height (Johnson & Awe, 1994). This is a reasonable assumption because not only do ground cues fill more of the optic array when altitude is low, but objects on the ground will also extend further into the upper optic array and generate larger angles on the retina. According to Warren, global flow rate is a source of information independent of changes in surface texturing that can be used to explain egospeed judgments.

The type of motion portrayed by flow rate is dependent upon where the observer is looking in relation to the direction of travel. For example, radial flow is viewed when an observer views an object approaching head-on and the motion is expanding in nature. On the other hand, lamellar flow is observed when looking at directions other than the direction of travel and is characterized by moving-displacement cues. The weighted average of optic flow is therefore composed of many different types of motion cues representing different magnitudes of motion based on perceived speed, distance, and orientation of cues relative to the observer. Perceiving optic flow is automatic and unavoidable while someone is moving because the suggested motion results from countless elements in the entire optic array. Since the driving context essentially standardizes altitude (at least within most vehicle types), global flow rate is a valuable concept when used as a conceptualization of egospeed.

Observers are most sensitive to changes in the patterns of velocities viewed within the optical array. When cues are particularly salient they not only provide strong global optic flow cues but their velocity can be used in comparison to other moving or stationary reference objects within the array. Denton (1980) defined *edge rate* (ER) as the perceived speed of visual cues or features passing through an observer's field of view or passing some observed envelope over a given unit of time. This may be defined as

$$ER = V_g / T_g \qquad (2)$$

where T_g is the distance, on the ground, between the edges of texture elements or objects (Johnson & Awe, 1994). Edge rate can also be used to assess and control changes in velocity and is not limited to hard edges but may be brought on by any change in surface texture (Warren, 1982). Because of this, ER may be perceived not only from the changes in size or movement of an object's boundary edges on the retina, but also from any retinal patterns resulting from the perception of texture variations on the surface of that object.

The detection of ER is often complicated by the fact that sources of ER are free to move independently from the optical flow within the optic array. This generates interesting interactions between visual cues, such as when a driver is traveling at a slower speed than surrounding vehicles. In this instance, the traffic appears to be moving in the opposite relative direction from the global flow rate from the driver's viewpoint. This presents a potential conflict between proximal ER cues and the optic flow rate. This example shows how the global flow rate could confirm the driver's perception of forward motion (an expanding flow pattern) while the ER from passing vehicles (a contracting ER pattern) may give the driver the opposite impression of moving slower than the actual speed of travel. Although this is a typical set of circumstances that a driver may experience, this relationship between conflicting visual cues has not been examined in a controlled experimental setting to determine how a driver's perception of egospeed and resulting speed choice are affected.

The relationship between egomotion perception and a driver's choice of speed is also influenced by the method which the observer is using to estimate speed (i.e., estimation or production); common misperception of movement cues; and some specific perceptual cues that affect speed judgments. Each of these issues will now be discussed in turn.

Speed Estimation vs. Speed Production

To begin this discussion of egospeed perception, it is necessary to define some of the speed estimation terms used in the reviewed literature. There are two methods that may be used to have observers report their egospeed or to report the observed speed of another moving object. The first is to have the observer report a speed *estimate*. The second way is to give the participant control of a vehicle (or an experimental equivalent) and have them actively *produce* the speed. Both methods may be accomplished by having the person estimate or produce an absolute speed (e.g., 50 miles per hour) or a speed differential (ratio) relative to some reference speed (i.e., faster, slower, match). Both estimation and production methods can be used to examine the effects of elements within the roadside environment on speed perception in different ways. In speed estimation, underestimated speeds are represented as slower reported speeds by an observer. In speed production, an interaction between perception and behavior exists wherein, "an overproduction of a desired speed suggests that an observer tends to underestimate speed, as a result of which he increases speed to obtain a subjective match to what is requested" (Triggs, 1986, p. 97). Thus a (reported) underestimation of speed and an observed overproduction of speed may be considered equivalent behaviors that both result from an underestimation of egospeed.

A general pattern of underestimation and overproduction of speed has been found in a series of test track and on-road experiments (Recarte & Nunes, 1996; Conchillo et al., 2006). In a comparison between active speed production and passive speed estimation, Recarte and Nunes (1996) found that when participants were asked to produce a stated speed, they reached a speed faster than the requested (absolute) speed. However when participants were asked to estimate how fast they were traveling at that moment, they reported a slower speed than their actual speed. The magnitude of absolute error was slightly smaller during the production task, suggesting that the act of driving may give observers additional cues that assist in making more accurate judgments of egospeed, even though participants only had control over the accelerator during the production task (steering was performed by the experimenter within the vehicle). There is a possibility that giving drivers complete control over a vehicle may provide additional cues that result in more accurate egospeed estimations. To generalize these effects of ER cues on egospeed perception, it would be necessary to see if similar effects existed for a driver with complete control of the vehicle rather than acting as just an observer using the accelerator pedal.

Common Misperceptions

Accurate perceptions of egomotion and the motion of other objects within the environment are typically processed without thought or conscious awareness. This may explain why, when asked to predict simple motion paths, a large percentage of adults appear to hold surprisingly erroneous views about principles that govern the motion of physical objects. For example, predictions of motion paths for objects falling straight down (McCloskey, Washburn, & Felch, 1983; Kaiser, Proffitt, Whelan, Hecht, 1992) or objects released from a curvilinear motion (McCloskey & Kohl, 1983) often do not match what is expected from (presumably) known physics principles. These effects (what is known as "naïve physics" or "intuitive physics") may be due to misconceptions of the movement of moving objects. These misperceptions are speculated to result from years of interacting with and viewing objects moving in the environment (McCloskey, et al., 1983; Proffitt, 1999). For example, observed from the ground, a falling object released from a plane appears against a featureless frame of reference (the sky) and in proximity to a moving reference (the plane). After being released, the dropped object may appear to fall straight down or move backwards relative to the plane when in fact it is still maintaining forward momentum relative to the ground. This is the type of misperception that is often cited as naïve physics. McCloskey and colleagues (1983) proposed that multiple exposures to this sort of stimuli can teach observers to incorrectly interpret what is happening. Because drivers focus (consciously or unconsciously) on these same relationships between proximal ER cues, these errors in understanding may also help explain why drivers incorrectly estimate their egospeed.

Oftentimes these cases of naïve physics involve a misperception of the direction of motion. In other cases of naïve physics that are arguably more difficult to comprehend—such as predicting a motion vector after an object is released from curvilinear motion, as when a rock is released from a rotating sling—it has been speculated that observers' beliefs are integral components of their predictions (McCloskey & Kohl, 1983). Related to this is the phenomenon known as boundary extension (see Bertamini, Jones, Spooner, & Hecht, 2005, for a recent review of this phenomenon), wherein observers falsely remember additional details that were not present or are outside the boundaries of the visual stimuli presented. Relative to these findings, we may expect that drivers harbor misperceptions of their own speed-magnitude resulting from both the way they perceive and the way they process visual cues relating to egomotion. In this manner it seems that drivers may change their interpretation of perceived visual cues to fit preconceived expectations. Although the magnitude of each small misperception while driving may be minor, the accumulation of repeated misperception may lead to more systematic errors in perception. Furthermore, drivers may actively prioritize the importance of visual cues based on the amount of risk that is apparent in the observed circumstances. These misperceptions are not limited to observer interpretation but also have their basis in the perceptual cues themselves.

Perceptual Cues That Affect Speed Judgments

This section describes how perceived speed and changes in velocity of object-motion may be affected by observed size, expansion, contrast, and spatial frequency characteristics. Observed size and expansion cues are elements that may assist the perception of both flow rate and ER. When an object is perceived as changing in size, this signals movement on a radial trajectory in respect to the observer. The velocity of this object can be expressed as the change in subtended visual angle on the retina over time. Relative to an observer, this angle expands and increases in size as the object moves closer, or the angle contracts and decreases in size when the object recedes; these may collectively be referred to as “looming” cues. Angular rate change is affected by the object’s size such that the rate change for larger objects is much more gradual than that for smaller objects, especially at further distances.

To explain this relationship, Regan and Gray (2000) proposed that movement detection is generated from a weighted average of signals from local relative motion filters that encode changes in the angular size of (1) the entire approaching object; (2) texture elements on the surface of the object; (3) separation between adjacent texture elements on the surface of the objects; and (4) the rate of change difference between the object and a fixed reference point. During binocular perception of visual cues, the relationship between these filters loses sensitivity with increased distance, such that correct detection is relatively more accurate the closer the object is to the observer. However, the effect of self-motion should be greater for small objects because the filters are smaller for expansion and texture-expansion cues. This often leads to a size-velocity illusion where larger objects or patterns are perceived as traveling at slower speeds than smaller objects when both are traveling at the same velocity (Leibowitz, 1985; Snowden, 1997). This illusion is frequently cited as a reason why drivers are hit by trains at railroad crossings. The large size of oncoming trains, especially in comparison to most other vehicle types on the road, causes drivers to perceive them as traveling at a much slower velocity than their actual speed. Drivers are led to misperceive the amount of time remaining to safely cross over the tracks with their vehicle. In this manner the driver's perception of optic flow was compromised in that the train did not present expansion or movement cues to the degree that they were expected. Also, the train was not seen to pass or occlude relevant landmarks within the environment at a rate that provided adequate ER cues.

These considerations are highly relevant to egomotion perception. First, stationary objects will not have a profound effect on the observer's egomotion perception at far distances. Only when the object is closer to the observer will the looming cues from expansion become salient enough to have a noticeable effect from the greater influence of optical expansion information at closer distances. Since a large object can be perceived from further distances, the approach will seem to take longer than that of a smaller object which may appear suddenly and pass quite quickly. For these reasons, larger objects may appear to the observer as having a reduced speed through the environment. Conversely, smaller stationary objects in the environment will be perceived as moving past the moving observer at a faster rate than those that are larger. This will give the moving observer an exaggerated (and arguably stronger) sense of forward velocity. For these reasons, the perceived size of objects in the environment (composed of their actual size and their distance from the observer) must be considered to adequately understand the effects that these visual cues have on perceived egomotion.

Illumination level and contrast play a large role in perceiving the motion of other objects within the environment, and thus also in perceiving egomotion. Reduced illumination and related reduction in background detail has been found to produce overestimates of speed. Blakemore and Snowden (1999) found that contrast is essential to the correct and expedient perception of speed when someone is observing gradients in a small static viewing-window. Lower contrast levels significantly reduced velocity detection differences in horizontal gratings, random dot patterns, discs of varying contrast, and expanding discs drifting upward or downward. This relationship between speed and contrast is related to the concept of global optical flow in that low contrast would produce fewer visual cues on the retina. This relationship is also related to ER in that low-contrast moving objects have more indistinct edges and present an observer with weaker cues to compare against stationary objects, therefore weakening the observed ER. Both of these weakened visual cue relationships result in underestimations of speed. A real-world analog to driving while observing low contrast cues would be navigating through a thick fog. Snowden, Stimpson, and Ruddle (1998) trained drivers in a driving simulator to maintain a set speed and to replicate that speed when asked. As the contrast cues became more clouded by increasing fog, participants tended to drive at faster speeds, as is often observed during foggy conditions in real-world driving. These low contrast conditions lead to the perception of moving slower while driving and result in the need to produce a faster speed to make up for the perceived reduction in egospeed. This is also why a driver may produce faster speeds when driving through conditions where there are fewer global optic flow or ER cues, such as a rural road through the middle of plowed fields.

The pattern of objects placed within the environment or the texture patterns on the environmental objects themselves can also affect perceived egospeed. In this way, the flow of objects in the periphery can affect an observer’s perception of speed by providing strong ER cues. Distler and Bulthoff (1996) used a virtual driving environment to manipulate the texture of road surfaces in terms of contrast and spatial frequency features. Observers were shown two vehicles driving on different road surface textures. Observers were asked to make a forced-choice judgment as to which vehicle appeared to be moving faster. When observing scenes with higher contrast and higher surface texture spatial frequency, vehicles were perceived to be traveling faster. Again, the stronger flow rate (contrast) and ER (spatial frequency) cues led observers to an enhanced sense of egomotion.

The interplay of speed cues from moving objects within the environment and the observation duration of these cues also significantly influence egospeed perception. There is a taxonomy of optical flow characteristics used to measure the relationship between objects moving in the environment and objects moving in relation to an observer. These characteristics are typically quantified by having observers make predictive judgments of when objects will collide with the observer (time-to-contact, TTC) or with another object (e.g., time-to-pass, time-to-arrival). At their root, these metrics are observations of the time it takes for a single object to encounter another object within the environment. Similar to this, ER is a series of cues that are observed to pass a stable landmark within the field of view that are experienced during egomotion. It therefore follows that ER experienced during egomotion may be thought of as a series of TTC observations. For this reason, research that examines how object speed and visual angle cues affect perceptions of TTC can help explain the relationship between these visual cues and egospeed perception.

The speed and changing visual angle of approaching objects are important visual cues for making TTC judgments. Over a series of two studies, Manser and Hancock (1996) had participants observe a virtual driving environment containing a vehicle approaching on a collision course from an angle of either 0 or 40 degrees from the center of the observer's forward view. During the first experiment, this vehicle appeared at 200 m from the observer and then traveled at a constant velocity towards the observer until it disappeared at one of three distances from the observer. During a second experiment, the vehicle was viewed for a constant 8.8 seconds while it traveled at one of three speeds and disappeared at one of three distances from the observer. In both experiments, participants were to press a hand-held button at the time they thought the approaching vehicle would have reached their position. They found that participants had greater TTC accuracy when the vehicle disappeared at closer distances to the observer, when it was traveling at faster speeds, and when it approached at the head-on angle (compared to 40 degrees). These findings also suggest that observers were more accurate when the vehicle disappeared at closer distances and therefore subtended a larger visual angle and featured stronger, expanding, looming cues near the retinal center. Regan and Gray (2000) supported the findings of Manser and Hancock (1996) when they proposed that the increased effectiveness of optical expansion information at shorter distances is expected since visual sensitivity to depth cues declines with the square of distance and is poor for distances greater than 10 m.

The perceived speed and angle of visual expansion cues may explain why estimations of TTC are often progressively underestimated as actual TTC increases. Some have suggested that this TTC underestimation effect is rooted in behaviors that err on the side of safety in an attempt to increase the observer's margin of safety (Schiff & Oldak, 1990). This would allow additional time and distance for an observer to take action in a threatening situation. Others have suggested that similar underestimations of time-to-passage intervals may result from a distortion of the visual/temporal scene, increased mental processing (Kaiser & Mowafy, 1993), or as a function of modified recollection (Stetson, Fiesta, & Engleman, 2007). Regardless of the reason, the context of environmental cues has been shown to cause observers to underestimate the speed and distance of visual cues within the environment (Manser, 1997). Furthermore, this relationship between visual cues and estimated speed also suggests that experiencing enhanced optic flow (e.g., looming cues) or ER within the flow field (i.e., a series TTC cues) would increase the accuracy of egospeed perception, especially when these cues are at closer distances and moving at a faster velocity in relation to the observer.

Perception of Speed Summary

Research in perceived object speed estimation and egospeed estimation use two common methodologies, either having participants report an estimation of speed or having participants produce a target speed. Observers typically believe that they are traveling slower than they actually are traveling, which results in speed estimations that are slower than the actual speed and in the production of speeds that are faster than the target speed (Recarte & Nunes, 1996).

Perceived object motion is a result of observing the environment and accurately perceiving changes in available cues. These observations may be incorrect in relation to what is truly happening in the environment because they may be biased by the observer's own egomotion, by differing vantage points, or by personal biases. Even though learned misperceptions uncovered through research on naïve physics do not seem to negatively affect the observer's performance in the real world, there is an opportunity to modify behavior by taking advantage of these misperceptions. Specifically, there is some evidence to suggest that driver behavior may be manipulated through the distance, contrast, and speed of cues within the environment to make drivers more aware of their egospeed. This suggests that safety could be improved by adding cues to the environment that limit speed underestimation and thereby improve the accuracy of egospeed perception. Towards this end, the effects of global optical flow and ER will be discussed in relation to the perception of egospeed. This will be followed by an examination of research that contrasts that effectiveness of these two cue types on egospeed perception.

Evidence Suggesting That Global Optical Flow Rate Has an Effect on Speed Estimation

The relative speed and direction of an observer's egomotion can be determined by observing environmental (or "geographic") cues within optical flow. However, it may be that the large body of research on perception using stationary observers has limited applicability toward situations where both the observer and observed object are moving. This is primarily because radial optic flow cues from perceived movement in depth are known to affect judgments of TTC (DeLucia & Meyer, 1999; Gray, Macuga, & Regan, 2004) and therefore may also affect egomotion perception. DeLucia and Meyer came to this conclusion after a series of experiments exploring the observed TTC of two vertical bars on a computer screen while varying the presence or absence of background texture or optical flow cues depicting self-movement direction. Their findings suggest ways in which egomotion may affect judgments of TTC, as well as how static and moving objects in the environment are perceived by moving observers. First, they found that information in the background texture contributed to TTC judgments when other information from the vertical bars was unavailable (e.g., when the bars did not appear to move but the background did move). This suggests that when an observer is moving, optic flow information comprising their entire field of view can give accurate cues as to their own movement through the environment, regardless of whether information is available from specific focal cues (i.e., the bars). DeLucia and Meyer also found that participants used the relative rate of expansion of the bars to judge the TTC between them, regardless of whether optical flow cues were available. Together this evidence suggests that observers make use of optic flow cues from multiple sources within the optic array when making judgments of perceived movement.

Gray, Macuga, and Regan (2004) found substantial interactions between the egospeed generated from a radially expanding optic flow field pattern and the speed of an observed object’s motion. Observers reported an approaching object to be moving faster when an expanding (forward self-motion) field pattern was simultaneously displayed compared to when a contracting (backward self-motion) field pattern was displayed. They also found the converse to be true: a receding object appeared to move faster when a contracting field pattern was simultaneously displayed. It is clear that cues provided by optic flow in the environment have an effect on object-speed perception, and therefore also on egospeed perception. Because of this, observed object motion should be studied with the optic flow patterns generated by egomotion because the information from both is integrated when making speed judgments. In addition, observers did not actually have to be moving to be affected by these cues, since the self-motion field patterns were compelling enough to cause similar perceptual effects. Together this evidence suggests that perceived egomotion should be measured while the observer is moving or is at minimum given stimuli that replicate movement. The presence of appropriate optical flow information ensures that the interactions between multiple optic flow cues are taken into account.

The observer is physiologically attuned to using both visual and proprioceptive feedback when determining what produced speed is most appropriate. As an example of this, Sun, Lee, Campos, Chan, and Zhang (2003) used virtual reality goggles linked to the resistance level of a stationary bike to demonstrate that visual optic flow alone was sufficient to have a reliable effect on speed discrimination. Although 21 percent of riders' performance was accounted for by the influence of optical flow visual cues, 79 percent of the effect was accounted for by proprioceptive cues through the action of pedaling the bike. From this it must be conceded that the exact speed cannot be directly gleaned from flow rate alone, since this perception may be affected differently for moving and nonmoving observers. Even so, optical flow rate plays a large role during speed perception especially within the context of driving, where proprioceptive cues relating to self-motion are less readily available.

In fact, the redundancy between visual and proprioceptive feedback may play an important role in quickening speed perception. This redundancy creates a feedback loop whereby errors in proprioceptive judgments are identified using the more expedient visual cues. Proffitt, Stefanucci, Banton, and Epstein (2003) found that when an observer of a virtual scene (on a computer screen) wore a heavy backpack, they perceived distances as longer than they actually were. Mohler, Thompson, Creem-Regehr, Pick, and Warren (2007) also studied the relationship between these two types of cue in a series of experiments within a virtual walking environment. Participants walked on a large treadmill-type moving floor (the “treadport”) while observing a 180-degrees horizontal forward field of view. The environment depicted an “endless hallway” featuring an occasional doorway, pop machine, or perpendicular hallway. To increase the salience of these optic flow cues, participants were given the task of noting aloud the direction of doors (i.e., right or left) that they walked past at the moment they walked past them. The experimenters varied the speed of the environmental optic flow to be slower (half speed), visually same, or faster (twice the speed) than the speed of the moving floor. During the first experiment, the speed of the floor was gradually increased from 1.0 m/s to 2.75 m/s at a rate of 0.1 m/s^2 so that the participant would have to switch from a walking gait to a running gait (a “walk-run” transition). Then the moving floor gradually decreased in speed back to 1.0 m/s so that participants would switch back to a walking gait (a “run-walk” transition). Mohler and colleagues found that when the optic flow was slower than the walking speed, the participant’s gait transition occurred later (i.e., at a faster walking speed) than during the visually same optic flow condition. When the optic flow was faster than the walking speed, the participant’s gait transition occurred sooner (i.e., at a slower walking speed), and similar effects were found for both the walk-run and run-walk transitions. This demonstrates that optic flow cues have a direct influence on proprioceptive performance such that walkers modified their gait transitions to better-match their perceived egospeed.

In a second experiment using the treadport, Mohler and colleagues instructed participants to walk at a comfortable speed while the environmental optic flow was presented at half as fast, visually same, or twice as fast as the speed of the floor. This allowed the experimenters to measure the participants’ comfortable-walking speed choice based on the visual cues within the virtual world. When the optic flow was slower than the floor speed, participants chose faster speeds than when the optic flow matched the floor speed; conversely, when the optic flow was faster, participants chose slower speeds. Here, the optic flow information had a direct effect on speed estimation and resulted in modified speed production. Specifically, when egospeed was perceived to be slower it resulted in the participant producing a faster speed, and vice versa.

Longer exposures to optic flow cues may cause a driver to become acclimated to a particular speed by gradually influencing their perception of speed cues over time. This “recalibration” dynamically adjusts the observer’s baseline perception of visual cues, which may affect how visual cues and resulting egospeed are perceived. This adjustment provides us with another way to measure the effects of optic flow on speed perception. In another set of experiments, Mohler, Thompson, Creem-Regehr, Willemsen, Pick, and

Rieser (2007) found this type of recalibration after removing faster or slower optic flow cues in a similar endless hallway used during the previous experiments (Mohler, Thompson, Creem-Regehr, Pick, & Warren, 2007). Participants walked on the treadport for ten minutes with the floor moving at a rate of 1.0 m/s to adapt to one of three visual conditions: an optic flow that was visually twice as fast, the same, or half the speed as the floor was moving. After the adaptation period, participants were taken off the treadport, presented a target on the floor and then blindfolded. Participants were asked to walk to one of three target distances without any visual assistance. Walking distances from the target were compared to pre-adaptation performance. Participants who saw the slower optic flow overshot the target by 11 percent and participants who saw the faster optic flow undershot the target by 6 percent on average. Similar to the previous study, optic flow cues modified how participants perceived the length of their own gait. However they were no longer being exposed to the optic flow cues when they made this judgment, signifying that their perception had been recalibrated.

These results also suggest that a prolonged exposure to optic flow clues might have a similar effect on a driver’s perception of visual cues and the resulting perception of egospeed. The recalibration effect can often be seen after driving long distances on fast highways: a driver exiting from a faster roadway onto a slower roadway often perceives their speed is slower than it actually is (Matthews, 1978). Denton (1980) called this recalibration effect a negative speed adaptation.

The use of simulated driving environments has aided researchers in identifying what elements in the optic array have a more significant influence on negative speed adaptation. Gray and Regan (2000) used a virtual environment to show that cues from road texture can be significantly influential in combating recalibration effects. Viewing and adapting to a naturalistic, expanding optic flow pattern led to faster produced speeds and shorter critical time headway values (i.e., the time until the front bumper of the participant's car reaches the location on the roadway currently occupied by a lead vehicle), especially when a road texture was present. The opposite effect occurred when the adapted optic flow pattern was contracting in nature, resulting in longer critical time headways. This latter effect is interesting in that it shows that when two cues are viewed simultaneously and are perceived as moving in opposite directions (e.g., expansion from optic flow and adapted contraction), there appears to be a subtractive effect of one cue from the other on perceived egospeed.

Collectively, these results suggest that if the effect of recalibration can be reduced during simulated walking and driving situations it is also possible to reduce the recalibration effect for drivers through the intelligent enhancement of optic flow cues on the road and roadside. During typical driving situations, drivers expect a congruent set of visual cues for accurately judging and modulating speed performance. Not only is the optical flow important to speed perception, but so are cues that move separately from the optic flow pattern and can be compared to static objects within the driver's field of view. For this reason, we must also consider the effects of ER cues that capitalize on salient borders and texture elements.

Evidence Suggesting That Edge Rate Has a Significant Effect on Speed Estimation

When the movement of cues within the optic array is compared with a static cue, ER essentially applies a measurement of periodicity to elements of the optic flow array. In doing this, ER distinguishes itself as a distinct cue within the optic array that is dependent upon changes in surface texture or surface edges, while optic flow in general relies on a collection of expanding/contracting points within the array. Work in the field of aviation simulation has explored ER, defined as the local discontinuity frequency across a fixed point in the observer's field of view (Warren, 1982). Aviators have been found to rely on ER cues when they make continuous comparisons of distant moving edges in their field of view to static points such as the frame of the cockpit window or points on the aircraft body. Drivers also have the opportunity to make this type of comparison when passing roadside objects or other vehicles. Because drivers experience ER at close distances and the resulting rates are more likely to be at a higher frequency, it is expected that ER would have a stronger influence on drivers' egospeed perception, as it has been shown to improve the accuracy of TTC judgments (Manser & Hancock, 1996).

This effect may be explained by the relationship between the size of an object and how fast it is perceived to be moving (Snowden, 1997; a review of multiple findings in Triggs, 1986). Smaller objects and patterns tend to be perceived as moving faster than larger objects, although this relationship can be affected by comparisons to other cues within the environment. At the basis of this issue are differences in detecting motion-in-depth signals between approaching or receding objects. In a series of studies examining the speed perception of moving dot patterns, Snowden (1997) found that a larger pattern appeared to move more slowly than a smaller pattern moving at the same speed when both had a constant size and density. A second experiment found that this effect was not due to an averaging function from a larger portion of the pattern invading the peripheral retina. His hypothesis then was that the edges of the pattern in larger stimuli are further from the center of the retina, thus proving less effective for assisting in judgments of speed. He tested this by overlaying stationary dots over the pattern to act as points of reference, which is essentially what happens during perception of ER cues. He found that the stationary points added to the apparent speed of the moving patterns, with the smaller pattern still being perceived as moving faster than the larger pattern. It appears that the smaller pattern made it easier for observers to compare the moving edges to the stable points within the optic array, providing the observer with additional information relating to speed. This is not to downplay the role of the periphery in speed perception, as the review by Triggs (1986) concluded that distinct peripheral vision cues can produce accurate and less variable estimates of speed. In fact, as egospeed increases the number of discernible cues within the periphery decreases as peripheral cues blur, leading to ER from the visual pattern viewed through the frame of a vehicle’s window. Therefore, ER may affect speed perception when cues are perceived actively (i.e., indirect perceptual mechanisms) in central vision or when perceived unconsciously (i.e., direct perceptual mechanisms) through peripheral cues, similar to DeLucia’s proposed framework for space perception (2008).

Driving involves many instances wherein speed is increased and peripheral cues are blurred to the point of activating direct mechanisms of ER cue perception. A number of studies in virtual driving environments have found a decrease in speed production resulting from the presence of ER in texture patterns (Manser & Hancock, 2007) or objects such as trees, guardrails, curbs, (van der Horst & de Ridder, 2007), buildings, oncoming vehicles, highway furniture, or billboards (Horberry, Anderson, Regan, Triggs, & Brown, 2006). In a real-world observation of stopping behavior, Chihak (2007) observed drivers approaching intersections in wooded (stronger ER cues) and less visually-populated (weaker ER cues) environments. His results indicated that in areas with sparse visual cues, drivers adopted the more conservative stopping technique of decelerating earlier. This suggests that drivers may depend on ER cues from the environment to make safe stopping maneuvers, similar to making a series of time-to-pass judgments. When these cues are not available during sparsely populated approaches, drivers compensate for the perceived increased risk by decreasing their driving speed at a further distance from the intersection. Therefore, a higher level of caution was required to accurately stop their vehicles in cases where it was more difficult to accurately perceive their egospeed in the presence of weak ER cues.

It is apparent that ER cues are significant and useful for making accurate estimations of speed or egospeed. While moving in a vehicle, observers may experience continual global optic flow and any number of different ER cues at the same time. Because these two cue types operate separately, there may be instances when simultaneously perceived optic flow and ER cues are not congruent; for example, optic flow presents expanding cues while traffic presents contracting cues. Therefore it is important to consider whether one type of cue may have a stronger effect on speed estimation or if the effects of optic flow and ER may interact to produce another type of influential cue.

Evidence Suggesting That Edge Rate May Have a Stronger Effect on Speed Estimation than Global Optic Flow Rate

Both global optic flow rate and ER play significant roles in egomotion perception. Optical flow rate involves cues drawn from the entire visual field independent of changes in surface texture and combines the cues into a coherent awareness of self-movement. The change in position of all these points within the field, including motion-in-depth cues such as looming, is sufficient for perceiving the direction of egomotion. Edge rate is comprised of specific visual cues within the optic array, including surface texture features, which are compared to stationary references. Although both cue types assist an observer in egomotion judgments, optical flow enhances the driver's perception of egomotion direction, while ER enhances the observer's perception of egospeed and egospeed changes (Triggs, 1986; Owen, Wolpert, & Warren, 1984).

A number of experiments have compared the effects of optical flow and ER cues on their ability to assist observers in making judgments of egomotion. Larish and Flach (1990) examined reported-speed from egomotion cues after observing a desktop simulation. Over two experiments, they compared an ER pattern to an optic flow pattern by asking participants to report the observed speed on a relative scale from 1 to 100. In the first experiment, ER was represented as a grid texture consisting of regularly spaced rectangles, randomly colored in earth tones and stretching in front of the viewer towards the horizon as a road would. Optical flow was depicted as a white dot texture on a black field of view, where each dot was placed at the corresponding intersection-point of the squares from the ER condition. There were five equivalent measured speeds for the two types of cues: edge rate was measured in the number of edges passing the bottom of the screen per second, and optic flow was measured in meters per second. Larish and Flach found that participants' estimates of speed increased as the ER increased and optical flow (speed) increased, although ER accounted for the greatest proportion of variance for all participants. In a second study, the authors used the same methodology but changed the optical flow depiction so that it appeared as a random pattern of dots. Also, depth cues were added to the displays by increasing the intensity of points and the texture density within the scene as the points approached the observer. Finally, the experimenters added a secondary Sternberg test to ensure that participants were not counting the frequency of ER cues to determine relative speeds. The results confirmed their findings from the first experiment, further suggesting that ER cues played a stronger role in improving the accuracy of egospeed perception during simulated egomotion.

Owen et al. (1984) presented observers with a series of situations depicting movement down a virtual runway. The aviation simulator used a wraparound projection to display a runway environment comprising regularly textured road-surface polygons. Optical flow was varied by manipulating the speed of the movement over the runway on the projected display. Edge rate was varied by manipulating the presentation of orthogonal pavement edges. The display conditions presented six flow rates, three edge rates, and three levels of acceleration over three different durations to determine if participants were sensitive to acceleration of optic flow, ER, and the combination of both during different durations of exposure. Participants were presented each condition alone and their task was to report whether the observed patterns were moving at a constant rate or accelerating. Overall, acceleration was detected during both ER and flow rate conditions, although observers were more accurate at detecting acceleration when the ER cues were present. Observers' responses suggested that when both ER and flow rate were consistent, the effect of acceleration detection was additive. In terms of task duration, ER benefited from longer exposures in that accuracy was increased relative to exposure to the scene (as was also concluded by Triggs, 1986). This effect was strengthened when both optic flow and ER cues were presented together. It seems that both optical flow and ER cues helped observers determine if a first-person viewed scene was accelerating or moving at a stable speed, although ER acceleration cues proved more helpful than those of optical flow.

These findings suggest that drivers may benefit more from viewing ER cues than from viewing optical flow alone. It was also suggested that a longer exposure to ER cues might increase their overall effectiveness at improving egospeed perception. In an experiment using the same methodology and visual cues as Owen et al. (1984), Johnson and Awe (1994) concluded that ER information relating to ground speed was less affected by adaptation and could therefore be considered a more reliable predictor of egospeed perception. However, in the context of driving, van der Horst and de Ridder (2007) found that the speed-reducing effects from novel ER information may decay in potency as the driver becomes accustomed to the cue over time. In this driving simulation study, drivers reduced their speeds only when approaching and at their initial passing of barriers and guard rails on the roadside; with subsequent exposures their speeds slowly increased upwards towards previous speeds. This suggests that ER cues lose their effectiveness over a prolonged exposure due to the effects of recalibration (Gray & Regan, 2000; Mohler, Thompson, Creem-Regehr, Willemsen, Pick, & Rieser, 2007). Although it would not take long for a driver to perceive ER cues within the environment, it is unclear how long these effects remain before a driver would recalibrate to these cues. In addition, most research on the topic has not examined the effects of adaptation to ER cues within the context of driving while providing observers full control of the vehicle.

Speed Estimation Considerations

Some of the initial and often-cited studies in speed perception were completed by Denton (1976, 1980). Denton had participants accelerate to a proposed speed in a “Dynamic Visual Field Generator” (DVFG) that produced visual-field patterns for a stationary observer. The DVFG presented observers a projected pattern of lateral lines, the speed of which was controlled by the participant’s throttle control. Observers were asked to accelerate the pattern to a starting speed and later asked to either double or to reduce by half their current speed. This method of using speed ratios allowed Denton to measure relative differences between conditions that depend upon the degree of speed change perceived necessary to reach each target speed. Having the participant produce a target speed allowed Denton to examine how the environment affected their speed choice. Having the participant produce a reduced or increased (ratio) speed allowed Denton to examine how cues in the environment or the driver’s recalibration to the situation may have affected speed choice over time. Adapting this methodology to a modern driving simulator, drivers could be asked to maintain a comfortable speed without the benefit of seeing the speedometer. Within this context, asking drivers to change their speed by a ratio may be a more tangible goal. This also has the experimental advantage of not having to calibrate participants to drive at any particular speed as long as the focus is on within-subject comparisons of comfortable speed choice. For these reasons, a “Modified Ratio Method” (MRM) of eliciting target-ratio speeds (described in the Outline of Experiments section, below) was applied and evaluated for the research questions within this set of experiments.

Denton (1980) showed that a speed illusion could be used to counteract the effect of negative speed adaptation (the recalibration-type effect of thinking one is driving slower than they are actually traveling after having calibrated to visual stimuli during a prolonged period of driving). His findings found a strong relationship between transverse line cues (perpendicular lines painted all the way across a road lane) at the approach to a roundabout with reduced speeds, similar to his findings in the DVFG. Godley, Triggs, and Fildes (2000) also found that similar transverse cues observed in a driver’s peripheral vision (short lines protruding into the lane from the lane boundaries), were also sufficient to produce reductions in speed for both speed adapted and non-adapted drivers. Shinar et al. (1980) also found a reduction in crash rate when they added this type of road striping to the exit from highways onto lower speed roads, showing a direct relationship between these speed countermeasures and crash reductions.

There have been numerous other attempts to apply visual cues for the purpose of deceiving drivers into thinking that they are driving too fast for the current conditions (Denton, 1980; Scallen & Carmody, 1999; Godley et al., 2000; Corkle & Giese, 2002).

These experiments found that driver-speed reduction was possible by increasing the salience of visual cues and thereby also increasing a driver's estimation of egospeed, resulting in a reduction in produced speed. That said, the presence of speed countermeasures may lead drivers to adapt in a way that reduces the safety benefit in other ways, sometimes referred to as "risk compensation" (Lewis-Evans & Charlton, 2006). Some examples of this include when a driver shortens her time-headway after the introduction of anti-lock brakes; increases average speed on a road segment that has improved lighting conditions; or shows increased speed or less cautious lateral performance once lane width is increased. Shinar and colleagues suggest that, with experience, drivers may overcome this effect by taking advantage of optical flow rate alone, as also suggested by the simulated driving results of van der Horst and de Ridder (2007). Therefore it is important to examine the long-term effects of ER on speed perception. These factors are why this set of experiments considered the effects of ER cues on speed performance over relatively long periods of time.

The environment in which speed estimations and productions are collected may also play a large role in perceptions of egomotion. In an on-road experiment, Conchillo et al. (2006) had participants sit as passengers and estimate their speeds while on a closed track, a secondary road, and the highway. While driving on the slower closed track and the slower-speed secondary road (both of which included only driving at slower speeds), they found that errors were reduced as speed increased. However, for the faster highway driving, including while traveling at speeds that matched those of the closed track and secondary roads, the opposite pattern emerged wherein observers' magnitude of errors increased as speed increased. The researchers speculated that this may have been due to "medium density" parallel traffic flow since this was typical during highway conditions, while the other two roadway types experienced "low density" traffic flow parallel to their own point of view. It is also possible that ER cues may be hidden by ambient traffic during highway driving. This may suggest that the observers were more sensitive to the ER from proximal objects (i.e., vehicles) than ER from cues further away (i.e., roadside objects or global optic flow cues). These results also follow from those of Snowden (1997) that suggested paired ER cues (e.g., expanding optic flow presented with contracting ER cues from traffic) would cause modifications in object speed and egospeed perception. Conchillo et al. recommended that future studies of speed estimation be conducted on different types of roads, different traffic densities, and under different weather conditions. For these reasons, this set of experiments will examine the effects of traffic ER cues both alone and when other ER cues (roadside buildings) are visible within the environment.

Measuring this type of effect would be a difficult goal for a real-world experiment, especially in the case of having replicable driving conditions. A driving simulator methodology provides an easy way to implement the varying and numerous ER cues necessary for these conditions. A simulator can also model ambient traffic behaviors that would be nearly impossible to coordinate in a real-world setting. In regards to the issue of ecological validity and its importance in measuring speed perception, Hancock and Manser (1997) argued that ecological validity should be emphasized as a way to make more accurate observations of speed estimates. Taking advantage of ecologically realistic virtual worlds and situations also has the advantage of increasing the validity and applicability of the results to real-world situations. No virtual environment can claim to completely reproduce the visual information or proprioceptive cues found in a real-world setting. For example, judgments of distance are often compressed as compared to real-world estimates (Witmer & Sadowski, 1998) and perceived distances have an effect on speed estimation. Since the motion quality in virtual environments is not perfectly accurate, results from simulator studies should be used to compare relative differences between conditions tested within a single simulated environment rather than comparing results between two simulators. Significant findings in virtual environments can be applied to real-world settings by taking into account that the direction of an effect (i.e. relative validity) exists rather than the actual performance seen in the virtual world. This relationship between simulated and real-world environments for speed and lane position performance exists for tunnel environments (Tornros, 1998), curve environments, and during stopping maneuvers (Godley, Triggs, & Fildes, 2002)—namely, that relative (but not absolute) behavioral patterns exist between virtual and real-world behaviors. In this way, a speed estimation methodology would be sufficient for determining the effects of proximal ER cues (e.g., traffic speed direction ER cues) in comparison to distant ER cues (e.g., "geographic" building ER cues). However in this study a more active methodology within a virtual driving environment was preferred so observations could be made of the integration of multiple sensory modalities into speed judgments.

Direct vs. Indirect Perceptual Mechanisms

It is helpful to consider how ER cues are perceived based on the circumstances in which egospeed judgments are made. In a synthesis of neuro-psychological, neuroimaging, and behavioral research findings, DeLucia (2008) has proposed a framework to explain the critical roles of distance, task, and motion during space perception. She proposes that the interaction between these dimensions determines how the observer perceives object-motion within the environment. The distance at which objects are viewed determines how visual cues are perceived, what actions are possible, and what area of the brain processes the information (see the Perceptual Cues That Affect Speed Judgments subsection in the Perception of Speed section for more details). Threshold limitations of the visual system result in impoverished information at further viewing distances, such that binocular disparity and motion perspective are more effective within 30 m of an observer (Cutting & Vishton, 1995). In fact, optical expansion information is more effective at closer distances (Manser & Hancock, 1996) while the visual sensitivity to depth cues declines with the square of distance and is poor for distances greater than 10 m (Regan & Gray, 2000). Gibson (1966) proposed that, when there is less information to make perceptual judgments, inferential processes assist the observer in determining the motion path of the observed cues. Furthermore, motion cues are more effective when the object and observer are in motion compared to when both are static due to the additional optic flow information that is available while moving (e.g., looming and depth cues).

Based on this evidence and Goodale and Milner’s (2005) model of two visual systems, DeLucia contended that brain mechanisms related to the perception of near space (dorsal pathway) rely on absolute information to generate observer-based, or egocentric, judgments that serve visually guided actions. On the other hand, mechanisms related to the perception of far space (ventral pathway) rely on relative information to generate scene-based, or allocentric, judgments that serve conscious perceptual judgments. As a result of this, perception of close space works in real time as an unconscious process while perception of far space is consciously guided by awareness and may be affected by remembered cues. For a driver, this model of motion perception suggests that proximal cues will not only influence egospeed by virtue of having stronger visual cues but also because they must be related to more direct, unconscious responses to the immediate environmental circumstances. In contrast, cues further from the driver necessitate that additional attention be mediated by mental processes to make accurate assessments of a cue's relevance to egospeed perception. Cues further from the driver are also judged more often against other objects within the environment which may affect the accuracy of judgments, depending upon whether the other objects are in motion.

When an observer is not moving and observes stationary objects far away, this will typify the use of *indirect perceptual mechanisms*. This "classical" theory of perception assumes that the information from the world is naturally ambiguous and therefore needs interpretation to be meaningful (e.g., Helmholtz's rule relating to matching patterns of sensations from events, as cited by DeLucia). Within this report, indirect perceptual processes are those that involve conscious, higher-level processing whereby a driver has the ability to mitigate their sensations by using conscious, cognitive mechanisms (e.g., inferences, memories, schemata). On the other hand, when an observer is moving fast and observing objects at a near distance, this will result in unconscious perceptual judgments that typify *direct perceptual mechanisms* (e.g., Gibson, 1966). In these instances the optic array provides the observer with the properties and behavior of that environment such that accurate reactions are possible without high-level processing.

Within this report, direct perceptual processes are those that are more visceral (immediate and unconscious) in nature whereby a driver is not able or does not have time to mitigate their sensations by using other cognitive mechanisms.

Most perceptual situations, including driving, lie on a continuum between these two sets of situations, whereby observers must rely on a combination of direct and indirect perceptual mechanisms. By doing so, drivers take advantage of the distance, task, and motion cues in a way that is most useful at that moment, including switching their perceptual emphasis between direct and indirect mechanisms as the circumstances change. Note that the distinction between direct and indirect mechanisms are not necessarily Gibsonian or classical distinctions but are used to distinguish between more direct (visceral: immediate and unconscious) and more indirect (cognitively-mediated) aspects of motion perception (respectively) within this report.

According to this framework, drivers may switch between direct and indirect perceptual mechanisms while approaching an object from a far distance: indirect perceptual mechanisms will be favored while observing the optical size of the distant object, while direct perceptual mechanisms such as changes in looming cues and tau play a larger role when the object draws closer. Therefore objects on the roadside may allow the driver to take advantage of both direct and indirect perceptual mechanisms when they approach from a far distance. This combination of visceral and cognitively-mediated perceptual cues should assist the driver in perceiving accurate egospeed. On the other hand, egospeed judgments in the presence of closer objects such as ambient traffic may only elicit perceptual cues from direct mechanisms. This should have a strong, direct perceptual effect on the visceral perceptual comparisons, leading to the driver producing speeds similar to those of the ambient traffic.

The right combination of both geographic ER cues and traffic ER cues may provide an opportunity to facilitate the most accurate judgments of egospeed by activating both direct and indirect perceptual mechanisms. On the other hand, a combination of geographic and traffic ER cues (e.g., if one cue provides expanding ER while another provides contracting ER) could lead to misinformed judgments of egospeed. For example, Hesketh and Godley (2002) found that having one type of cue in the environment (buildings or vehicles) increased the accuracy of time-to-contact estimations, especially when the observer was moving towards a stationary target. Observers had moderate accuracy when both the observer and target vehicle were moving (but a level of accuracy higher than when observing an approaching vehicle while not moving). These findings suggest that a driver experiencing traffic ER cues (especially traffic traveling at a different speed than the observer) will make less accurate estimations of egospeed than a driver experiencing static, roadside ER cues. As for an instance where both roadside and traffic ER are present, Hesketh and Godley found that providing both environmental and traffic cues to the driver did not necessarily make drivers more accurate at estimating time to contact. However, there is no previous evidence to suggest whether drivers will effectively integrate the two sources of ER, or if traffic moving faster or slower than the driver will make a difference in the accuracy of their egospeed perception.

Perceived Risk

Finally, perceived risk is a factor that may be considered during the process of converting egospeed estimations into produced target speeds. Whether an egospeed judgment is being made with direct or indirect perceptual mechanisms, the resulting assessment is made within the contextual constraints of an individual's perceived comfort level. Perceived risk may have an inherent influence on produced speed and may affect egospeed perception differently over time based on each driver's experience with different sets of visual cues. Therefore, perceived risk should be considered a motivational factor that affects produced speed choice by interpreting estimated speed within the current context (e.g., close objects may be perceived to be of a greater risk when driving at a faster speed compared to driving at a slower speed).

However, risk is a natural part of speed production decisions and it would be difficult to accurately separate the effects of perceived risk from the effects of egospeed estimation within the current methodology. It was recognized that the perceived risk may have been different during each of the separate ER cue types (geographic ER in Experiment 1, traffic speed direction ER in Experiment 2, and ER cue pairs in Experiment 3). Because of this, efforts were taken to mitigate the potential effect of risk on produced speed within each experiment. First, the focus of this research was not on the absolute assessment of produced speeds, but instead a within-subjects methodology was used so that differences in perceived risk over participants would be minimized. Second, as opposed to requiring drivers to produce an absolute speed (e.g., "drive at 50 miles per hour") that they may not normally be comfortable producing, it was important to task drives with driving at a relative speed (e.g., “drive at a speed you feel comfortable maintaining”). The intention of this was to reduce the potential of introducing additional risk perceived by the driver during the experiment. Therefore, drivers were asked to produce speeds that were egocentrically comfortable to them to reduce the potential for heightened perceptions of risk from producing an uncomfortably high or low absolute speed. Also, drivers were acclimated to the vehicle and environmental conditions before the experimental driving sessions so that these factors did not add to their perceived risk level due to additional anxiety and performance variability. Therefore, these experiments were designed so that the residual effect of risk would be equitable across conditions and similar to the amount of risk that a driver would experience in the real world. Though the author recognizes that perceived risk may have had an influence on produced speed performance, results will be described in terms of how the different visual cues affect egospeed estimation.

Conclusions and Research Questions

Optical flow and ER cues are important for the estimation of perceived egospeed. These cues affect observers’ perceptions of speed in the same way (i.e., they are perceived and processed similarly) whether they are observed naturally in the environment or whether they are observed from artificial cues designed to affect speed perception. While optic flow rate may be more quickly realized by the observer, ER information may be a more accurate and stable cue for the purpose of perceiving egospeed. The interaction between these two cue types may have a stronger effect on perceived egomotion overall, although little research exists on the effects of opposing cues on a driver's perception of egospeed within an ecologically valid driving context. Understanding this complex relationship would help to improve the effectiveness of speed reduction interventions, especially when traffic is present in the lanes surrounding the driver. Therefore, examining the effects of these different cue types could facilitate direct improvements in traffic safety interventions.

Three research questions have emerged from this review of literature and will be examined in a virtual driving environment with realistic controls: (1) Will speed production be affected by the presence of ER cues from objects at near and far distances from the road? (2) Will speed production be affected by ER cues moving at similar, faster, or slower speeds than the observer's speed (e.g., vehicles traveling in adjacent lanes)? (3) Will differences in speed production found while experiencing geographic or traffic ER change when they are experienced at the same time? Specifically, will these two cue types have additive or subtractive effects when the separate ER types are in agreement with or opposition to each other, respectively? To address the issue of adaptation to ER cues, these questions will be explored using a novel methodology (the Modified Ratio Methodology) which examined performance during short and prolonged exposures.

OUTLINE OF EXPERIMENTS

In the past, these research questions were addressed through passive methods such as having an observer watch a video of a road scene or ride as a passenger and estimate how fast they were traveling (or other related estimation measures, e.g., TTC). These methods remove the observer from their active role as a driver and may produce results that are not congruent with perceptions that drivers typically have while producing a particular speed. We can also assume a degree of error in estimates given during previous studies where participants were not presented an adequate representation of egomotion. This is especially the case when asked to give speed estimations or to produce speeds in static environments or ones that do not include peripheral cues. Virtual environments provide a context to examine speed production in driving situations that would be dangerous or impossible to accomplish in the real world. A virtual environment with realistic visual, motion, and auditory cues was expected to provide participants with an appropriate test situation for the following methodology without placing them or other motorists in danger.

Apparatus: Driving Simulator

Participants drove the HumanFIRST Program advanced driving simulator at the University of Minnesota (Figure 1). This was an immersive motion-base driving environment operating SCANeR II simulation software (http://www.oktal.fr). The HumanFIRST simulator was linked to a full-sized 2002 Saturn SC1 vehicle with a vehicle dynamics model operating at 100 Hz and a data sampling rate of 20 Hz. The visual images consisted of a realistic virtual roadway environment projected using six Epson 7600 projectors (1024 x 768, 2200 lumens, 400:1 contrast, 24-bit color) at a frame rate greater than 30 Hz projecting at 1.96 arc-minutes per pixel resolution. This driving simulator provides auditory and haptic feedback using a number of coordinated systems. A 3-D audio system included four speakers placed around the car's exterior near the base of the intermediate and outer screen-panels. Each speaker received independent inputs from the simulator's 3-D sound generation system. These speakers were also used to deliver recorded instructions to the participants. Low frequency audio (engine noise) was delivered using a ten-inch subwoofer placed inside the simulator vehicle's engine compartment.

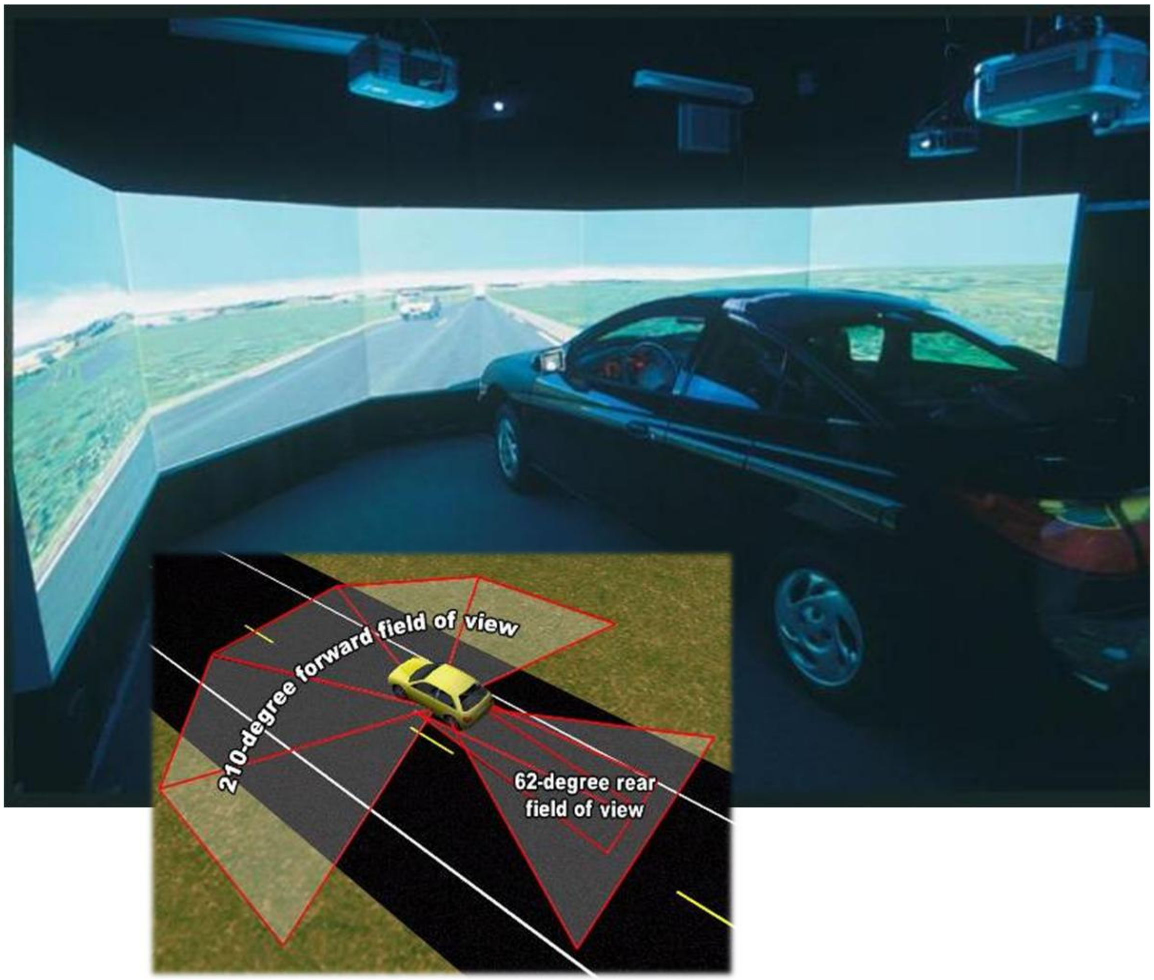


Figure 1. HumanFIRST Program driving simulator with insert diagram of forward and rear fields of view.

The forward scene comprises a five-channel 210-degree field of view on white-painted flat panels, each 1.43 m (4.70 ft) high and 2 m (6.54 ft) wide. The front screen was centered on the line of sight of a simulator driver looking straight ahead through the windshield and down the road. Two intermediate screens flanked the center screen on both sides, positioned at 138-degree angles to the front screen. On the outer edge of each intermediate screen was another panel positioned at a 138-degree angle relative to the intermediate panels. Figure 2A presents a diagram of the five channels that compose the

210-degree forward field of view. Note that images on the left-most and right-most panels were in the driver's peripheral vision, such that the left and right-most edges of the objects on the screens are shown at 90-degree angles from the participant's viewpoint. Figure 2B presents a 2-dimensional representation that will be used throughout this report to depict the 3-dimensional 210-degree forward field of view, for simplicity. The rear view was projected onto a 3.05 m (10 ft) high by 2.13 m (7 ft) wide display screen behind the simulator vehicle and was visible to the participant from the rear view mirror and through the back windshield (see insert of Figure 1). Rearview mirror housings contained 7-inch LCD monitors which displayed their portion of the virtual world, adjusted to match the view of standard side mirrors.

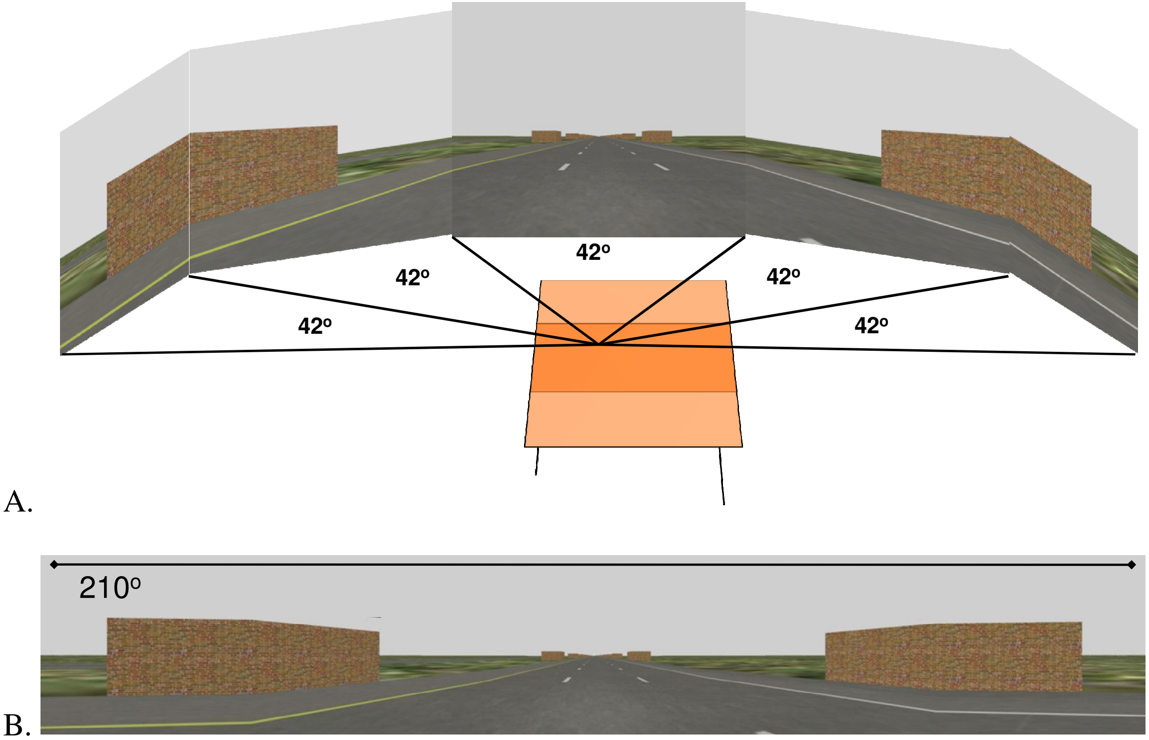


Figure 2. A) Diagram of the driver's 210-degree forward field of view in the simulator, and B) a 2-dimensional composite representation of the driver's view.

The controls of the simulator vehicle contained sensors to collect steering, accelerator, brake, transmission control, and in-vehicle control (e.g., turn signal) information. The driver's accelerator pedal, brake pedal, and steering wheel behavior were also recorded. The vehicle's position and current speed on the virtual roadway were recorded at a rate of 20 Hz. The steering wheel and brake pedals were equipped with force feedback mechanisms to provide an ecological driving experience. A servomotor was attached to each of the simulator vehicle's suspension arms to provide a partial-motion base (roll, pitch, z-axis). A small, low-frequency bass shaker was attached to the frame of the vehicle to provide additional low-frequency vibration. For all drivers the speedometer was covered so that participants could not associate visual, haptic, or auditory cues with the vehicle's "actual" speed within the virtual environment.

The driving environment consisted of a straight, six-lane divided highway with three lanes going each direction (see Figure 3). The entire road width in one direction was 18.3 m (60 ft) wide which included an emergency lane on each side of the road. The road had a slight curvature (1 m of lateral deviation per longitudinal 1 km driven) which was intended to increase the steering effort involved in maintaining a steady lane position. A similar technique was used to make a driving task more engaging while also decreasing boredom and fatigue by requiring active steering responses (van der Horst & de Ridder, 2007). Anecdotal reports from participants in the current experiment suggested that drivers were not aware that the road was curved, only that the simulated vehicle took more effort to maintain lane position than they would have expected it would.

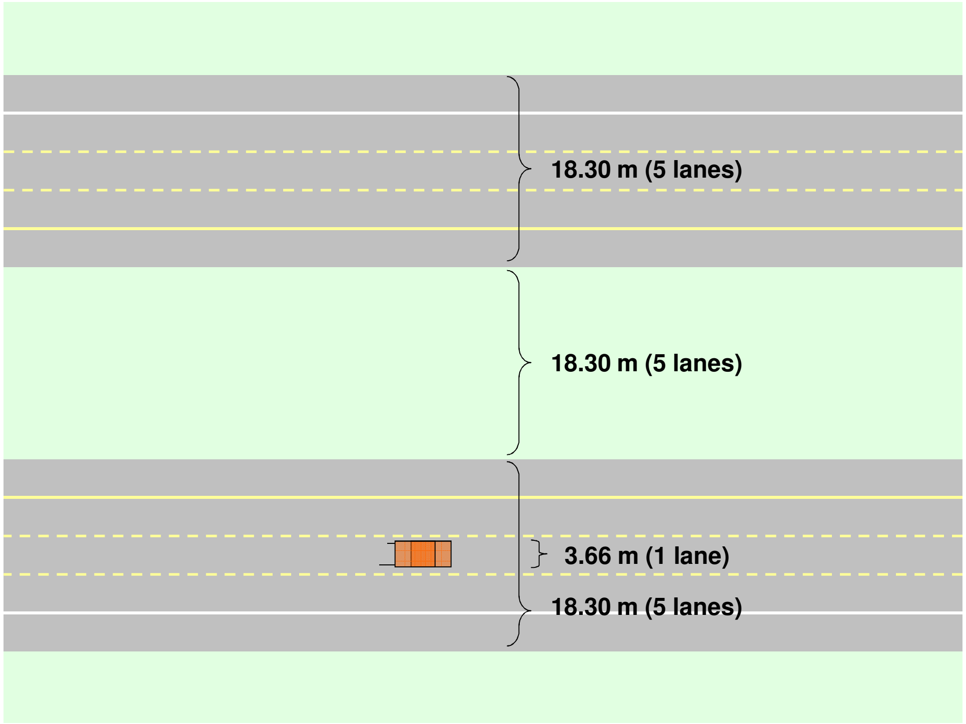


Figure 3. Depiction of the driving environment.

Participant Replacements Due to Reaching Simulator Maximum Speed

Because there was an interaction between the driver's awareness of speed and an inherent limitation in simulator speed, it was necessary to replace some participant data. The simulated vehicle had a "governed" top speed of 142 km/h (90 mph). This condition could only be achieved by pressing the accelerator as far down as is possible for about a minute. At higher speeds it is more difficult to discern differences in speed, and if the driver was allowed to continue accelerating they might never stop accelerating. Because participants were not able to view the speedometer, when they reached this maximum speed they were unaware that they had reached a maximum speed and were not able to continue accelerating. While driving at the simulator's maximum speed, the driver's variability in speed performance approaches 0 due to the invariant nature of their accelerator pedal being placed in the maximum position against the floor.

Mean speed performance greater than 138 km/h (85.75 mph) was taken to indicate that the participant had reached and maintained the maximum speed allowed by the simulator. Mean speed above 138 km/h could only be achieved by having the pedal to the floor for a majority of the task, as was suggested from a post hoc observation of the pedal variation for all participants (included and excluded) in Experiments 1, 2, and 3. Drivers who had a mean speed above 138 km/h in at least one comfortable speed task had significantly lower pedal variation during all tasks ($N = 31$, $M = 0.024$) when compared to those who did not reach the maximum speed during any task ($N = 81$, $M = 0.033$), $F(1,110) = 4.64$, $p < .05$. It was therefore necessary to exclude and replace any participant whose mean speed was greater than 138 km/h during any speed maintenance task (although this was only necessary during the C1 or C2 tasks, as described in the Modified Ratio Methodology section, below). Each participant had six opportunities to meet this exclusion criterion during the C1 and C2 tasks completed during each of three ER conditions. Participants who reached the maximum speed during one task were likely to do so in another task, and this explains why the number of tasks meeting the exclusion criterion is greater than the number of actual participants excluded.

Modified Ratio Methodology

The current investigation develops a novel methodology, the *Modified Ratio Methodology* (MRM), for measuring perceived egospeed within a simulated environment. This methodology was named to imply that participants would be asked to modify the speed they are driving to produce *ratio speeds,* similar to Denton's (1980) methodology of having participants modify their speed to half or double the current rate. The MRM was designed to examine speed production while overcoming the limitations of previous efforts that only focused on passive methodologies (e.g., observer estimations; Recarte & Nunes, 1996) or provided limited control of the vehicle (e.g., pedal control but no steering control; Conchillo et al., 2006). Passive methods of speed estimation remove the observer from the context of physical and cognitive demands associated with driving, resulting in perceptions that may not be congruent with what one would experience while actually producing a particular speed and steering the vehicle. The current experiment has the advantage of observing egospeed produced by participants who are fully engaged in all aspects of driving while also facilitating the controlled manipulation of visual cues that would be dangerous or impossible to establish in the real world. This includes exposing drivers to extended periods of standardized visual cues to examine any resultant changes in speed maintenance over time.

Another advantage of the MRM is that a typical speed production methodology may ask participants to drive at an absolute speed, for example, "Drive at 50 mph." Using this type of procedure, a large range of individual differences in speed preference and performance would be expected. To help control the effect of these individual differences, an adaptation of Denton's (1980) methodology was developed wherein participants were asked to produce ratio speeds. In his study, participants were asked to accelerate to a speed and later signaled to either double their speed or to reduce their speed by half. The MRM provided a means to bypass the subjectivity of each participant's experience with the virtual world in the following three ways. First, it asked them to drive at, "a comfortable speed that you could see yourself maintaining in similar conditions in the real world." This task was intended to uncouple participants' preconceptions of the virtual environment's realism from their judgments of speed. Second, asking a driver to produce a comfortable speed also bypassed any anxiety (or perceived risk) should they be forced to drive at an absolute speed they felt was slower or faster than they would like to drive. Third, the methodology asked them to maintain a comfortable speed, switch to half of that comfortable speed, then return to their comfortable speed—all without stopping. The intention of this instruction was to uncouple their perceptions of speed from absolute 0 (i.e., stopping), to vary their task and alleviate boredom, and to provide enough time within each condition to observe those ER cues. The use of these three speed tasks also allowed for the measurement of additional metrics: what speeds they felt were comfortable (mean comfortable and half speeds); their ability to make relative judgments about their speed (target ratio); their ability to maintain a consistent speed over the course of the task (speed drift ratio, reliability ratio); and their judgment of task difficulty (ease rating).

During each of the experimental drives, each participant was asked to remain in the middle lane and to begin driving at a speed they felt comfortable maintaining; this was called the *first comfortable speed task* (C1). When this speed was reached, participants indicated with the left turn signal that they had reached this comfortable speed. Drivers were then instructed to maintain that speed until they were given another instruction to stop. After 180 seconds (the task duration was not disclosed to participants), drivers were asked to reduce their speed to one-half of their comfortable speed, to indicate when they reached that half speed, and then to maintain that speed until instructed to stop; this was called the *half speed task* (H). After another 180 seconds, drivers were asked to again drive at their comfortable speed, to indicate when they reached that comfortable speed, and then to maintain that speed until instructed to stop; this was called the *second comfortable speed task* (C2). After another 180 seconds, drivers were instructed to stop the simulated vehicle. All instructions were automatically administered by the simulator via pre-recorded audio files at the specified times.

The length of each task (180 seconds) was chosen with the intention of maximizing the data collected within each task (C1, H, and C2) while also attempting to reduce boredom and potential fatigue of driving that might occur during longer periods in the simulator. The convention which has worked most effectively when using the HumanFIRST simulator has been to limit the length of each drive to 10 minutes. Pilot tests using the MRM suggested that significant differences in mean speed could be observed between geographic ER cues by using 180-second-long tasks (Rakauskas, 2009). This pilot testing also suggested that 180 seconds might be long enough to produce differences in drift ratio between ER conditions. Based on this evidence, three 180-second-long (3-minute) tasks were selected as an appropriate length for each experimental drive.

Participants were never asked to drive at double their comfortable speed because drivers often underestimate their speeds in simulated environments, and an underestimation of speed will result in a faster-produced speed (Recarte & Nunes, 1996). This is especially the case when the driver cannot reference the speedometer because it is hidden (Tornros, 1998). Some drivers did produce the maximum speed allowed by the simulator and were excluded from the analyses (see the Participant Replacements Due to Reaching Simulator Maximum Speed section in the Outline of Experiments, above). The benefit of performing two comfortable speed tasks separated by a half speed task is threefold. First, having H and C2 tasks that are subsequent to an initial C1 task allows for two separate within-subject examinations of comfortable speed performance relative to their own chosen comfortable speed. Second, speed performance comparisons between C1 and C2 tasks can be used to examine the drivers' ability to be consistent over a longer exposure of the ER cues. Third, the use of the H task ensures that the driver cannot use their initial (stopped) speed as a reference for their C2 speed in the same way it is possible to do during C1, when they begin the drive from a stop.

A practice drive was administered before each experimental drive for two reasons. The first was to retrain drivers to the speed maintenance tasks and make sure they maintained an adequate and consistent level of performance. The second purpose was to negate any calibration carry-over effects of the previous ER cue condition. Also, when an observer views a strong set of motion cues over a period of time, such as the drivers in this study were doing over the course of each 10-minute experimental drive, there was the possibility that part of the observer's retina would establish a temporary set of motion cues counter to the ER cues experienced. Although these "motion aftereffects" typically do not last long, there was a possibility that they could affect the driver's perception of ER cues during the next experimental drive. Therefore, the practice drives were included to make sure that drivers did not experience any lingering motion aftereffects.

The ambient visual environment used in the practice drives always consisted of a few farmhouses at far distances. During these practice drives, participants performed the comfortable speed (C1) and half speed (H) tasks as they would during the experimental conditions, only for periods of 90 seconds instead of 180 seconds. Once the drive was completed, speed maintenance performance was assessed for consistency. Consistency was quantified as the percentage of time during the "performance" segment of each task (the last 30 seconds; see Pc and Ph in Figure 4) that drivers could maintain a speed within +/-8 km/h (5 mph) of the mean speed they exhibited during the "baseline" segment of each task (the first 60 seconds; see Bc and Bh in Figure 4). Participants who did not maintain 75 percent consistency were instructed that they needed to focus on maintaining a consistent speed and then repeated the practice drive until they could reach that level of performance. No participant needed to repeat the practice drive more than once.

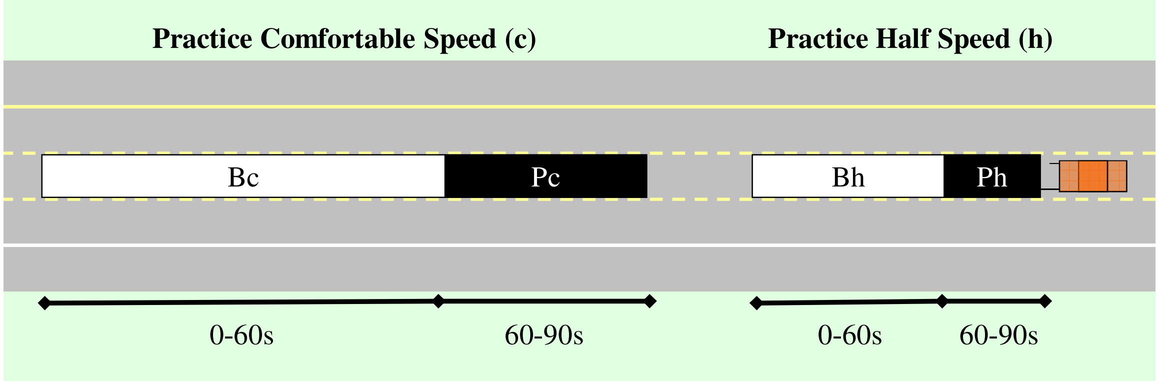


Figure 4. Timeframe and diagram of tasks during a practice drive.

The MRM methodology was intended to be useful for researchers who would like to quantify the effects and interactions between ER cues that are present for prolonged periods of time. The research questions posed earlier were addressed in three separate experiments so that specific ER cue comparisons could be made, as outlined in Table 1 and described below.

Experiment 1

Experiment 1 addressed the first research question: would speed production be affected by the presence of ER cues from objects at near and far distances from the road? This question was addressed by examining the effects of “geographic” ER cues on comfortable speed choice. Participants drove while the surrounding environment contained no distinct ER cues or contained objects at two distances from the road. This experiment also served as an initial validation of the MRM for examining perceived egospeed.

To examine the effect of the geographic ER cues’ presence on comfortable speed choice, performance was compared between the no ER condition and both the far and near geographic ER cue conditions (see

Table 1). These comparisons test whether comfortable speed choice was affected by the presence of geographic ER cues and whether this effect was mitigated by the apparent distance at which the cues were placed from the driver. The presence of ER cues was expected to lead to a heightened perception of egospeed and result in slower mean speeds, in the same manner that adding ER cues from transverse lines to the road surface reduces speeds (Denton, 1980; Godley et al., 2000; Shinar et al., 1980). The addition of ER cues in the form of speed-calming applications within the roadside environment (Scallen & Carmody, 1999; Corkle & Giese, 2002) has also suggested that speed may be reduced for those driving at excessive speeds. On the other hand, throughout the no ER condition over the course of the speed maintenance task, there were only weak optical flow and ER cues to provide drivers information about their egospeed. The no ER condition was expected to produce similar effects to driving in low contrast fog, that being reducing perceived egospeed and resulting in faster speeds; Snowden et al., 1998). Therefore it was hypothesized that drivers experiencing no ER geographic cues would produce faster comfortable speeds (mean speed); have more difficulty producing target speeds (target ratio); gradually increase their speed during each task (speed drift ratio); and have more difficulty maintaining a consistent speed (reliability ratio and ease rating).

Table 1. ER cue types for all three experiments.

		ER Cue Types					
		Geographic Cues			Traffic Speed Cues		
Experiment	ER Cue Comparison	No ER	Far	Near	Faster	Same	Slower
1	Presence	√					
			√				
				√			
	Distance		√				
				√			
2	Traffic-Speed Direction (TSD)	√			√		
		√				√	
		√					√
3	Cue Pairs			√	√		
				√		√	
				√			√

To examine how comfortable speed choice was affected by the distance that geographic ER cues were placed from the driver, performance was compared between objects with comparable ER frequency and subtending the same retinal angle placed at far and near distances from the driver (see Table 1). Because ER frequency and visual angle are controlled for, this comparison determined whether the perceived distance of an object from the driver was compelling enough to produce significant differences in comfortable speed choice. Because the visual angle of objects was controlled for but the objects were placed at different visual distances, the objects in the near and far ER conditions would appear to be different sizes.

Perception of objects at a closer distance will more-closely resemble direct perceptual mechanisms as compared to cues that are viewed to be further from the road (DeLucia, 2008). It was predicted that the proximity of the near geographic ER objects would provide the driver with stronger visceral comparisons of egospeed in addition to any cognitively-mediated comparisons of cues that are available during both near and far ER conditions. Because drivers viewing the near ER objects could take advantage of multiple perceptual mechanisms, they were predicted to have faster egospeed perception resulting in slower egospeed production than drivers viewing far ER objects. Specifically, in contrast with the far geographic ER cue condition it was hypothesized that drivers experiencing the near geographic ER cues would: produce slower comfortable speeds (mean speed); have less difficulty producing target speeds (target ratio); be less likely to gradually increase their speed during each task (speed drift ratio); have less difficulty maintaining a consistent speed (reliability ratio); and not show differences in perceived ease in maintaining their speed because the processing of the ER cues is happening at both conscious and unconscious levels during both conditions (ease rating).

Results of Experiment 1 were expected to inform traffic safety practitioners whether speed reduction is possible by adding a pattern of geographic ER cues to the driving environment. Results would also suggest the difference in effectiveness of these ER cues when they are perceived to be at near and far distances from the driver.

Experiment 2

Experiment 2 addressed the second research question: would speed production be affected by ER cues moving at similar, faster, or slower speeds than the observer's speed (e.g., vehicles traveling in adjacent lanes)? This question was addressed by examining the effects of ER cue direction on comfortable speed choice. Participants drove down the center lane of a three-lane road while traffic in the surrounding two lanes traveled at consistently faster, similar, or slower speeds.

To examine the effect of traffic-speed direction (TSD) ER cues on comfortable speed choice, performance was compared between conditions containing faster, same, and slower ambient traffic (see Table 1). Pair-wise comparisons of the three conditions were made to establish the relative effect of the three TSD conditions: traffic passing the participant (faster traffic creating a contracting ER cue); traffic remaining in a stable position relative to the participant (same speed traffic creating a relatively constant occlusion of global optical flow); or traffic being passed by the participant (slower traffic creating a expanding ER cue).

Vehicle passengers traveling with traffic moving in the same direction have been found to make larger errors in their estimations of speed in comparison to making estimations while on roads with less traffic or no traffic at all (Conchillo et al., 2006). Observers were found to underestimate speeds while traffic was present and moving in the same direction. The presence of traffic may have primarily activated direct perceptual mechanisms in reaction to the TSD ER cues, as suggested by DeLucia (2008). Because these cues were very close to the driver, they were expected to have a strong unconscious and immediate influence on egospeed perception. Therefore, drivers experiencing the TSD ER cues were expected to produce speed similar to the traffic around them because they were forced to make direct, visceral judgments without the benefit of other ER cues within the environment. Furthermore, drivers were expected to be unaware of this influence on their speed. Specific trends in egospeed perception are related to the type of TSD ER cue observed, and are discussed in detail below.

The faster TSD condition provided a contracting ER cue and was expected to influence drivers to perceive they were driving slower than they actually were traveling. This was suggested by Mohler, Thompson, Creem-Regehr, Pick, & Warren (2007), who found that walkers matched their walking speed to the optic flow they were viewing. In an attempt to maintain their comfortable speed, drivers were expected to compensate by increasing their produced speed. Therefore, compared to the other two TSD ER cues, it was hypothesized that drivers experiencing the faster TSD ER cues would produce the fastest comfortable speeds (mean speed); have the most difficulty producing target speeds (target ratio); gradually increase their speed during each task (speed drift ratio); and have the most difficulty maintaining a consistent speed (reliability ratio and ease rating).

Conversely, the slower TSD condition provided an expanding ER cue and was expected to influence drivers to perceive they were traveling faster than they actually were traveling. In an attempt to maintain their comfortable speed, drivers were expected to compensate by decreasing their produced speed. Therefore, compared to the other two TSD ER cues, it was hypothesized that drivers experiencing the slower TSD ER cues would produce the slowest comfortable speeds (mean speed); have similar difficulty producing target speeds as during the faster TSD ER condition (target ratio); be the least likely to gradually increase their speed during each task (speed drift ratio); and have similar difficulty maintaining a consistent speed as during the faster TSD ER condition (reliability ratio and ease rating).

Finally, the same speed TSD condition provided a stable or occluding ER cue and was expected to have a neutral effect on egospeed perception. This was because these ER cues maintained a similar position within the driver's field of view throughout the task and so produced neither contracting nor expanding ER cues. However, it was possible that these cues would serve to occlude information from the optical flow array and potentially produce similar effects to those experienced during foggy (low contrast) conditions—slower egospeed and faster produced speeds (Snowden et al., 1998). It was therefore hypothesized that drivers experiencing the same TSD ER cues would have performance on all measures that was at a level between the faster and slower TSD ER cue conditions, but potentially closer to the faster TSD ER cue condition, due to the potential effect of optic flow occlusion.

Results of Experiment 2 will inform traffic safety practitioners how produced vehicle speed is affected by the relative direction of ambient traffic. Differences in produced speed resulting from the TSD ER cues may provide evidence for the prevalence of speeding on road segments where other traffic is traveling at a faster speed than the driver. Conversely, results may also provide evidence for the prevalence of reduced speeds on segments where other traffic is traveling at a slower speed than the driver. Finally, results were expected to uncover the behavior of drivers when traveling amongst traffic that is traveling at that same speed as the driver's speed. This last finding will suggest how influential TSD ER cues are in a traffic situation that is quite typical.

Experiment 3

Experiment 3 addressed the third research question: would differences in speed production found while experiencing geographic or traffic ER change when they are experienced at the same time? Specifically, would the effects found during Experiments 1 and 2 be retained or changed when the two types of ER were presented together. It was possible that the combination of these ER cue types would lead to additive effects (i.e., a stronger perception of egospeed) when they were in agreement with each other and subtractive (i.e., a weaker perception of egospeed) when they were in opposition. These hypotheses were addressed by examining comfortable speed choice while the environment contained objects at a close distance to the road (geographic ER cues from Experiment 1) and while traffic in the surrounding two lanes traveled at consistently faster, similar, or slower speeds than the participant's current speed (TSD ER cues from Experiment 2).

To examine the effect of ER cue pairs, performance was compared between conditions containing pairs of opposing, occluding, or agreeing ER cues (see Table 1). Pair-wise comparisons of the three traffic conditions were made to further establish the relative effect of the three ER cue pairs: opposing ER cues (faster TSD creating a contracting ER cue in opposition to the near ER from objects in the environment); occluding ER cues (same TSD creating a relatively constant occlusion of optic flow and near ER); or agreeing ER cues (slower TSD creating an expanding ER cue in agreement with the near ER from objects in the environment).

It was predicted that the presence of the near geographic ER cues would serve as a reference for strong visceral comparisons of egospeed while potentially also being weakly mediated by cognitive processes. The presence of the TSD ER cues were predicted to serve as a second reference for direct, visceral judgments of egospeed cues. In this way, observing both TSD ER and geographic ER cues together was expected to activate a combination of strong, direct mechanisms (and potentially indirect, cognitively-mediated processes as well). Because drivers viewing the ER cue pairs could take advantage of multiple perceptual mechanisms, their perceived egospeed was predicted to be the most accurate of all three experiments. That said, the proximity of the TSD ER cues would still have the greatest influence on their speed choice. Therefore, the produced egospeed resulting from this combination of cues would be dependent upon the combination of expanding geographic ER cues and the particular type of traffic direction ER cue, as described below, although more similar to the trends observed during Experiment 2.

Previous research suggests that viewing a contracting optic flow pattern along with an expanding optic flow pattern would cause observers to perceive that they are traveling at a slower speed than they are actually moving (Gray & Regan, 2000). While producing comfortable speeds, drivers' egospeed perceptions may have been modified by opposing ER cue pairs such that traffic passing them (faster TSD ER cues) produced a type of contracting optic flow pattern while the near geographic ER cues produced a type of expanding optic flow pattern. The net result was hypothesized to be the perception of traveling slower than they were actually traveling. In an attempt to maintain what they thought was their comfortable speed, drivers were expected to compensate by increasing their produced speed. Therefore, compared to the other two ER cue pairs, it was hypothesized that drivers experiencing the opposing ER cues would produce the fastest comfortable speeds (mean speed); have the most difficulty producing target speeds (target ratio); gradually increase their speed during each task (speed drift ratio); and have the most difficulty maintaining a consistent speed (reliability ratio and ease rating).

Conversely, viewing an expanding optic flow pattern along with another expanding optic flow pattern may cause observers to perceive that they are traveling at a faster speed than they are actually moving (Gray & Regan, 2000). While producing comfortable speeds, drivers' egospeed perception may have been modified by the agreeing ER cue pairs such that traffic being passed by them (slower TSD ER cues) produced a type of expanding optic flow pattern while the near geographic ER cues also produced a type of expanding optic flow pattern. The net result was hypothesized to be the perception of traveling faster than they were actually traveling and drivers were expected to compensate by decreasing their produced speed. Therefore, compared to the other two ER cue pairs, it was hypothesized that drivers experiencing the agreeing ER cues would produce the slowest comfortable speeds (mean speed); have the least difficulty producing target speeds (target ratio); be the least likely to gradually increase their speed during each task (speed drift ratio); and have the least difficulty maintaining a consistent speed (reliability ratio and ease rating).

Comparably, it was expected that the same TSD ER cues would reduce the beneficial effects of the near geographic ER cues during the occluding ER cue pair condition. This set of conditions was expected to affect drivers similarly as when there are reduced environmental contrast cues, such as when fog is present and drivers increase their speed to compensate for the reduction in perceived egospeed (Snowden et al., 1998). The result of this would be that drivers would perceive that they are driving slower and the resulting produced speed would more closely resemble the opposing ER Cue pair condition than it would resemble the agreeing ER Cue pair condition.

Results of Experiment 3 will inform traffic safety practitioners how produced vehicle speed is affected by the relative direction of ambient traffic in the presence of strong geographic ER cues. Differences in produced speed resulting from the opposition of geographic and TSD ER cues may provide an explanation for the prevalence of speeding when ER cues are observed to move in opposite directions. Conversely, results may also provide evidence for the prevalence of reduced speeds when two sets of ER cues are observed to move in the same direction. Finally, results were expected to uncover the behavior of drivers when traveling amongst traffic traveling at a speed similar to that of the driver, essentially occluding the geographic ER cues. This last finding will suggest how influential TSD ER cues are when strong geographic ER is also present in a traffic situation that is quite typical.

Interaction Between Geographic Presence and TSD ER Cues

Comparisons were also made across the conditions in Experiments 2 and 3 to explore the interaction between geographic ER cue presence and TSD ER cues. This interaction was examined while geographic ER cues were either not present (no ER, Experiment 2) or present at the near distance (Experiment 3) for all three TSD ER cues (faster, same, and slower).

A main effect for presence of geographic ER cues would indicate that having the near geographic ER cues behind the proximal traffic had an effect on comfortable speed choice regardless of the traffic conditions. Because Experiment 3 presented two ER cues simultaneously (distant ER cues from buildings and proximal ER cues from traffic), it was predicted that there would be an effect for presence of geographic ER cues. Specifically, drivers were expected to have more accurate egospeed perceptions by perceiving two ER cues and integrating the information. Thereby, egospeed perception would be more accurate during Experiment 3, resulting in slower overall speeds and less speed variability compared to the egospeed judgments during Experiment 2. It was hypothesized that the presence of geographic ER cues would lead drivers to produce slower comfortable speeds (mean speed); have less difficulty producing target speeds (target ratio); be less likely to gradually increase their speed during each task (speed drift ratio); and have less difficulty maintaining a consistent speed (reliability ratio and ease rating). A main effect for TSD ER cues would indicate that the speed of the proximal vehicles had an effect on comfortable speed choice. It was expected that, if the difference between TSD ER cues was significant during Experiment 2, this main effect for TSD would also be significant in this interaction analysis. It was hypothesized that the effects for TSD would be the same as those predicted for the TSD ER cues during Experiment 2.

Although no explicit interactions were predicted for these conditions, a significant interaction between geographic presence and TSD would indicate a more complex pattern of behavior had emerged when these ER cues were presented in combination. For example, it is hypothesized that the occlusion of optic flow cues by traffic would be a stronger influence on egospeed estimation during Experiment 3 (where there were strong geographic ER cues to be occluded) compared to Experiment 2 (where these were weak-to-nonexistent geographic ER cues). This comparison would only be possible by examining the interaction between Experiments 2 and 3.

Significant main effects or interactions will inform traffic safety practitioners on the strength of geographic and TSD ER cues and if their combination leads to additive or reductive speed estimation effects. For example, a significant main effect for the presence of geographic ER would indicate that these cues can be used to reduce produced speed regardless of the effect of traffic ER; a significant interaction would indicate whether the presence of geographic ER cues changed a driver's ability to estimate egospeed while driving alongside a particular type of TSD ER cue.

EXPERIMENT 1

This experiment was designed to examine whether speed production would be affected by the presence and distance of geographic ER cues (in this experiment, “objects” resembling small, brick-textured buildings). Participants drove through environments containing no distinct ER cues or environments containing objects at one of two distances from the road. This experiment will also begin to validate the MRM for examining perceived egospeed, enhancing its usefulness in subsequent experiments.

Methods

Participants

Thirty-three participants completed the experimental protocol; one was excluded for having variation in speed greater than 3 standard deviations from the mean speed and one participant’s data were lost due to a computer error. Seven additional participants were excluded for having a mean speed above 138 km/h during at least one speed maintenance test (see Participant Replacements Due to Reaching Maximum Speed in the Outline of Experiments section); in total there were 8 instances of reaching the maximum speed during the no ER condition: 7 during the far condition, and 6 during the near condition.

The final sample consisted of 24 participants (12 female, 12 male, *M* = 20.8 yrs, *SD* = 3.2, *Range* = 18–30) who experienced all ER cue conditions in a counterbalanced order to minimize any effects of presentation order. Participants were recruited from the University of Minnesota campus, and those recruited from the psychology volunteer pool received course credit for their participation.

Apparatus

The driving simulator's physical setup, functionality, and driving environment were consistent with those described in the Outline of Experiments. In addition, this experiment included three types of geographic ER cues, as described below.

Edge Rate Cues: Distant Geographic Cues

During Experiment 1, participants experienced three types of geographic ER cues to explore the effects of ER cue presence and distance on comfortable speed choice. The no Edge Rate (no ER) condition (Figure 5A) contained only a pattern of grass alongside the road. The far condition (Figure 5B) used the no ER condition as background but also included objects placed 5 lane widths (18.3 m, 60 ft) from the center of the center lane, as presented in the diagram of the relative size and arrangement of objects (Figure 6). Objects to the participant's right were located on the roadside while objects to the participant's left were located in the median of the divided highway. These objects were 21 m (68.9 ft) long, 9.7 m (31.8 ft) wide, and 3.1 m (10.2 ft). The near condition (Figure 5C) used the no ER condition as background but also included objects placed 2.5 lane widths (9.2 m, 30 ft) from the center of the center lane (Figure 6). These objects were 10.5 m (34.4 ft) long, 4.8 m (15.7 ft) wide, and 2.1 m (6.9 ft) high. From the driver's point of view, these objects were designed to take up the same visual angle as the objects in the far condition. Because of this, differences in produced speed could not be attributed to a difference in the subtended visual angle of the objects, which has been shown to affect motion perception of approaching objects (Regan & Gray, 2000).

Both the far and near ER cues were expected to produce expanding ER cues towards the driver. Both far and near objects repeated at a constant frequency along both sides of the road, 76.2 m (250 ft) apart from center-to-center. Under these conditions, a participant traveling at 80.5 km/h (50 mph) would pass a pair of objects every 3.4 seconds and pass 17.6 objects per minute. Distler and Bulthoff (1996) found that the perceived velocity of observed vehicles was higher when observing scenes with higher surface texture spatial frequency. Therefore, it was important that both near and far did not differ in spatial frequency so that differences in produced speed could not be attributed to a difference in the frequency of passing geographic ER cues.

Finally, the objects in the far and near conditions featured the same brick-pattern surface texture. This was important to control for because texture has been found to have an effect on drivers' perception and production of speed (Manser & Hancock, 2007). Therefore, differences in produced speed could not be attributed to a difference in the surface texture between the near and far objects. There was no ambient traffic on the road in either direction during Experiment 1.

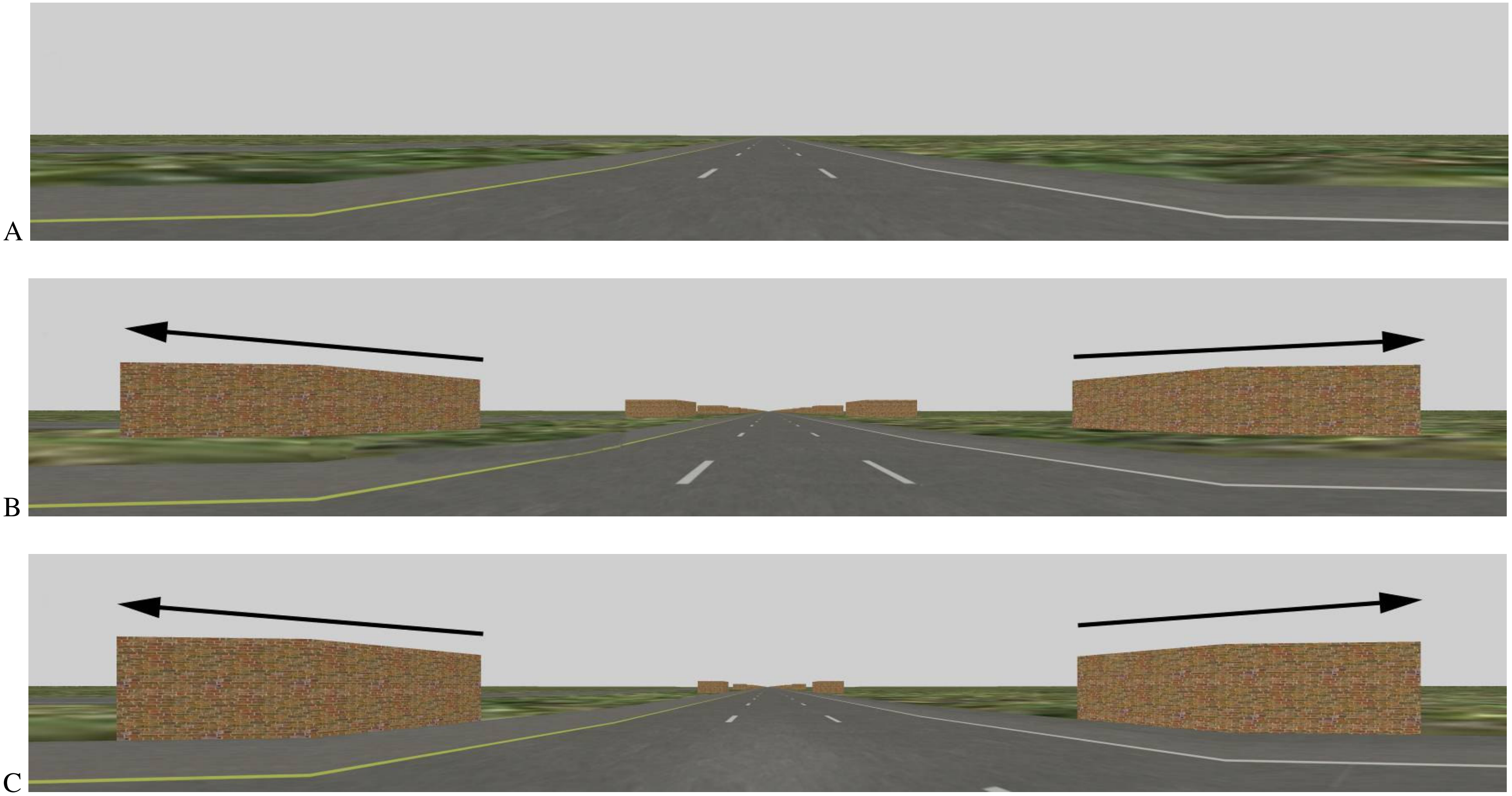


Figure 5. Forward 210 by 40 degree field of view for the A) no ER; B) far; and C) near geographic ER cue conditions, with black arrows added to emphasize the pattern of closest ER cues.

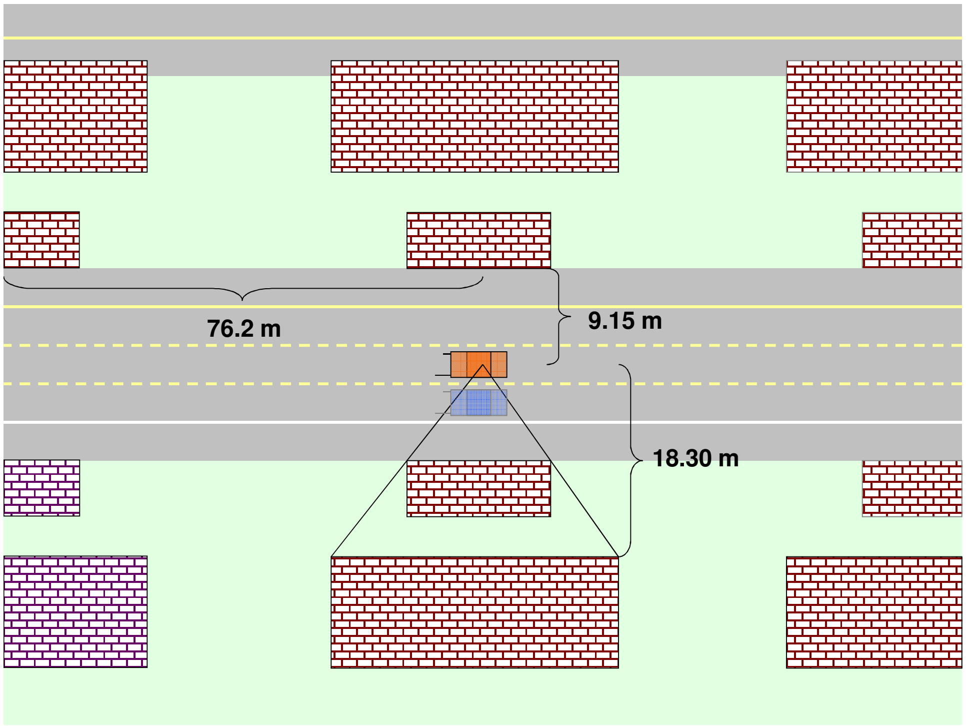


Figure 6. Depiction of the geographic ER cue conditions for Experiment 1. Distances between objects are not to scale. The grayed-out car is presented as a size reference and was not present during these drives.

Procedures

Each experimental session began with the experimenter overviewing the study with participants (Appendix A), who then read and signed the University of Minnesota Institutional Review Board-approved consent form (Appendix B). Participants then completed an acuity test (stereo, for far distances) and a lateral visual field, peripheral vision test (detection of flickering lights at 35-degree nasal and 55-degree, 70-degree, and 85-degree temporal) using an Optec Vision Tester, Model No. 2500 (Stereo Optical Co., Inc., Chicago, IL; for administration instructions and results reporting sheet, see the experimenter note sheets in Appendices F and G). Participants were required to have a minimum of 20/40 acuity and be able to detect the peripheral cues at a minimum of 70^{o}

(in at least one eye) to participate. They then entered the driving simulator and were instructed by the experimenter on how to operate the vehicle controls. The experimenter then left the participant in the simulator room and monitored the experiment using unobtrusive cameras and a microphone. This setup was designed to make the participant believe they were driving alone and unmonitored, as they would in typical driving situations.

The participant first completed a 10-minute acclimation drive which served to familiarize participants with the virtual environment and the controls of the driving simulator. This drive consisted of driving through a world similar to the one used in the practice drives while following a lead vehicle and following instructions presented over the vehicle's audio system using audio files triggered by the simulator. Then participants were asked to read a set of instructions on how to complete the MRM (Appendix C) before the experimenter reviewed the procedure with them and answered any questions they had.

Participants then completed a 10-minute speed maintenance acclimation (SMA) drive to become familiarized with the MRM procedure by completing each of the C1, H, and C2 speed maintenance tasks (see the Modified Ratio Methodology section in the Outline of Experiments for more details). The visual environment used in the SMA drive consisted of a few farmhouses at far distances. Initially the SMA drive was not included because it was assumed that drivers received enough practice in the speed maintenance tasks from the practice drives. However, data from the first set of participants revealed a tendency toward increasing mean speed over each successive experimental drive. This trend suggested that experimental drive order might be confounding speed performance.

To determine if additional practice would help reduce this speed trend, a comparison was made between the first 18 participants: nine (6 female, 3 male) who did not complete the SMA drive, and nine (4 female, 5 male) who completed the SMA drive. Because the practice drives were standardized in visual environment and task content, the difference in the minimum speed from the practice drives before and after each experimental drive was used as a metric of speed change due to task order. When drivers did complete the SMA drive, they had smaller increases in speed over successive practice drives (M = 1.96 km/h) compared to the non-SMA drive group (M = 7.40 km/h), $F(1,16) = 4.95$, $p < .05$. Therefore, adding the SMA drive was important to standardize drivers' level of competence and practice with the speed maintenance tasks while also reducing overall speed gain between successive conditions. For these reasons, the first 9 participants were excluded from further analyses and the SMA drive was completed by all participants before completing the experimental drives.

Participants then completed the following sequence three times, once per each of the three ER conditions: (1) successfully complete a practice drive; (2) complete an experimental drive; (3) report aloud how easy it was to maintain comfortable and half speeds; and (4) exit the car to complete the NASA-RTLX mental workload questionnaire on a computer (results for this questionnaire are not reported here). It was important to have participants exit the vehicle and engage in a non-driving task between experimental drives for two reasons. First, this gave participants a break whereby they were moving outside of the vehicle. This was intended to alleviate boredom and fatigue from sitting for long periods in the simulator and focusing on the virtual world images. Second, the break was intended to have participants view the real world again to mitigate any motion aftereffects that may have lingered from their last 10-minute exposure to an ER condition.

Dependent Variables

All dependent variables examined driving performance during the time segment starting 40 seconds after the participant signaled they had reached the target speed (C1, H, or C2) and ending 180 seconds after their signal. The first 40 seconds were excluded because an initial examination of the data suggested that participants had a tendency to indicate they had reached the target speed although they continued to accelerate (during the comfortable speed tasks) or decelerate (during the half speed tasks). This appeared to occur for approximately 30 seconds after their speed indication, on average. For the mean speed data of the final participant sample during Experiment 1, a comparison was made of performance during the entire trial (0 s to 180 s) to data from the proposed time segment (40 s to 180 s). The change in sampling segment did not affect participants' mean half speed ($F(1,23) = 0.04$, $p > 0.05$; $M = 75.2$ km/h), however results indicated that including the initial 40 seconds of data produced a significant decrease of mean speed during C1 ($F(1,23) = 11.31$, $p < .01$; from 111.7 km/h to 111.4 km/h) and C2 ($F(1,23) = 15.65$, $p \leq .01$; from 110.8 km/h to 110.3 km/h). Although this difference may not be practically significant, the presence of any difference suggests that participants were adjusting their speed to reach their comfortable speed after their turn signal indication. To be conservative and to verify that the data represent drivers' true comfortable speed choice, the initial 40 seconds of speed data were excluded from all analyses. In Figure 7, the initial red areas of each diagram (towards the left and containing an “X”) denote the 40 s of data which were excluded from the observed time segment and not examined. The C1 and H tasks depict the time segments when the mean of the entire task was calculated. The C2 task depicts how the time segment was split for the speed Drift Ratio measure.

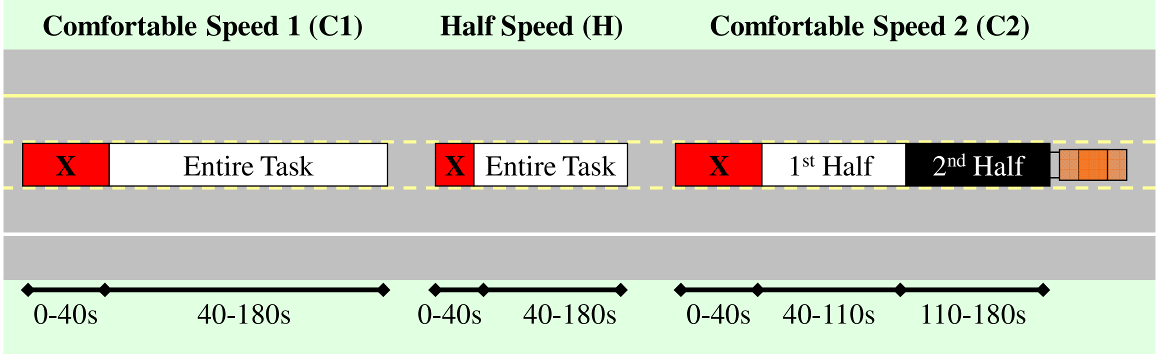


Figure 7. Diagram of C1, H, and C2 speed maintenance tasks and time segment samples.

Five dependent variables were examined in this study. Some metrics are in the form of ratios because this provides a uniform way to describe and quantify differences within conditions (e.g., between speed maintenance tasks [target ratio] and within tasks [speed drift ratio]) as well as a standardized way to quantify differences between ER cue conditions (reliability ratio).

Mean speed was calculated as the average speed signal during the experimental time segment. Drivers were told to maintain a consistent, comfortable speed. If they perceive they are driving faster than they are actually traveling, they will compensate by driving slower. Similarly, if they perceive that they are driving slower than they think they should be, they will compensate by increasing their speed. Therefore, produced mean speed is an indirect measure of egospeed perception.

Target ratios were calculated to make comparisons between task types. Drivers' mean speed performance during the H and C2 tasks were compared to performance during C1 to determine how accurately they could produce half speeds and reproduce comfortable speeds. Specifically, the comfortable speed target ratio was calculated as the mean speed during C2 (performance speed) over the mean speed during C1 (target speed). The half speed target ratio was calculated by taking the mean speed during H (performance speed) over one-half of the mean speed during C1 (target speed). A ratio of 1 indicates a perfect match between performance and target speeds; a ratio greater than one indicates that the performance speed was greater than the target speed; and a ratio less than one indicates that performance speed was less than the target speed. Therefore, the comfortable speed target ratio is a measure of speed accuracy over time, and the half speed target ratio is a measure of speed accuracy across tasks. Both target ratios are also potential indicators of recalibration over time.

Speed drift ratios were calculated to examine if drivers' speed changed over the course of each task. They were calculated by taking the mean speed during the second half of a task (the time segment between 110 s – 180 s) over the mean speed performance during the first half of that same task (40 s – 110 s); see the C2 task in Figure 7 for a depiction of these time segments. A ratio of 1 indicates no change in speed over the course of the task; a ratio greater than one indicates that speed had a tendency to increase during that task; and a ratio less than one indicates that speed had a tendency to decrease during that task. Therefore, speed drift ratios are a measure of speed change within each task and a potential indicator of recalibration over time.

Reliability ratios were calculated to examine the amount of variation that existed within each task. Because different levels of mean speed may be related to the amount of variation that is possible (i.e., higher speeds are typically associated with lower variation), it was necessary to take into account mean speed. To account for mean speed, the reliability ratio was calculated by taking the standard deviation of speed performance and dividing by the mean speed. Ratios closer to 0 indicate lower overall variance within that data set. These ratios were intended to compare variation in speed performance across ER cue conditions.

Ease ratings were collected to examine whether drivers were consciously compensating for different levels of effort during each ER condition. These ratings were collected after each drive by asking participants to give a rating to indicate how easy it was to maintain their comfortable and half speeds. In the simulator vehicle, participants could refer to a sheet of paper where this question was posed above two seven-point scales, ranging from 1 (*difficult)* to 7 (*easy*) (Appendix F). It would be difficult for participants to accurately differentiate between C1 and C2, especially since they were responding post-task and their experiences with completing C2 might have influenced their remembered perception of ease during C1. Therefore, participants were asked to rate the ease of the C1 and C2 tasks collectively. Ease ratings were also intended to capture whether drivers were conscious of changes in their behavior across ER conditions, such that if one ER condition was perceived without their awareness they may not report a difference in ease of maintaining their speed during that condition.

Results

Analyses

Due to the inherent differences between the comfortable speed (C1 and C2) and half speed (H) tasks, data from the H task were analyzed separately from the C1 and C2 tasks. Aside from mean speed performance compared within the target ratio, comparisons between half and comfortable speed performances on the other metrics are not equivalent because of the inherently larger frequency of exposure to geographic ER cues at faster speeds and smaller frequency at slower speeds. Thus the observed differences between performance at half and comfortable speed may signify how differences in ER cue frequency are related to speed. Therefore, although this was not one of the main research questions and statistical comparisons between comfortable and half speed were not made, these differences were discussed in the discussion.

A 3 x 2 within-subject ANOVA was performed to examine the effects of the presence and distance of geographic ER cues (no ER, far, near) and task type (C1, C2) on comfortable speed performance. A separate 3-way within-subject ANOVA was performed to examine the effects of presence and distance from geographic ER cues on half-speed performance. Follow-up tests for main effects of geographic ER cues were examined with planned pair-wise contrasts between the three ER cue conditions. Differences between means were considered significant at the $\alpha = .05$ level for all main effects and a Bonferroni-corrected significance level of $\alpha = .017$ (family-wise error rate of $\alpha = .05$ divided by 3, the number of follow-up tests) for each of the three pair-wise follow-up effects for geographic ER cue type. Main effects at the $\alpha = .06$ level and follow-up effects at the $\alpha = .05$ level were considered to approach significance and are noted in the Discussion because they may indicate potential trends in the data. Bars within all graphs indicate +/- 1 standard error.

Mean Speed

Mean comfortable and half speed results are presented in Table 2.

Table 2. Mean (SD) speed during Experiment 1.

	Comfortable Speed		Half Speed
Geographic ER	C1	C2	H
No ER	116 (12)	115 (10)	77 (11)
Far	111 (15)	111 (15)	77 (14)
Near	108 (16)	105 (16)	72 (15)

For comfortable speed task performance, there was a significant main effect for geographic ER cues, $F(2,46) = 8.27$, $p \leq .01$ (Figure 8). Pair-wise follow-up tests suggest that comfortable speeds were slower while driving with near geographic ER cues compared to driving with no ER cues ($t(23) = 3.45$, $p = .002$) or with far cues ($t(23) = 2.73$, $p = .012$). The comparison of mean comfortable speed between the no ER and far cues was not significant, $t(23) = 1.96$, $p > .05$. The main effect for comfortable speed task type (i.e., C1 compared to C2) was not significant, $F(1,23) = 0.80$, $p > .05$.

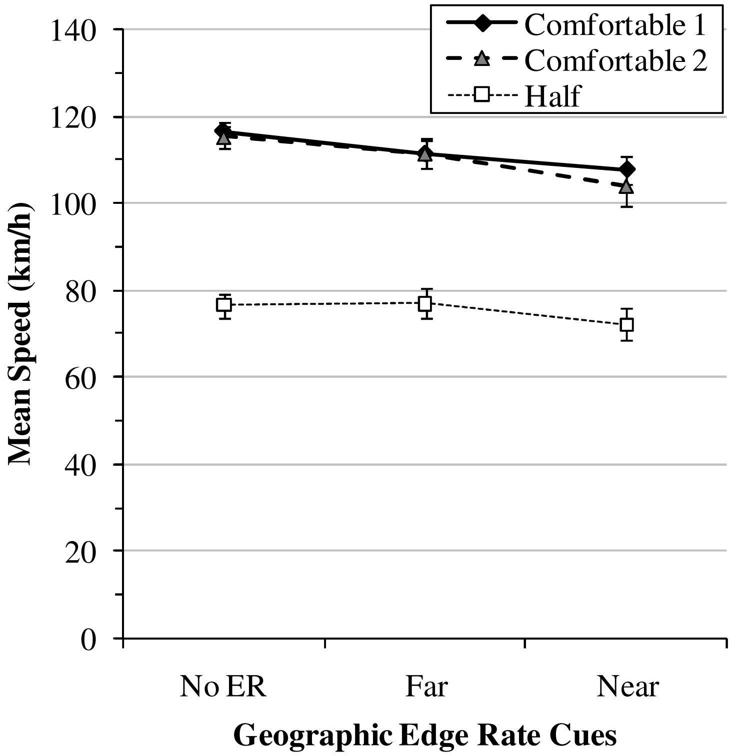


Figure 8. Mean speed performance during Experiment 1.

For half speed task performance, there was a significant main effect for geographic ER cues, $F(2,46) = 4.82$, $p < .05$ (Figure 8). Pair-wise follow-up tests suggest that mean half speeds were slower while driving with the near geographic ER cues compared to driving with far cues, $t(23) = 2.92$, $p = .008$. The comparison of mean half speeds between the no ER and near ER cues approached significance ($t(23) = 2.34$, $p = .028$), and the results suggest that the no ER condition may have produced higher speeds than the near ER condition. The comparison of mean half speed between the no ER and far geographic ER cue conditions was not significant ($t(23) = -0.04$, $p > .05$).

Target Ratio

Target ratio results are presented in Table 3 for comfortable and half speed.

Table 3. Mean (SD) target ratio during Experiment 1.

Geographic ER	Comfortable Speed	Half Speed
No ER	0.995 (.051)	1.330 (.153)
Far	1.002 (.078)	1.385 (.158)
Near	0.981 (.082)	1.329 (.155)

For the comfortable speed target ratio (C2 / C1), the main effect for geographic ER cues was not significant, $F(2,46) = 1.03$, $p > .05$. The mean target ratio for all three geographic ER cue conditions collectively found that drivers' second comfortable speed was on average 99 percent of their first comfortable speed.

For the half speed target ratio (H / (C1 / 2)), the main effect for ER cues approached significance, $F(2,46) = 3.02$, $p = .059$. The pair-wise follow-up comparison between far and near geographic ER cues approached significance ($t(23) = 2.23$, $p = .036$), suggesting that the far condition may have had a higher target ratio than the near condition. Follow-up comparisons did not find significant differences between no ER and far ($t(23) = -2.03$, $p > .05$) and the no ER and near ($t(23) = .05$, $p > .05$) conditions. In general, the mean target ratio for all three geographic ER cue conditions found that drivers' half speed was on average 35 percent higher than the target half speed (i.e., half of their C1 mean speed).

Speed Drift Ratio

Speed drift ratio results are presented in Table 4 for comfortable and half speed.

Table 4. Mean (SD) speed drift ratio during Experiment 1.

	Comfortable Speed		Half Speed
Geographic ER	C1	C2	H
No ER	1.024 (.024)	1.015 (.025)	1.009 (.068)
Far	1.004 (.031)	1.015 (.028)	1.010 (.067)
Near	0.996 (.040)	1.016 (.036)	1.020 (.064)

For comfortable speed drift ratio, the interaction between geographic ER cue condition and task type was significant, $F(2,46) = 4.54$, $p < .05$ (Figure 9). There were no significant differences between the follow-up comparisons of C1 and C2 during the no ER ($t(42) = 1.71$, $p > .05$), far ($t(23) = -1.78$, $p > .05$), or near ($t(23) = -1.88$, $p > .05$) geographic ER cue conditions. However, the results suggest that driving with near geographic ER cues may have resulted in a lower drift ratio during C1 than during C2. The main effects for geographic ER cues ($F(2,46) = 2.52$, $p > .05$) and comfortable speed task type ($F(1,23) = 1.95$, $p > .05$) were not significant.

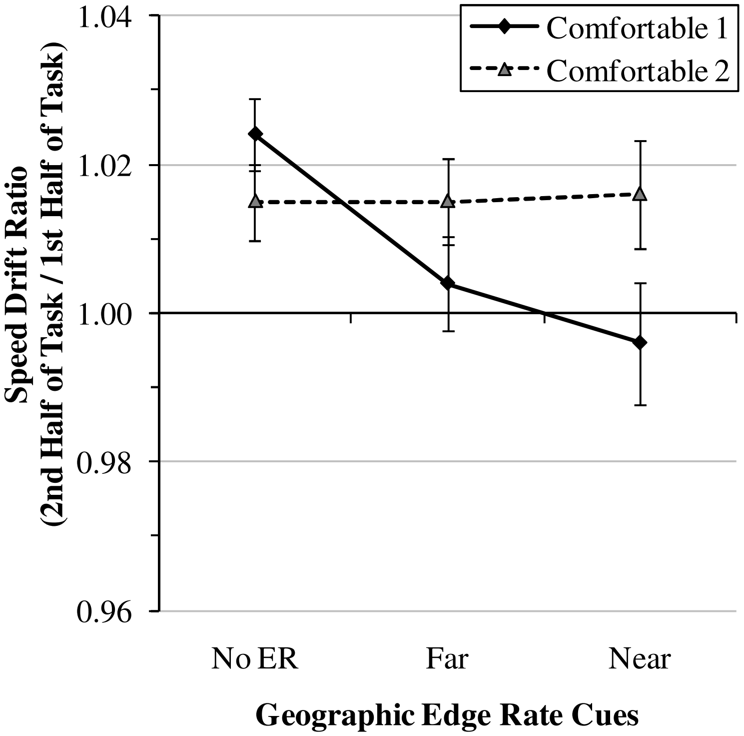


Figure 9. Speed drift ratio performance for comfortable speed tasks during Experiment 1.

The main effect for geographic ER cues was not significant for half speed task performance, *F*(2,46) = 0.32, *p* > .05.

Reliability Ratio

Reliability ratio results are presented in Table 5 for comfortable and half speed.

Table 5. Mean (SD) reliability ratio during Experiment 1.

	Comfortable Speed		Half Speed
Geographic ER	C1	C2	H
No ER	0.023 (.016)	0.018 (.010)	0.043 (.026)
Far	0.021 (.013)	0.022 (.013)	0.048 (.029)
Near	0.026 (.015)	0.025 (.016)	0.052 (.035)

For comfortable speed reliability ratio, the main effects for geographic ER cues, ($F(2,46) = 2.87$, $p > .05$) and task type ($F(1,23) > 0.01$, $p > .05$) were not significant. For half speed reliability ratio, the main effect for geographic ER cues was not significant, $F(2,46) = 0.72$, $p > .05$.

Ease of Maintaining Target Speeds

Ease rating results are presented in Table 6 for comfortable and half speed.

Table 6. Mean (SD) ease ratings during Experiment 1.

Geographic ER	Comfortable Speed[a]	Half Speed
No ER	5.5 (1.1)	4.8 (1.4)
Far	5.5 (1.0)	5.1 (1.3)
Near	5.5 (1.1)	4.8 (1.4)

[a] Ease ratings were asked in terms of comfortable speed in general and pertain to both C1 and C2 collectively.

The main effect of geographic ER cues was not significant for ease of maintaining comfortable speed (*F*(2,46) = 0.02, *p* > .05) or ease of maintaining half speed (*F*(2,46) = 1.43, *p* > .05).

Summary

The purpose of Experiment 1 was to examine the effects of the presence and distance of geographic ER cues on speed choice. In terms of speed performance, the presence of closer objects on the roadside (near geographic ER cues) was associated with slower comfortable driving speeds than while driving with objects further from the roadside (far ER) or when no ER cues were present. While driving at half speed, the near ER cues were also associated with slower speeds than while driving with objects further from the roadside (far ER). These effects resulted from the drivers having more proximal ER references that were not available during the far ER condition. As a result, drivers estimated that they had faster egospeed and they produced slower comfortable and half speeds compared to the other ER conditions.

Drivers' speed during the half-speed task (H) was on average 34 percent faster than their target speed (half of the speed they produced during C1). Drivers were able to reproduce their C1 speed during C2 (target ratio equal to 0.99), so it was unlikely that drivers' inability to produce a half speed accurately was due to an inability to understand the task or control the vehicle. Interestingly, trends in the data suggest that drivers were the least accurate at producing a target half speed when geographic ER cues were at a far distance compared to when they were at a near distance or when no ER cues were present. In addition, the initial presence of geographic ER cues may have assisted drivers in maintaining a more-consistent speed during the C1 task. The speed drift ratios of drivers during the near ER condition had a trend to be lower and closer to 1 during the C1 task compared to their performance later during the C2 task. Because this effect was not observed during the H task (see Table 4) and because the drift ratios were essentially uniform during C2 (see Figure 9), this suggests that drivers in all geographic ER cue conditions produced speed drift ratios slightly greater than 1 after longer exposures to the ER cues. This finding during the near ER cue condition was similar to the findings of van der Horst & de Ridder (2007), wherein roadside infrastructure only had an effect on behavior when it was first encountered and the effect diminished quickly afterwards. However, the lack of a main effect for speed drift ratio between the geographic ER conditions in the current study may have resulted from these cues being further from the driver than those trees and guardrails employed by van der Horst & de Ridder. Their participant drivers viewed roadside cues at a minimum distance of 1 lane away (approximately 3.6 m) while the closest the drivers came to the near geographic ER objects was a distance of 2.5 lanes (approximately 9.2 m). These conclusions would follow from DeLucia's framework for space perception (2008) which suggested that distance plays a critical role in the influence of perceived visual cues. This framework would also suggest that ER cues presented at closer distances will have an even stronger influence on speed drift ratio, as was examined during Experiment 2.

There were no significant differences between geographic ER cue conditions or between comfortable speed tasks on the variability (reliability ratio) for comfortable and half speeds. This suggests that the presence and distance of geographic ER cues did not affect drivers' ability to maintain consistent speeds. It was interesting that there were no differences in drivers' subjective ease ratings for maintaining comfortable and half speeds between the three geographic ER cue conditions. This may suggest that the differences in mean speed by participants were not related to the drivers' subjective opinions of how easy it was to maintain those speeds.

Overall, the presence of near geographic ER cues was found to reduce produced speeds during the comfortable speed task and potentially during the half speed task compared to absence of ER cues. The closer distance of the near geographic ER cues was also found to reduce speeds, potentially have a lower speed drift during initial exposure to ER cues, and potentially produce more accurate production of half speeds compared to situations with far ER cues. The MRM found no differences between these geographic ER conditions for measures of reliability and subjective ease. These findings suggest that this methodology would be equally useful for uncovering differences in mean speed, differences between tasks (target ratio), and speed drift, while remaining objectively and subjectively reliable. Therefore, there was reasonable confidence that similar trends would be uncovered by using the MRM to examine differences in speed choice between traffic speed direction (TSD) ER cues and ER cue pairs within the subsequent experiments.

Drivers in this experiment experienced geographic ER cues that came as close as the side of the road, while in the real world drivers almost always experience ER cues that are much closer than that, especially when there are vehicles in the surrounding lanes. Experiment 2 will examine how the presence of traffic speed direction ER cues may affect comfortable speed performance.

EXPERIMENT 2

This experiment was designed to examine whether speed production would be affected by the relative direction of ER cues that are available from traffic in surrounding lanes. Participants drove through environments devoid of the roadside objects used during Experiment 1 but containing traffic in the lanes to their immediate right and left. The ambient traffic traveled at speeds that were consistently faster, the same speed, or slower than the participant’s speed.

Methods

Participants

Forty participants completed the experimental protocol. One was excluded for falling asleep and leaving the center lane, a second participant's data were invalidated due to not following the experimental protocol, and a third participant’s data were lost due to a failure in the driving simulation during the experiment. Thirteen additional participants were excluded for having a mean speed above 138 km/h during at least one speed maintenance task; in total there were 20 instances of reaching the maximum speed during the faster (being passed) TSD ER condition, 18 during the same TSD ER condition, and 7 during the slower (passing) TSD ER condition.

The final sample consisted of 24 participants (12 female, 12 male, *M* = 20.8 yrs, *SD* = 2.9, *Range* = 18–30) who experienced all the ER cue conditions in a counterbalanced order to minimize any effects of presentation order. Participants were recruited from the University of Minnesota campus, and those recruited from the psychology volunteer pool received course credit for their participation.

Apparatus

The driving simulator's physical setup and functionality were consistent with those described in the Outline of Experiments. The virtual driving worlds displayed the same road and environment views as were used during the no ER condition of Experiment 1. In addition, this experiment used traffic speed direction (TSD) ER cues, as described below.

Edge Rate Cues: Traffic Speed Direction (TSD) Cues

Participants experienced three TSD ER cues during Experiment 2 to explore the effects of ambient traffic speed and direction on a driver's comfortable speed choice. In the lanes to the right and left of the participant were 16 other vehicles (8 in each lane), all of which were the same size and shape (Figure 10). No vehicles entered the center lane in front of or behind the participant's vehicle at any time. Vehicles were 4.9 m (16.1 ft) long, 1.8 m (5.9 ft) wide, and 1.5 m (4.9 ft) high. The geographic ER objects used in Experiment 1 were designed to take up the same visual angle as these vehicles, so that the visual angle of these two ER cue types was controlled between experiments. The same brick texture used for the geographic ER Cues in Experiment 1 was also used for all visible car body elements so that the texture of the ER cues was controlled between experiments. This was important to control for because texture has been found to modify drivers’ perception and production of speed (Manser & Hancock, 2007). Although this pattern is unusual for vehicles, it did not appear to be distracting to participants, as indicated by only a few participants commenting on the pattern.

Figure 10. Vehicle used for TSD ER cues.

The vehicles were spaced approximately 31.8 m (105 ft) apart on average from center to center, as presented in the diagram of the relative size and arrangement of vehicles (Figure 11). An invisible perimeter was established 250 m (820 ft) in front of and behind the participant, a point far enough away that the participant could not discern many details due to limitations in the resolution of the virtual environment and the fact that visual sensitivity to depth cues declines with the square of distance and is poor for distances greater than 10 m anyway (Regan & Gray, 2000). Whenever a vehicle traveling at a faster speed than the participant would pass this boundary, the vehicle would disappear and reappear within that same lane only at the back of the line of traffic. Similarly, a vehicle passing this boundary while traveling slower than the participant would disappear and reappear within that same lane only at the front of the line of traffic. The speed of these vehicles was unaffected by this traffic replacement. As a result of this process, the participant appeared to be continuously surrounded by a swarm of vehicles in the neighboring lanes.

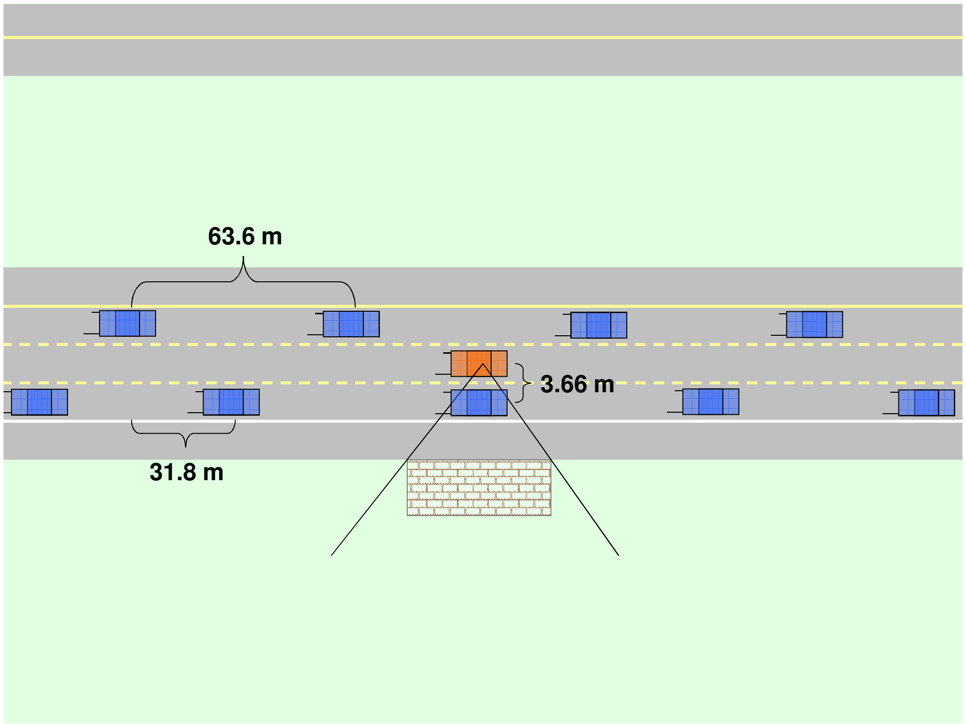


Figure 11. Depiction of the TSD ER cue conditions for Experiment 2. Distances between vehicles are not to scale and not all of the 16 vehicles are depicted. The grayed-out geographic ER cue object is presented as a size reference and was not present during these drives.

The speed of all vehicles was uniform to that of all other vehicles throughout the scenario, and this speed changed dynamically in relation to the participant's speed. These vehicles also moved independently of each other, and sometimes the vehicles had to readjust their speed and lane position upon reappearing, leading to a small amount of variability in the vehicle spacing.

The faster TSD ER cue condition (Figure 12A) consisted of traffic passing the participant at a consistent rate equal to five percent faster than the participant’s speed. This condition was equivalent to presenting the driver with a consistent contracting ER.

The same TSD ER cue condition (Figure 12B) consisted of vehicles attempting to match the participant’s speed at all times and therefore remaining at a relatively stable location within the participant's field of view. This condition was equivalent to having a consistent occlusion of ER cues beyond the ambient traffic. The participant’s speed was constantly changing, and this led to a minor delay in translating the driver’s speed signal into actual speed for these vehicles. Because of this, the vehicles sometimes appeared to “creep” forward or backward while the participant was accelerating or decelerating (respectively). This readjustment did not last long but resulted in the same TSD vehicles making minor location changes throughout this condition and not being perfectly stable in position relative to the participant. It should also be noted that due to the vehicles’ location-independence, vehicles often held a position directly to the left or right of the driver.

The slower TSD ER cue condition (Figure 12B) consisted of traffic consistently being passed by the participant at a consistent rate equal to five percent slower than the participant’s speed. This condition was equivalent to presenting the driver with a consistent expanding ER. In general, a participant traveling at 80.5 km/h (50 mph) during the faster or slower TSD ER cue conditions would encounter one vehicle approximately every 28.6 seconds and encounter 2.1 vehicles per minute, in alternating lanes.

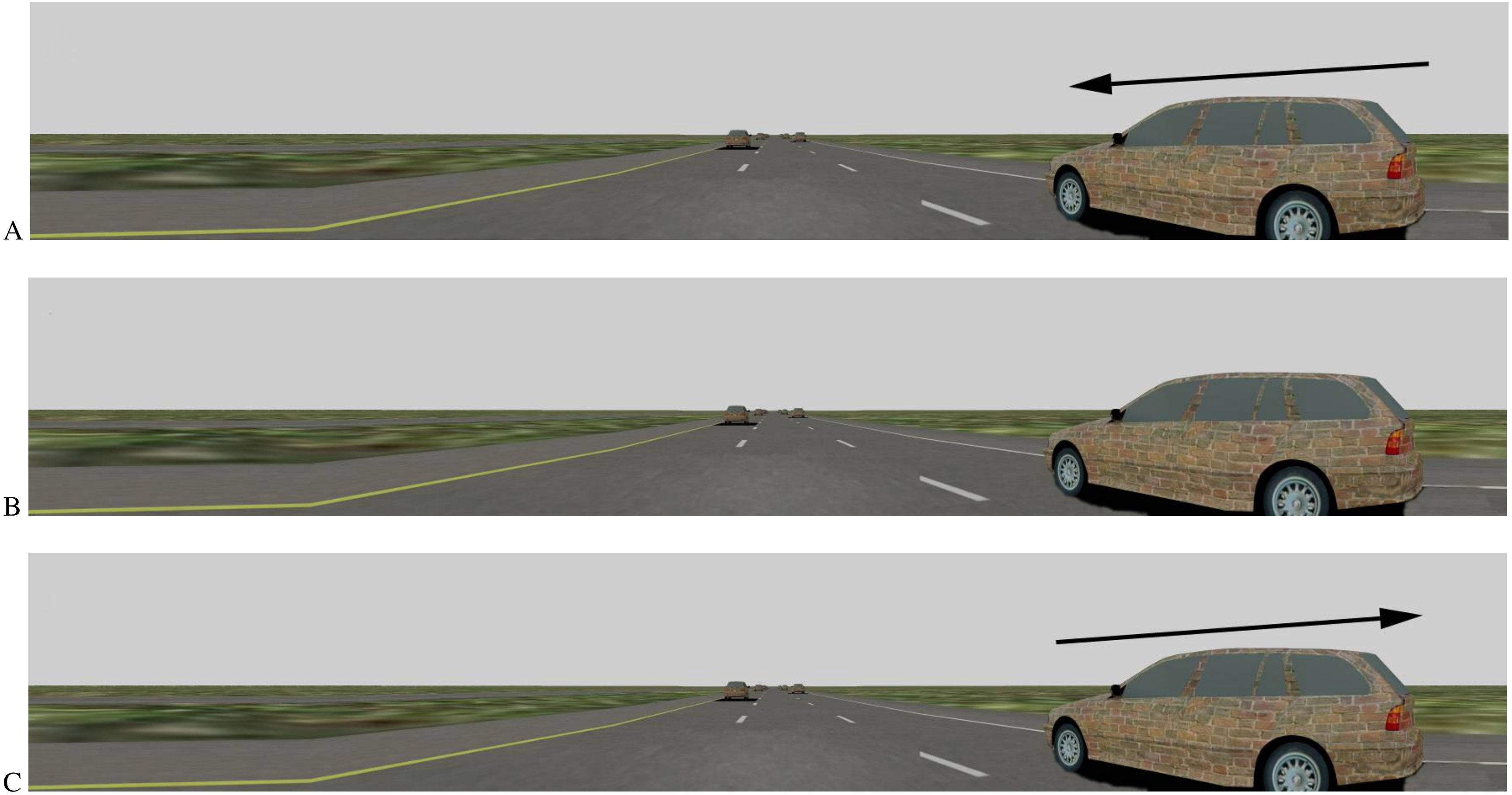


Figure 12. Forward 210 by 40 degree field of view for the A) faster, B) same, and C) slower TSD ER cue conditions, with black arrows added to emphasize the pattern of closest ER cues.

Procedures and Dependent Variables

The procedures for Experiment 2 were consistent with those described for Experiment 1. This includes using the MRM within the experimental drives as well as replacing participants due to their reaching the maximum speed allowed by the driving simulator. The dependent variables were also consistent with those described for Experiment 1.

Results

Analyses

A 3 x 2 within-subject ANOVA was performed to examine the effects of TSD ER cues (faster, same, slower traffic speeds) and comfortable speed task type (C1, C2). A separate 3-way within-subject ANOVA was performed to examine the effects of TSD ER cues on half speed performance. Follow-up tests for main effects from TSD ER cues were examined with planned pair-wise contrasts between the three ER cue conditions. Differences between means were considered significant at the $\alpha = .05$ level for all main effects and a Bonferroni-corrected significance level of $\alpha = .017$ (family-wise error rate of $\alpha = .05$ divided by 3, the number of follow-up tests) for each of the three pair-wise follow-up effects for TSD ER cue type. Main effects at the $\alpha = .06$ level and follow-up effects at the $\alpha = .05$ level were considered to approach significance and are noted in the discussion because they may indicate potential trends in the data. Bars within all graphs indicate +/- 1 standard error.

Mean Speed

Mean comfortable and half speed results are presented in Table 7.

Table 7. Mean (SD) speed during Experiment 2.

	Comfortable Speed		Half Speed
TSD ER	C1	C2	H
Faster	117 (16)	115 (18)	85 (19)
Same	110 (18)	109 (20)	77 (18)
Slower	103 (19)	105 (18)	72 (20)

For comfortable speed task performance, there was a significant main effect for TSD ER cues, $F(2,46) = 21.91, p < .01$ (Figure 13). Pair-wise follow-up tests suggest that comfortable speeds were slower while driving alongside same ($t(23) = 4.44, p < .01$) and slower ($t(23) = 6.28, p < .01$) TSD ER cues compared to driving alongside faster TSD ER cues. Participants also drove slower while driving alongside the slower TSD ER cues compared to driving alongside same TSD ER cues ($t(23) = 2.77, p < .01$). The main effect for task type was not significant, $F(1,23) = 0.17, p > .05$.

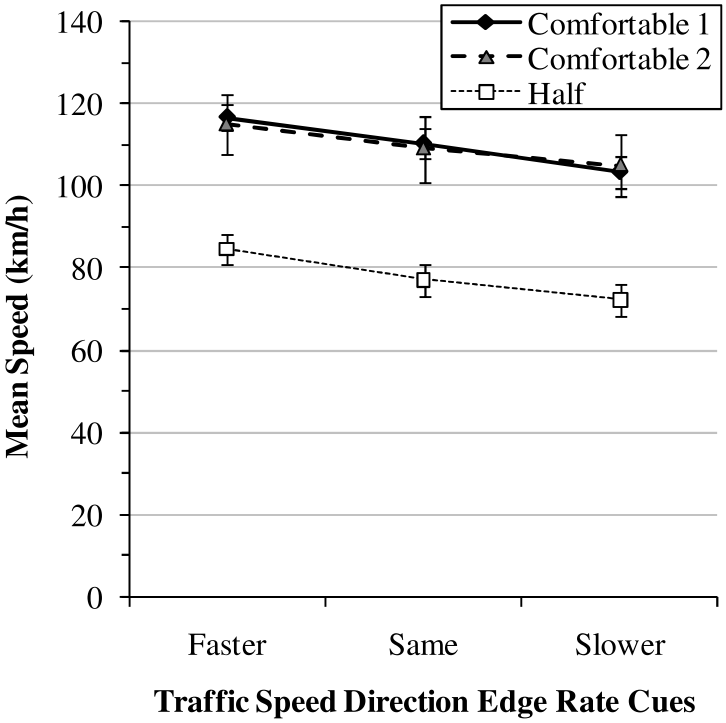


Figure 13. Mean speed performance during Experiment 2.

For half speed task performance, there was a significant main effect for TSD ER cues, *F*(2,46) = 12.93, *p* < .01 (Figure 13). Follow-up tests suggest that half speeds were slower while driving alongside same (*t*(23) = 4.15, *p* < .01) and slower (*t*(23)=4.72, *p* < .01) TSD ER cues compared to driving alongside faster TSD ER cues. The comparison of mean comfortable speed while driving alongside same and slower TSD ER cues was not significant, *t*(23) = 1.75, *p* > .05.

Target Ratio

Target ratio results are presented in Table 8 for comfortable and half speed.

Table 8. Mean (SD) target ratio during Experiment 2.

TSD ER	Comfortable Speed	Half Speed
Faster	0.985 (.047)	1.445 (.208)
Same	0.988 (.073)	1.398 (.231)
Slower	1.021 (.084)	1.386 (.212)

The main effect for TSD ER cues was not significant for either the comfortable speed target ratio ($F(2,46) = 2.35$, $p > .05$) or the half speed target ratio ($F(2,46) = 2.10$, $p > .05$). The mean target ratio for all three TSD ER cue conditions collectively found that drivers' second comfortable speed was on average the same ($M = 1.0$) as their first comfortable speed, and their half speed was on average 41 percent higher than the target half speed (i.e., half of their C1 mean speed).

Speed Drift Ratio

Speed drift ratio results are presented in Table 9 for comfortable and half speed.

Table 9. Mean (SD) speed drift ratio during Experiment 2.

	Comfortable Speed		Half Speed
TSD ER	C1	C2	H
Faster	1.007 (.019)	1.015 (.031)	1.011 (.082)
Same	0.998 (.031)	0.992 (.022)	0.988 (.066)
Slower	0.996 (.039)	0.994 (.044)	0.997 (.041)

For comfortable speed task performance, there was a significant main effect for TSD ER cues, *F*(2,46) = 4.01, *p* < .05 (Figure 14). Pair-wise follow-up tests failed to find significant differences between faster and same (*t*(23) = 2.34, *p* = .028), faster and slower (*t*(23) = 2.35, *p* = .028), or same and slower (*t*(23) = .07, *p* > .05) TSD ER cue conditions. However, the means suggest that the faster cues may have produced larger drift ratios (greater than 1) compared to the same or slower TSD ER cues (ratios less than 1). The main effect for task type was not significant, *F*(1,23) < 0.01, *p* > .05.

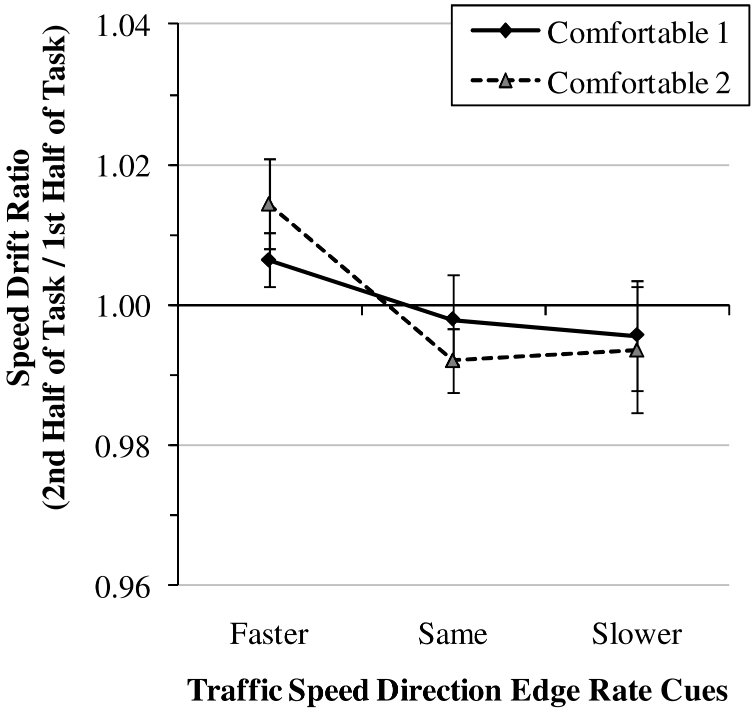


Figure 14. Speed drift ratio performance during Experiment 2.

The main effect for TSD ER cues was not significant for half speed drift ratio, *F*(2,46) = 0.70, *p* > .05.

Reliability Ratio

Reliability ratio results are presented in Table 10 for comfortable and half speed.

Table 10. Mean (SD) reliability ratio during Experiment 2.

	Comfortable Speed		Half Speed
TSD ER	C1	C2	H
Faster	0.012 (.010)	0.016 (.015)	0.037 (.038)
Same	0.020 (.015)	0.015 (.014)	0.044 (.040)
Slower	0.023 (.019)	0.023 (.020)	0.038 (.021)

For comfortable speed reliability ratio, there was a significant main effect for TSD ER cues, $F(2,46) = 4.60$, $p < .05$ (Figure 15). Pair-wise follow-up tests found that the reliability ratio was higher while driving alongside slower TSD ER cues compared to driving alongside faster TSD ER cues ($t(23) = -2.69$, $p = .013$). The comparison of reliability ratios between driving alongside faster and same TSD ER cues ($t(23) = -1.43$, $p > .05$) and between driving alongside same and slower TSD ER cues ($t(23) = -1.77$, $p > .05$) were not significant. The main effect for task type was not significant, $F(1,23) = 0.06$, $p > .05$.

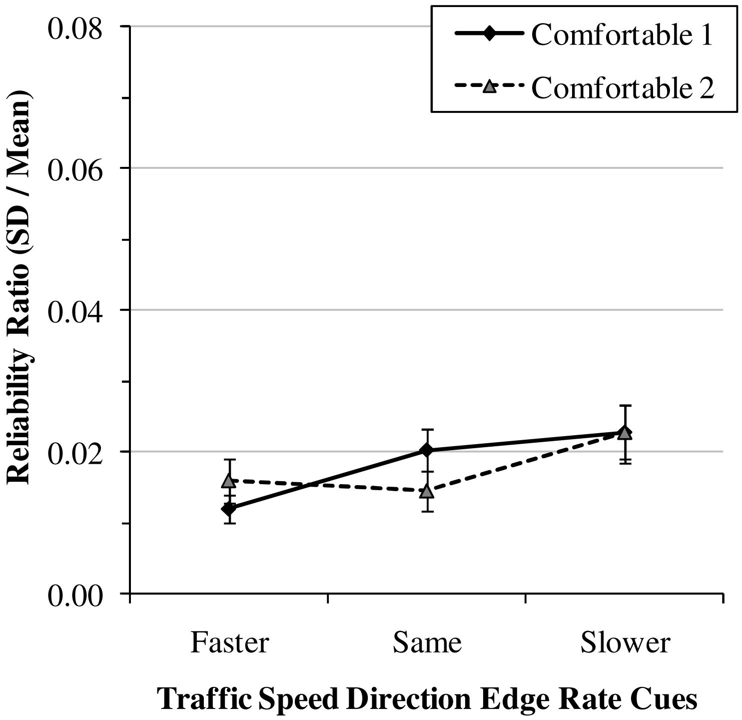


Figure 15. Reliability ratio performance during Experiment 2.

The main effect for TSD ER cues was not significant for half speed reliability ratio, *F*(2,46) = 0.78, *p* > .05.

Ease of Maintaining Target Speeds

Ease rating results are presented in Table 11 for comfortable and half speed.

Table 11. Mean (SD) ease ratings during Experiment 2.

TSD ER	Comfortable Speed [a]	Half Speed
Faster	5.6 (0.9)	4.9 (1.3)
Same	5.8 (0.9)	4.5 (1.4)
Slower	6.0 (0.9)	4.6 (1.4)

[a] Ease ratings were asked in terms of comfortable speed in general and pertain to both C1 and C2 collectively.

The main effect of TSD ER cues was not significant for ease of maintaining comfortable speed ($F(2,46) = 1.81, p > .05$) or ease of maintaining half speed ($F(2,46) = 1.66, p > .05$).

Summary

The purpose of Experiment 2 was to examine the effects of the relative direction of traffic ER cues on speed choice. In terms of speed performance, driving alongside traffic moving at a rate faster than the participant was associated with faster comfortable driving speeds and half driving speeds compared to driving alongside traffic moving at the same or slower speed than the participant. These results agree with the hypotheses that produced speeds would be similar to the speed of ambient traffic. This is because egospeed judgments to proximal TSD ER cues were based on direct perceptual processes emphasizing visceral comparisons between TSD ER cues with little opportunity for drivers to use cognitively-mediated perceptual processes (DeLucia, 2008). Similar to previous findings that when participants estimate speed amongst traffic traveling in the same direction (Conchillo et al., 2006), faster speed TSD ER caused drivers to estimate that they were traveling slower than they actually were traveling, resulting in higher produced speeds. The opposite effect was found when traffic was driving slower than the participant, where drivers produced slower comfortable and half speeds during the slower TSD ER cues compared to during the same speed TSD ER condition. Therefore, expanding TSD ER caused drivers to perceive that they were traveling at a faster speed than they really were traveling, similar to the effect of increasing perceived egospeed by painting transverse lines on the pavement at a gradually increasing frequency (Denton, 1980; Godley et al. 2000; Shinar et al., 1980).

When traffic was traveling at the same speed as the participant, participants produced comfortable speeds that were slower than they produced during the faster TSD ER condition and faster than they produced during the slower TSD ER condition. This supports the hypothesis that participants would produce speeds more neutral in nature. However there is some evidence that the occluding of visual flow cues caused participants experiencing the same speed TSD ER cues to drive faster in that half speeds were faster than those produced during the slower TSD ER condition. Overall this evidence is weak, probably because the optic flow cues being occluded were weak in nature. Therefore no strong conclusions can be drawn regarding the effect of occluding optic flow cues until stronger geographic ER cues are available in the environment, as was examined during the occluding ER cue pair condition in Experiment 3.

Drivers’ speeds during the half speed task (H) was on average 41 percent faster than their target speeds (target ratio), a larger trend than was observed during

Experiment 1. Drivers were able to reproduce their C1 speed during C2 tasks (target ratio equal to 1.0), so it was unlikely that drivers' inability to produce a half speed accurately was due to an inability to understand the task or control the vehicle. The fact that both distant (geographic ER in Experiment 1) and proximal (TSD ER) cues did not have a positive effect on participants' ability to produce accurate target half speeds may suggest that no type of visual ER cue would be effective at helping them produce accurate half speeds regardless of distance while using the MRM within this driving simulator. The evidence from both experiments also suggests that speed production behavior does not have a linear relationship with estimated speed, such that half of an estimated speed does not appear to be equivalent to half of a produced speed. Hollands, Tanaka, and Dyre (2002) reported that the Stevens exponent (β, obtained from proportion estimation and production judgments) may be used to understand the bias in proportion production. They predicted that drivers would underestimate half speeds and therefore overproduce target half speeds, based on Recarte and Nunes' (1996) findings while participants were estimating and producing a range of speeds ($\beta = 1.5$ for estimation and $\beta = 1.4$ for production). Because this was the case with the data from Experiments 1 and 2, it was expected that when both ER cue types were presented during Experiment 3 target ratios would also follow suit (comfortable speed close to 1.0 and half speed between 1.3 and 1.4).

The drift ratio results suggested that drivers were more likely to increase their comfortable speed when ambient traffic was traveling at the faster TSD ER compared to maintaining a more stable speed when traffic was moving at the same or slower TSD ER. This was not surprising in that drivers had faster mean comfortable speeds while driving with faster TSD ER. This positive speed drift may explain why drivers were most likely to reach the top simulator speed and be excluded while driving with faster TSD ER cues. Conversely, the presence of same or slower TSD ER cues assisted drivers in maintaining consistent speed behavior over both the C1 and C2 tasks. This effect was not limited to their initial exposure to the TSD ER cues as was observed for near geographic ER cues during Experiment 1. Although drivers maintained a stable speed (speed drift ratio) while viewing the same TSD cues, this ER condition was associated with a relatively large number of participant exclusions for reaching the top simulator speed as well. These participant exclusions may have been due to selecting an initial speed that was too high rather than drifting upwards in speed during the task. Therefore, faster TSD (proximal contracting ER cue patterns) may gradually decrease drivers' estimations of egospeed over the course of a task, but stable TSD (stable optic flow occlusion) or slower TSD (contracting) ER cue patterns do not appear to affect egospeed estimations over time.

In terms of task difficulty, drivers had higher reliability ratios while viewing the slower TSD ER condition. It appears that drivers achieved highly consistent speed performance (lower speed drift ratio) during this TSD ER condition by making more adjustments to their speed (higher reliability ratio). Drivers may have been trying harder to maintain speeds during the slower TSD ER cue condition because the expanding, slower TSD ER cues presented a different ER frequency than the expanding optic flow inherent in forward path-of-travel movement. Because the half speed reliability ratios were larger than the comfortable speed reliability ratios, this may also suggest that it was more difficult for participants to maintain slower speeds than it was to maintain faster speeds. In addition, the lack of differences between the TSD ER cue conditions in terms of subjective ease ratings suggests that the participants were not aware that they had made more adjustments to their speed during the slower TSD ER condition. This suggests that differences in performance were mediated by visceral (unconscious, immediate) direct perceptual processes. Therefore, the presence of multiple, expanding ER cues may have imposed a higher level of workload on drivers which resulted in more variable and slower speed performance compared to when contracting TSD ER cues were present.

Overall, the MRM was effective at examining differences in TSD ER cues available in surrounding lanes in terms of produced comfortable and half speeds. The faster traffic cues were found to produce faster comfortable and half speeds while also potentially producing a higher speed drift compared to viewing either same or slower TSD ER cues. Faster TSD ER cues were also found to produce less variability in comfortable speed production than slower traffic cues. Slower speed TSD ER cues related more to slower comfortable speeds than did driving alongside same speed TSD ER cues. The MRM found no differences between these TSD ER conditions for the target ratio and subjective ease measures. Similarly, there were only weak effects for the half speed target ratio and speed drift ratio, suggesting that the target ratio, speed drift ratio, reliability ratio, and ease ratings may not be reliable measures of differences between geographic and TSD ER cues. Therefore, when ER cue pairs were presented in Experiment 3, it was expected that differences would be found between ER cue conditions for mean speed but that differences for the other measures would be unlikely.

Overall it seems that participants felt compelled to drive faster while surrounded by traffic traveling faster than their own speed. The lack of geographic ER cues in these experimental drives may have strengthened this effect by forcing the participants to focus on the TSD ER cues because they constituted the only salient information in their field of view. Experiment 3 will examine this issue by observing how the trends observed in Experiment 2 are affected by the addition of near geographic ER cues.

EXPERIMENT 3

This experiment was designed to examine whether speed production would be affected by pairing geographic ER cues with TSD ER cues. Participants drove through environments containing traffic in the lanes to their immediate right and left as well as the near objects used during Experiment 1. The traffic traveled at speeds that were consistently faster, same speed, or slower than the participant’s speed.

Combined with the near geographic ER cues, these traffic conditions created ER cue pairs that were in opposition to, occluding, or in agreement with one another.

Methods

Participants

Thirty-six participants completed the experimental protocol; two were excluded for falling asleep and leaving the center lane and a third participant's data were invalid due to failure to follow the experimental protocol. Nine additional participants were excluded for having a mean speed above 138 km/h during at least one speed maintenance task; in total there were 9 instances of reaching the maximum speed during the opposing ER cue pair condition, 6 during the occluding ER cue pair condition, and none during the agreeing ER cue pair condition.

The final sample consisted of 24 participants (12 female, 12 male, *M* = 19.8 yrs, *SD* = 2.0, *Range* = 18–25) who experienced all the ER cue conditions in a counterbalanced order to minimize any effects of presentation order. Participants were recruited from the University of Minnesota campus, and those recruited from the psychology volunteer pool received course credit for their participation.

Apparatus

The driving simulator's physical setup and functionality were consistent with those described in the Outline of Experiments. The experimental drives also displayed the same road and environment views as were used during the near ER condition of Experiment 1. In addition, this experiment paired geographic and TSD ER cues, as described below.

Edge Rate Cues: Geographic and Traffic Speed Direction ER Cue Pairs

Participants experienced three ER cue pairs to explore the effects of viewing both geographic ER cues and TSD ER cues on comfortable speed choice. The appearance, placement, and behavior of other vehicles on the road were exactly the same as during Experiment 2. Participants also experienced the near geographic ER objects from Experiment 1 on the side of the road. These objects were designed to take up the same visual angle as the vehicles, as depicted in Figure 16. Both the objects and vehicles contained the same benign brick pattern that was used during Experiments 1 and 2. This was important to control for because texture has been found to modify drivers' perception and production of speed (Manser & Hancock, 2007).

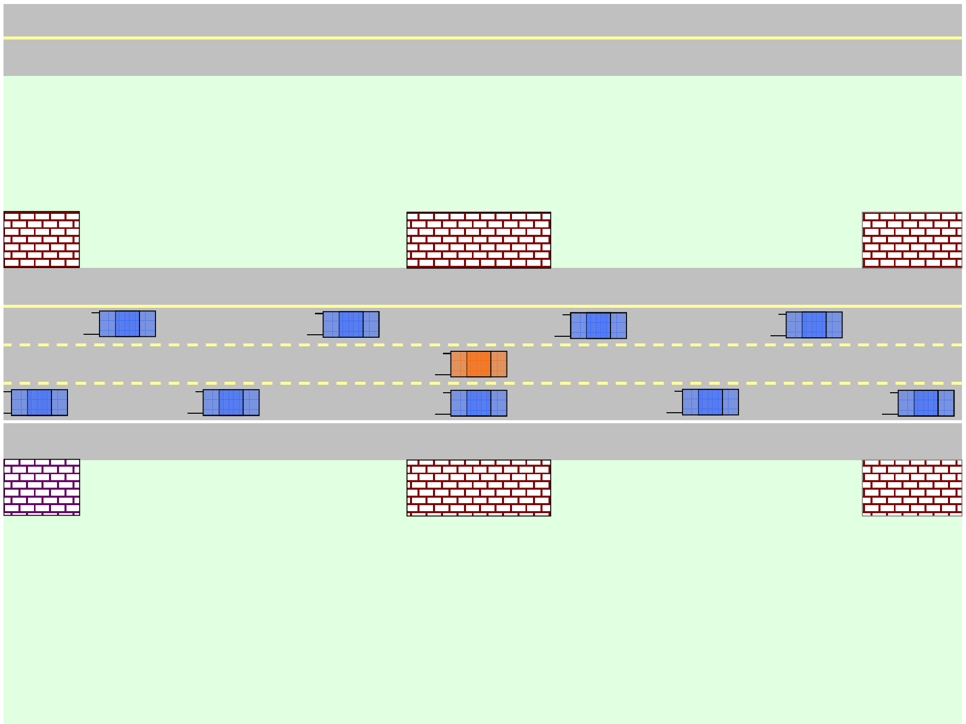


Figure 16. Depiction of the ER cue pair conditions for Experiment 3.
Distances between objects and vehicles are not to scale.

The opposing ER cues (Figure 17A) consisted of vehicles consistently passing the participant while also passing nearby roadside objects. In this condition the near ER cues were expected to produce expanding geographic ER cues in opposition to the contracting, faster TSD ER cues. The occluding ER cues (Figure 17B) consisted of vehicles matching the participant’s speed at all times while also passing nearby roadside objects. In this condition the traffic was expected to remain at a stable location within the participant's field of view and create a relatively consistent occlusion of the expanding ER cues from the near geographic ER objects. The agreeing ER cues (Figure 17C) consisted of vehicles consistently being passed by the participant while also passing nearby roadside objects.

In this condition the near ER cues were expected to produce expanding ER cues in agreement with the expanding ER cues presented by the slower TSD ER cues.

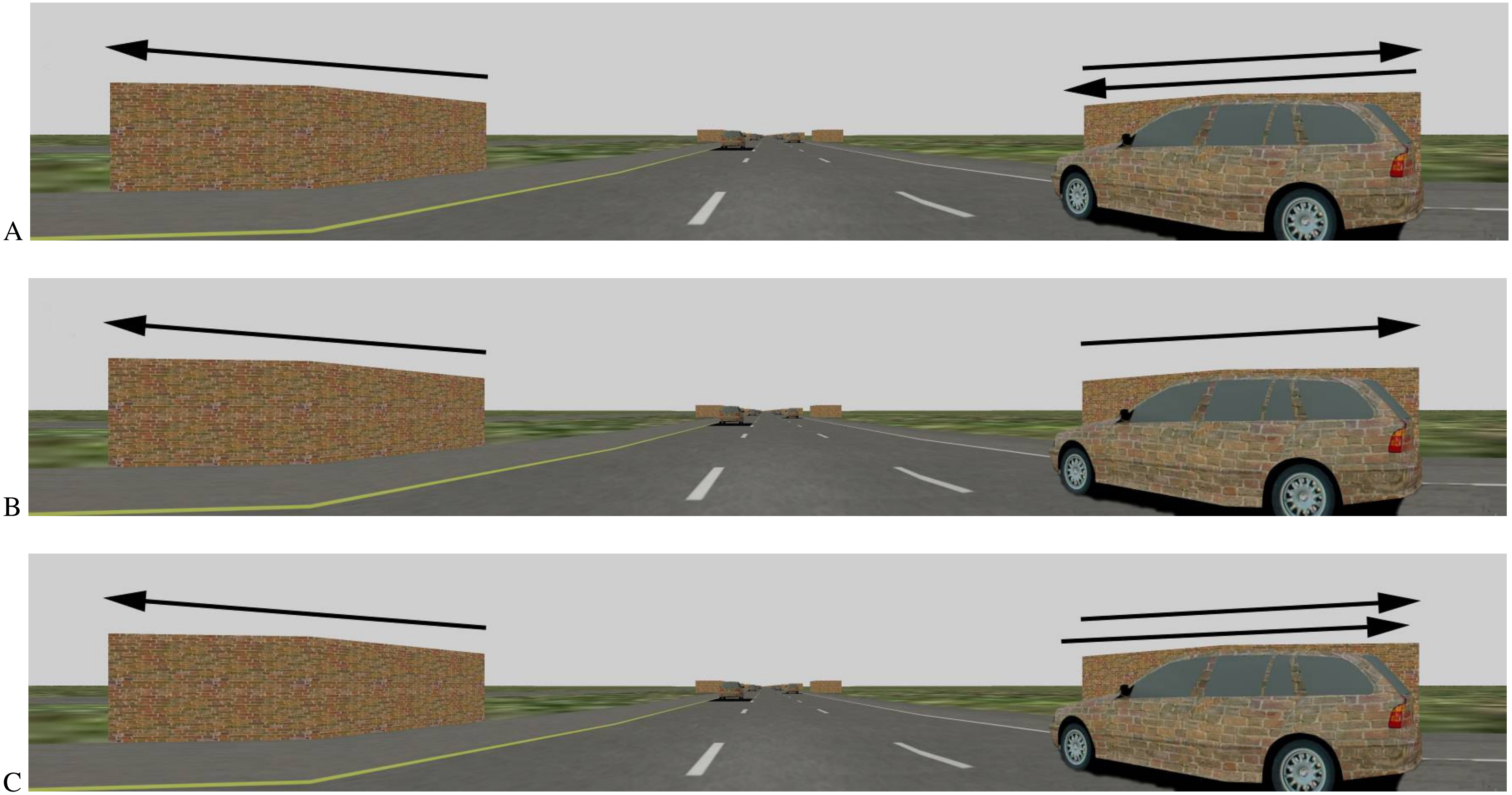


Figure 17. Forward 210 by 40 degree field of view for the A) opposing, B) occluding, and C) agreeing ER cue pair conditions, with black arrows added to emphasize the pattern of closest ER cues.

Although these ER cue pairs were designed to simply add or subtract the effects of geographic ER and TSD ER conditions, these cues may interact in a more complex fashion in a real-world setting. For example, consider the TSD ER cues of the occluding ER condition that were expected to block the driver's view of the geographic ER cues that lie behind them. The net result of this vehicle placement was not only that the geographic ER cues were less visible, but that multiple new ER cue "windows" between vehicles may also have provided additional edges which the geographic ER cues could be seen passing when they moved out of view behind a neighboring vehicle. It was expected that this new pattern of occlusion would produce a stronger perception of egomotion because both the geographic ER cues may now be referenced against the TSD ER cues at a relatively high frequency. In addition, these occlusion cues have a high level of ecological validity which has been found to improve estimates of TTC (Manser, 1997). From this it was predicted that drivers would also have an improved estimate of egospeed, thereby resulting in slower egospeed production. In a similar way, viewing the opposing or agreeing ER cue pairs may also produce multiplicative effects in that these ER cue windows allow viewing the geographic ER cues at faster or slower rates, respectively. For these reasons it was predicted that these ER cue pairs would be the strongest at influencing egomotion perception out of all three experiments, resulting in the ER cue pair conditions having lower speeds than drivers experiencing the near geographic ER cues or any of the TSD ER cues alone.

Procedures and Dependent Variables

The procedures for Experiment 3 were consistent with those described for Experiments 1 and 2. This includes using the MRM within the experimental drives and replacing participants due to reaching the maximum speed allowed by the driving simulator. The dependent variables were also consistent with those described for the previous 2 experiments.

Results

Analyses

A 3 x 2 within-subject ANOVA was performed to examine the effects of ER cue pairs (opposing, occluding, or agreeing cue pairs) and comfortable speed task type (C1, C2). A separate 3-way within-subject ANOVA was performed to examine the effects of ER cue pairs on half speed performance. Follow-up tests for main effects of ER cue pairs were examined with planned pair-wise contrasts between the three ER cue conditions. Differences between means were considered significant at the $\alpha = .05$ level for all main effects and a Bonferroni-corrected significance level of $\alpha = .017$ (family-wise error rate of $\alpha = .05$ divided by 3, the number of follow-up tests) for each of the three pair-wise follow-up effects for ER cue pair. Main effects at the $\alpha = .06$ level and follow-up effects at the $\alpha = .05$ level were considered to approach significance and are noted in the discussion because they may indicate potential trends in the data. Bars within all graphs indicate +/- 1 standard error.

Mean Speed

Mean comfortable and half speed results are presented in Table 12.

Table 12. Mean (SD) speed during Experiment 3.

	Comfortable Speed		Half Speed
ER Cue Pair	C1	C2	H
Opposing	106 (23)	106 (22)	71 (20)
Occluding	100 (25)	101 (26)	67 (23)
Agreeing	94 (25)	93 (26)	62 (23)

For comfortable speed task performance, there was a significant main effect for ER cue pairs, $F(2,46) = 7.42$, $p < .01$ (Figure 18). Pair-wise follow-up tests suggest that comfortable speeds were slower while driving in the agreeing ER cue pair condition compared to driving in the opposing ER cue pair condition, $t(23) = 3.78$, $p < .01$. The comparison between occluding and agreeing ER cue pairs approached significance ($t(23) = 2.19$, $p = .039$), suggesting that the occluding condition may have had a higher mean comfortable speed than the agreeing condition. The comparison between opposing and occluding ER cue pairs ($t(23) = 1.70$, $p > .05$) was not significant. The main effect for task type was not significant, $F(1,23) < 0.01$, $p > .05$.

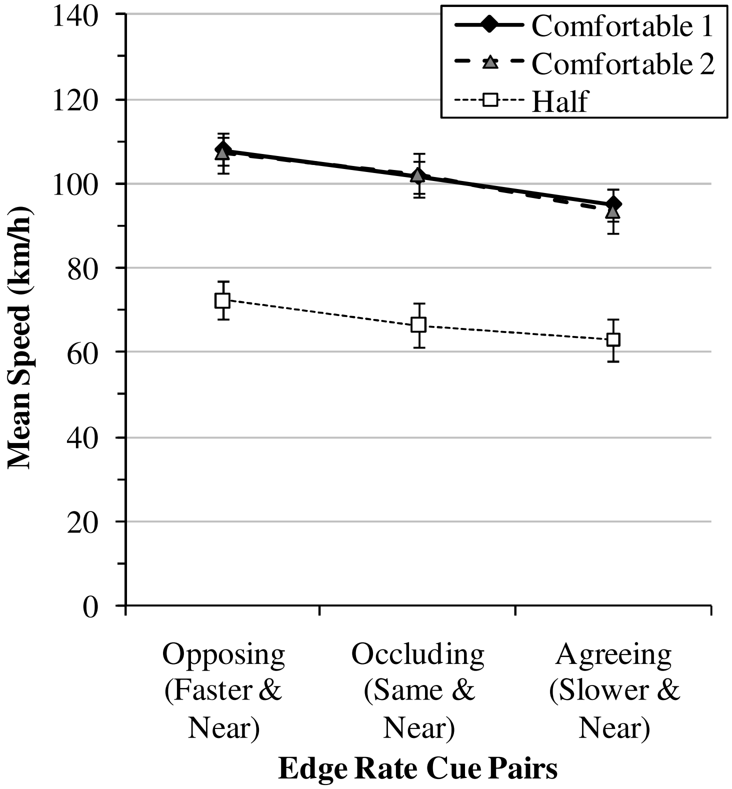


Figure 18. Mean speed performance during Experiment 3.

For half speed task performance, there was a significant main effect for ER cue pairs, $F(2,46) = 5.57$, $p < .01$ (Figure 18). Pair-wise follow-up tests suggest that half speeds were slower during the agreeing ER cue pair condition compared to driving in the opposing ER cue pair condition, $t(23) = 3.20$, $p < .01$. The comparisons between opposing and occluding ER cue pairs ($t(23) = 1.63$, $p > .05$) and occluding and agreeing ER cue pairs ($t(23) = 1.80$, $p > .05$) were not significant.

Target Ratio

Target ratio results are presented in Table 13 for comfortable and half speed.

Table 13. Mean (SD) target ratio during Experiment 3.

ER Cue Pair	Comfortable Speed	Half Speed
Opposing	1.000 (.073)	1.335 (.245)
Occluding	1.021 (.163)	1.325 (.291)
Agreeing	0.990 (.120)	1.292 (.235)

The main effect for ER cue pairs was not significant for either the comfortable speed target ratio ($F(2,46) = 0.57$, $p > .05$) or the half speed target ratio ($F(2,46) = 0.45$, $p > .05$). The mean target ratio for all three ER cue pair conditions collectively found that drivers' second comfortable speed was on average the same ($M = 1.0$) as their first comfortable speed, and their half speed was on average 32 percent higher than the target half speed (i.e., half of their C1 mean speed).

Speed Drift Ratio

Speed drift ratio results are presented in Table 14 for comfortable and half speed.

Table 14. Mean (SD) speed drift ratio during Experiment 3.

	Comfortable Speed		Half Speed
ER Cue Pair	C1	C2	H
Opposing	1.014 (.033)	1.004 (.039)	0.994 (.058)
Occluding	1.008 (.061)	1.007 (.040)	0.993 (.061)
Agreeing	0.996 (.037)	1.010 (.049)	0.991 (.089)

For comfortable speed drift ratio, the main effects for ER cue pairs (*F*(2,46) = 0.36, *p* > .05) and task type (*F*(1,23) = 0.01, *p* > .05) were not significant. The main effect for ER cue pairs was also not significant for half speed task performance, *F*(2,46) = 0.02, *p* > .05.

Reliability Ratio

Reliability ratio results are presented in Table 15 for comfortable and half speed.

Table 15. Mean (SD) reliability ratio during Experiment 3.

	Comfortable Speed		Half Speed
ER Cue Pair	C1	C2	H
Opposing	0.020 (.014)	0.021 (.021)	0.036 (.026)
Occluding	0.028 (.028)	0.022 (.022)	0.042 (.033)
Agreeing	0.024 (.024)	0.027 (.027)	0.055 (.044)

For comfortable speed reliability ratio, the main effects for ER cue pairs (*F*(2,46) = 0.87, *p* > .05) and task type (*F*(1,23) = 0.07, *p* > .05) were not significant.

For half speed reliability ratio, there was a significant main effect for ER cue pairs, *F*(2,46) = 4.25, *p* < .05 (Figure 19). The comparisons between agreeing and opposing (*t*(23) = -2.40, *p* = .025) and between agreeing and occluding (*t*(23) = -2.34, *p* = .028) ER cue pairs approached significance. These results suggested that drivers may have been able to maintain more stable speeds when the opposing and occluding ER cue pairs were present compared to when agreeing ER cue pairs were present. Pair-wise follow-up tests failed to find a significant difference between the opposing and occluding ER cue pair (*t*(23) = -0.90, *p* > .05).

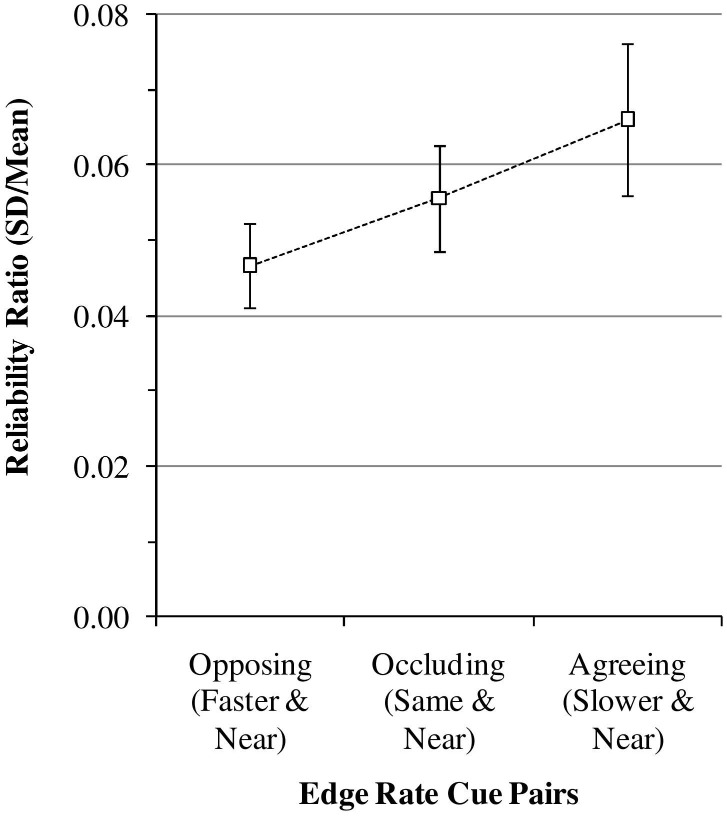


Figure 19. Reliability ratio for half speed task performance during Experiment 3.

Ease of Maintaining Target Speeds

Ease rating results are presented in Table 16 for comfortable and half speed.

Table 16. Mean (SD) ease ratings during Experiment 3.

ER Cue Pair	Comfortable Speed [a]	Half Speed
Opposing	5.9 (0.8)	5.9 (0.8)
Occluding	6.0 (0.9)	6.0 (0.9)
Agreeing	5.6 (1.0)	5.6 (1.0)

[a] Ease ratings were asked in terms of comfortable speed in general and pertain to both C1 and C2 collectively.

For subjective ease of maintaining comfortable speed, there was a main effect for environment, $F(2,46) = 4.39$, $p < .05$ (Figure 20). Pair-wise follow-up tests found that the difference in ease ratings between the occluding and opposing ER cue pairs approached significance ($t(23) = 2.47$, $p = .021$), suggesting that the occluding condition may have had higher ratings of ease than the opposing ER cue pair condition. Pair-wise follow-up tests failed to find significant differences between opposing and agreeing ($t(23) = 1.90$, $p > .05$) and occluding and agreeing ($t(23) = -1.14$, $p > .05$) ER cue pairs.

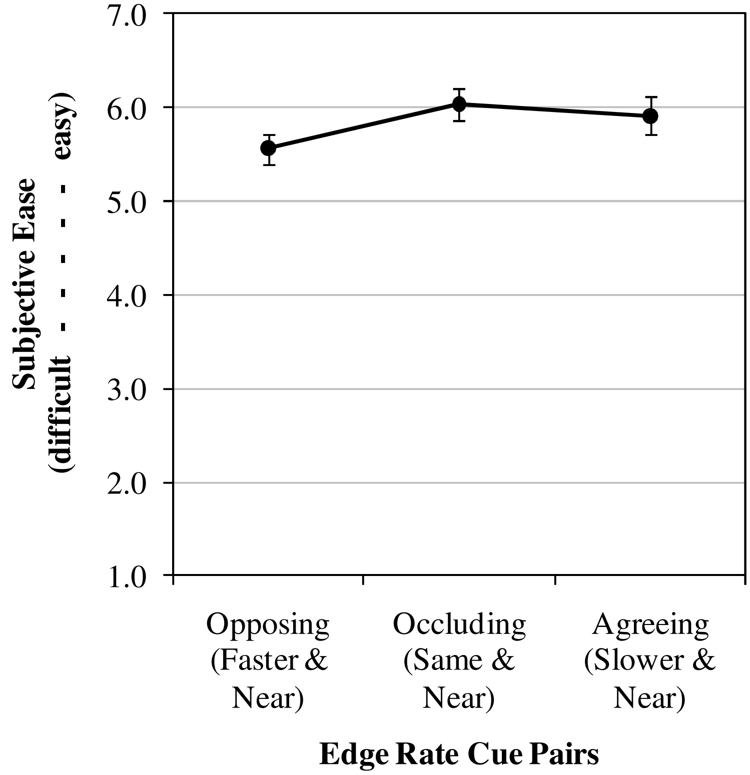


Figure 20. Mean ease ratings for comfortable speed during Experiment 3.

The main effect of ER cue pairs was not significant for ease of maintaining half speed, $F(2,46) = 2.31$, $p > .05$.

Summary

The purpose of Experiment 3 was to examine the effects of ER cue pairs on speed choice. Experiment 2 found that drivers produced significantly different comfortable speeds when traffic was moving faster, the same speed, and slower than the participant. In Experiment 3, these TSD ER cues were presented along with the geographic ER cues that (when presented alone) increased drivers' perception of egospeed and resulted in reduced speeds. Previous findings have indicated that a combination of contracting and expanding optic flow patterns would cause an observer to perceive the TTC of an approaching object as longer than it actually would be (Gray & Regan, 2000). Conversely, they also found that viewing two separate expanding patterns would cause observers to perceive the TTC of an approaching object as shorter than it actually would be. Similar effects were observed during this study when viewing the opposing ER cue pair caused drivers to perceive they had slower egospeed, resulting in faster produced mean comfortable and half speeds compared to when they viewed the agreeing ER cue pair.

Based on the results from Experiment 2, having the same TSD ER during the occluding ER cue pair condition was expected to produce speeds between those produced during the opposing and agreeing ER cue pair conditions. This hypothesis was supported by the non-significant trends between occluding ER and the other ER cue pairs for both mean comfortable and half speed tasks. Over all three ER cue pair conditions, the addition of near geographic ER cues to the TSD ER cues was expected to improve the accuracy of drivers' perceived egospeed and reduce their speed compared to those from Experiment 2. Drivers were expected to be more accurate during Experiment 3 because they could increase the accuracy of their estimated egospeed by mediating their direct perception of TSD ER cues with the assistance of cognitively-mediated, indirect perception of geographic ER cues. This effect will be examined in the subsequent interaction analysis between geographic ER cue presence and TSD ER cues (see below).

As hypothesized, target ratios were similar to those in Experiments 1 and 2 in that the comfortable speed ratio was close to 1.0, and drivers' speed during the half-speed task was on average 32 percent faster than their target speed. This result for half speed target ratio is closer to the average ratio while geographic ER cues were present compared to the average while TSD ER cues were present. This suggests that egospeed perception resulted from a combination of direct and indirect perceptual mechanisms from viewing both ER cue types rather than the lone influence of TSD ER cues. The analysis of the interaction of geographic presence and TSD ER cues (presented below) provides further insight into this comparison. Results from Experiment 3 also provide supporting evidence for the hypothesis that speed production behavior does not have a linear relationship with estimated speed, such that half of an estimated speed did not appear to be equivalent to half of a produced speed.

Observing the ER from TSD ER cues along with near geographic ER cues may have caused drivers to have less difficulty maintaining speed than when TSD ER cue conditions were presented alone (Experiment 2). For the reliability ratio measure, the only difference between ER cue pair conditions was that agreeing cues produced potentially lower reliability than did opposing cues during the half speed task. This may confirm that the addition of near geographic ER cues made the comfortable and half speed tasks less difficult because there are fewer main effects between ER cue pairs than between TSD ER cues (during Experiment 2). Interestingly, drivers' reports potentially signify lower ease of maintaining comfortable speed during the opposing ER cue pair condition compared to their reported ease during the occluding ER cue condition. This effect was not observed when only the TSD ER cues were available during Experiment 2, which may suggest that drivers were more aware of these cues when they were contrasted against the near geographic ER cues during Experiment 3. It may also suggest that the opposing ER cue pair may have been more salient than the other cue pair conditions, leading drivers to use indirect perceptual mechanisms and therefore become more conscious of these cues. Although these trends are interesting, both of these relationships only approached statistical significance.

The MRM identified reliable differences between ER cue pair conditions in terms of produced comfortable and half speeds. This methodology was expected to also identify differences between ER cue types across tasks (target ratio), over time (speed drift ratio, reliability ratio), and in terms of subjective ease. Although the results from Experiment 3 again found no differences between these ER cue pair conditions on the target ratio, speed drift ratio, reliability ratio, and ease rating measures, it is possible that differences may exist between geographic ER cues types (i.e., comparing Experiments 2 and 3) when TSD ER cues are present. This relationship will be explored in the analysis of the interaction between geographic ER cue presence and TSD ER cues.

Experiment 3 found evidence that the near ER cues in the environment had an effect on participants' egospeed perception. As hypothesized, it was observed that the opposing ER cue pair would have a speed-reducing effect while agreeing ER cue pairs would have an additive, speed-increasing effect on comfortable and half speed choice. From the analysis of Experiment 3, it was unclear whether the observed effects were due to the addition of geographic ER cues, due to the strength of the TSD ER cues alone, or an interaction between the two ER cue types. To explore this relationship between geographic ER cues and TSD ER cues on egospeed perception and comfortable speed choice, it was necessary to examine the interaction between geographic ER cue presence and TSD ER cues.

INTERACTION BETWEEN GEOGRAPHIC CUE PRESENCE AND TSD ER CUES

The purpose of this analysis was to identify any interactions between the presence of geographic ER cues and TSD ER cues. The data collected during Experiment 2 were considered because they included the three TSD ER cues with no geographic ER cues. The data collected during Experiment 3 were considered because they included the three TSD ER cues with the near ER geographic ER cues. Therefore, this analysis examined the interaction between these two data sets described in the preceding experiment sections. A main effect for geographic ER cue presence would suggest that the near geographic ER cues affect egospeed perception regardless of the effect of the TSD ER cues. A main effect for TSD ER cues would suggest that the perceived direction of traffic movement relative to the driver affects egospeed perception regardless of the effect of geographic ER cues. An interaction between the two ER cue types would indicate circumstances wherein the cues work together to affect egospeed perception differently depending on the particular pairing of geographic and TSD ER.

Results

Analyses

Two 2 x 3 mixed model ANOVAs were performed to examine the effects of the presence of geographic ER cues (no ER, near) on traffic speed direction ER cues (faster, same, slower speed traffic): one for comfortable speed performance and another for half speed performance. For the comfortable speed analyses, results were examined over both task types (C1, C2) because no main effects or target ratio differences were found for task type during all three experiment analyses. Follow-up tests for any main effects of TSD ER cues were examined with planned pair-wise contrasts between the three TSD ER cue conditions. Follow-up tests for significant interactions were examined using paired-samples *t* tests to compare the no ER to near geographic cue conditions under each TSD ER condition separately. Differences between means were considered significant at the $\alpha = .05$ level for all main effects and a Bonferroni-corrected significance level of $\alpha = .017$ (family-wise error rate of $\alpha = .05$ divided by 3, the number of follow-up tests) for each of the pair-wise follow-up effects for TSD ER cue type. Main effects at the $\alpha = .06$ level and follow-up effects at the $\alpha = .05$ level were considered to approach significance and are noted in the discussion because they may indicate potential trends in the data. Bars within all graphs indicate +/- 1 standard error.

Mean Speed

Mean comfortable and half speed results are presented in Table 17.

Table 17. Mean (SD) speed across Experiments 2 and 3.

	Comfortable Speed		Half Speed
ER Cue Type	C1	C2	H
Geographic Cues			
No ER	110 (34)	109 (36)	78 (33)
Near	100 (34)	100 (36)	67 (33)
TSD Cues			
Faster	111 (20)	110 (20)	78 (20)
Same	105 (22)	105 (23)	72 (21)
Slower	99 (22)	99 (23)	67 (22)

For comfortable speed task performance, there was a significant main effect for TSD ER cues, $F(2,92) = 21.54$, $p < .01$ (Figure 21). Pair-wise follow-up tests suggest that comfortable speeds were slower while driving alongside same ($t(47) = 3.35$, $p < .01$) and slower ($t(47) = 6.47$, $p < .01$) TSD ER cues compared to driving alongside faster TSD ER cues. Participants also drove slower while driving alongside the slower TSD ER cues compared to driving alongside same TSD ER cues ($t(47) = 3.37$, $p < .01$). The main effect for geographic ER cue presence ($F(1,46) = 2.90$, $p > .05$) and the interaction between geographic ER and TSD ER cue presence ($F(2,92) = 0.06$, $p > .05$), were not significant.

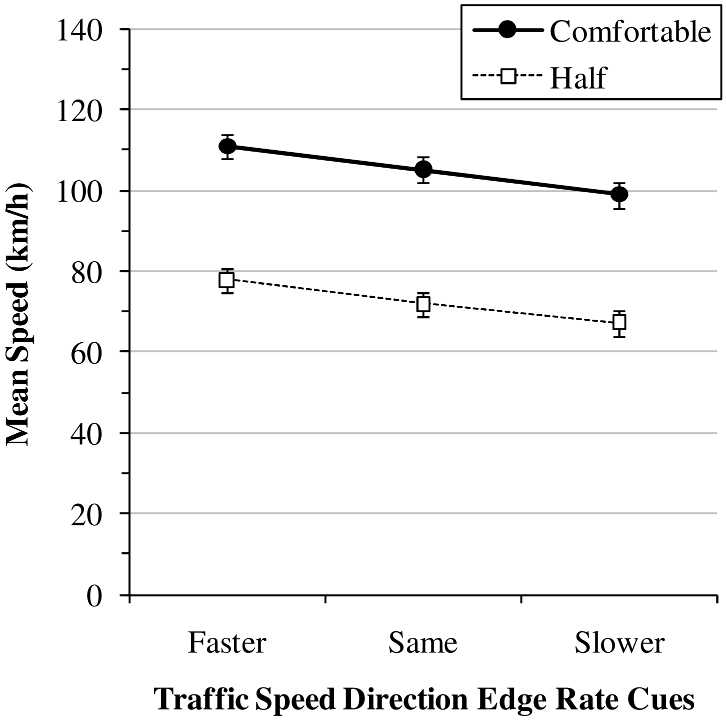


Figure 21. Mean speed performance across Experiments 2 and 3.

For half speed task performance, there was a significant main effect for TSD ER cues, *F*(2,92) = 17.45, *p* < .01 (Figure 21). Follow-up tests suggest that half speeds were slower while driving alongside same (*t*(47) = 3.67, *p* < .01) and slower (*t*(47) = 5.59, *p* < .01) TSD ER cues compared to driving alongside faster TSD ER cues. Participants also had slower half speeds while driving alongside the slower TSD ER cues compared to driving alongside same TSD ER cues (*t*(47) = 2.52, *p* = .015). The main effect for geographic ER cue presence was also significant, *F*(1,46) = 4.27, *p* < .05, suggesting that drivers chose slower half speeds in the presence of near geographic ER cues than they did during the no ER condition. The interaction between geographic ER cue presence and TSD ER cues was not significant, *F*(1,92) = 0.62, *p* > .05.

Target Ratio

Target ratio results are presented in Table 18 for comfortable and half speed.

Table 18. Mean (SD) target ratio across Experiments 2 and 3.

ER Cue Type	Comfortable Speed	Half Speed
Geographic Cues		
No ER	0.998 (.127)	1.410 (.365)
Near	1.004 (.127)	1.317 (.365)
TSD Cues		
Faster	0.993 (.062)	1.390 (.231)
Same	1.004 (.126)	1.362 (.263)
Slower	1.005 (.104)	1.339 (.226)

For comfortable speed target ratio, main effect for geographic ER cue presence ($F(1,46) = 0.09$, $p > .05$), the main effect for TSD ER cues ($F(2,92) = 0.33$, $p > .05$), and the geographic ER cue by TSD ER cue interaction ($F(2,92) = 1.80$, $p > .05$) were not significant. For half speed target ratio, the main effect for geographic ER cue presence ($F(1,46) = 2.35$, $p > .05$), the main effect for TSD ER cues ($F(2,92) = 1.64$, $p > .05$), and the geographic ER cue presence by TSD ER cue interaction ($F(2,92) = 0.21$, $p > .05$) were not significant. The mean target ratio for both geographic ER cue conditions collectively found that drivers' second comfortable speed was on average the same (M = 1.0) as their first comfortable speed and their half speed was on average 36 percent higher than the target half speed (i.e. half of their C1 mean speed).

Speed Drift Ratio

Speed drift ratio results are presented in Table 19 for comfortable and half speed.

Table 19. Mean (SD) speed drift ratio across Experiments 2 and 3.

	Comfortable Speed		Half Speed
ER Cue Type	C1	C2	H
Geographic Cues			
No ER	1.000 (.051)	1.000 (.051)	0.999 (.073)
Near	1.006 (.051)	1.007 (.051)	0.993 (.073)
TSD Cues			
Faster	1.010 (.027)	1.009 (.035)	1.003 (.071)
Same	1.003 (.048)	0.999 (.033)	0.990 (.063)
Slower	0.996 (.038)	1.002 (.046)	0.994 (.069)

For comfortable speed drift ratio, main effect for geographic ER cue presence ($F(1,46) = 0.85$, $p > .05$), the main effect for TSD ER cues ($F(2,92) = 2.61$, $p > .05$), and the geographic ER cue by TSD ER cue interaction ($F(2,92) = 0.88$, $p > .05$) were not significant. For half speed drift ratio, main effect for geographic ER cue presence ($F(1,46) = 0.18$, $p > .05$), the main effect for TSD ER cues ($F(2,92) = 0.52$, $p > .05$), and the geographic ER cue by TSD ER cue interaction ($F(2,92) = 0.39$, $p > .05$) were not significant.

Reliability Ratio

Reliability ratio results are presented in Table 20 for comfortable and half speed.

Table 20. Mean (SD) reliability ratio across Experiments 2 and 3.

	Comfortable Speed		Half Speed
ER Cue Type	C1	C2	H
Geographic Cues			
No ER	0.018 (.025)	0.018 (.025)	0.040 (.051)
Near	0.024 (.025)	0.023 (.025)	0.044 (.051)
TSD Cues			
Faster	0.016 (.013)	0.019 (.016)	0.036 (.032)
Same	0.024 (.024)	0.018 (.022)	0.043 (.036)
Slower	0.023 (.017)	0.025 (.020)	0.046 (.035)

For comfortable speed reliability ratio, there was a significant main effect for TSD ER cues, $F(2,92) = 3.88$, $p < .05$ (Figure 22). Pair-wise follow-up tests showed that ratios were smaller while driving alongside faster TSD ER cues compared to driving alongside slower TSD ER cues, $t(47) = -3.33$, $p < .01$. The comparison when driving alongside faster and same TSD ER cues ($t(47) = -1.60$, $p > .05$) and driving alongside same and slower TSD ER cues ($t(47) = -1.06$, $p > .05$) were not significant. The main effects for geographic ER cue presence ($F(1,46) = 2.39$, $p > .05$) and the geographic ER cue by TSD ER cue interaction ($F(2,92) = 0.57$, $p > .05$) were not significant.

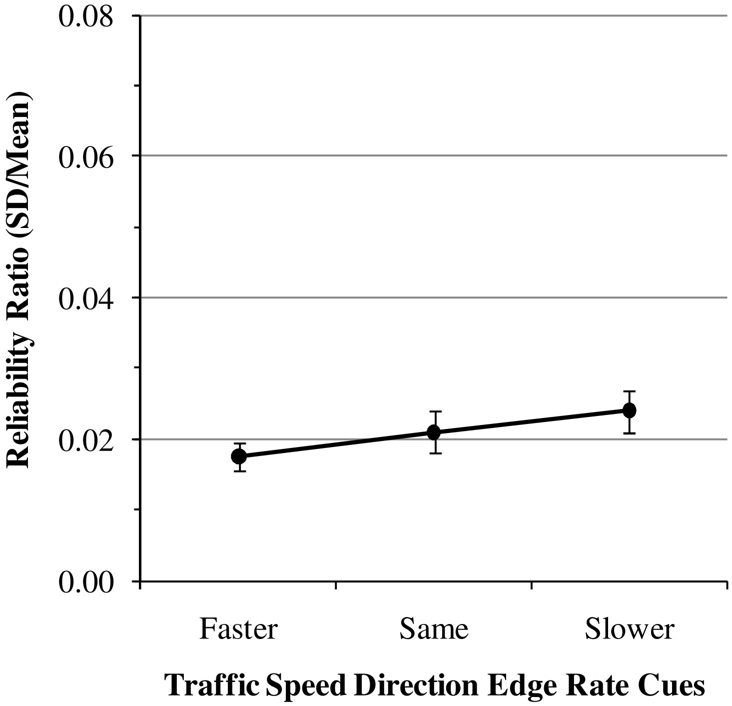


Figure 22. Speed drift ratio across Experiments 2 and 3.

For half speed reliability ratio, the main effects of geographic ER cue presence (*F*(1,46) = 0.30, *p* > .05), the main effect for TSD ER cues, (*F*(2,92) = 2.28, *p* > .05), and the geographic ER cues presence by TSD ER cue interaction (*F*(2,92) = 2.76, *p* > .05) were not significant.

Ease of Maintaining Target Speeds

Ease rating results are presented in Table 21 for comfortable and half speed.

Table 21. Mean (SD) ease ratings across Experiments 2 and 3.

ER Cue Type	Comfortable Speed[a]	Half Speed
Geographic Cues		
No ER	5.8 (1.3)	4.6 (2.1)
Near	5.8 (1.3)	4.4 (2.1)
TSD Cues		
Faster	5.8 (1.0)	4.4 (1.4)
Same	5.9 (0.9)	4.6 (1.4)
Slower	5.8 (1.0)	4.6 (1.4)

[a] Ease ratings were asked in terms of comfortable speed in general and pertain to both C1 and C2 collectively.

For subjective ease of maintaining comfortable speed, there was a significant interaction for the geographic ER cue presence by TSD ER cue interaction, $F(2,92) = 5.19$, $p < .01$ (Figure 23). Although follow-up tests failed to find significant differences between the no ER and near geographic ER cue conditions during the faster ($t(46) = 1.43$, $p > .05$), same ($t(46) = -1.09$, $p > .05$), or slower ($t(46) = -1.21$, $p > .05$) TSD ER cue conditions, the results suggest that participants may have thought it was more difficult to drive with opposing ER cue pairs than to drive just with faster TSD ER cues. The main effect for geographic ER cue presence ($F(1,46) = 0.07$, $p > .05$) and the main effect for TSD ER cues ($F(2,92) = 0.90$, $p > .05$) were not significant.

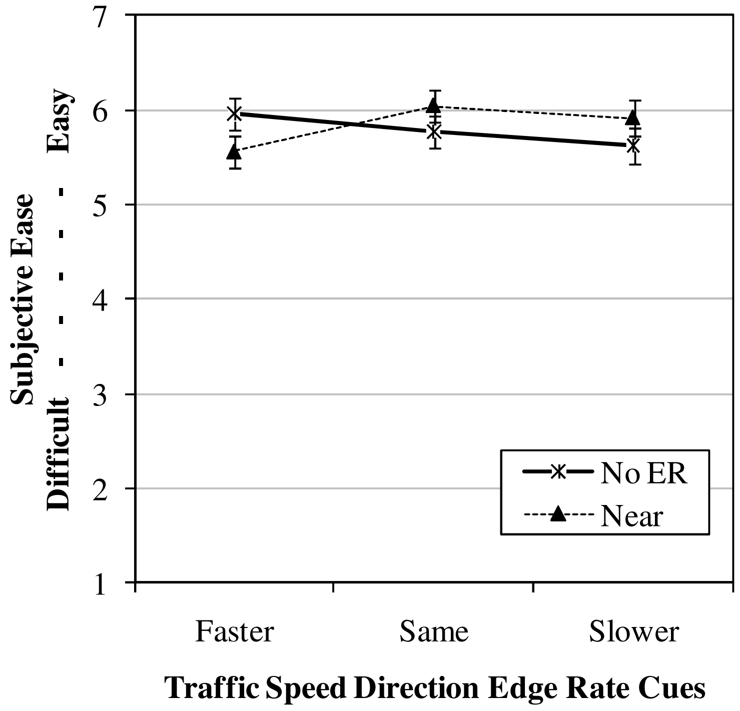


Figure 23. Mean ratings for maintaining comfortable speed across Experiments 2 and 3.

For subjective ease of maintaining half speed, the main effect for geographic ER cue presence ($F(1,46) = 0.36, p > .05$), main effect for TSD ER cues ($F(2,92) = 1.35, p > .05$), and the geographic ER cue presence by TSD ER cue interaction ($F(2,92) = 2.66, p > .05$) were not significant.

Summary

The purpose of this analysis was to examine the interaction between geographic presence and TSD ER cues on speed choice. It was expected that ER cue expansion information would have a stronger influence on egospeed perception at closer distances

(DeLucia, 2008; Manser & Hancock, 1996; Regan & Gray, 2000) such that the proximal TSD ER cues would have a stronger effect on speed production than would the more distant geographic ER cues. For all driving performance measures the interaction between the two ER cue types was not significant. This suggested that regardless of the TSD ER cues present, drivers had similar differences in performance whether the geographic ER cues were present or not. The between-subjects main effect for presence of geographic ER cues found that drivers in Experiment 2 had similar differences in performance between the TSD ER cue conditions as did the drivers in Experiment 3. Therefore, the focus of this summary will be on the main effects of geographic ER cues and TSD ER cues on speed production across Experiments 2 and 3, rather than on the interaction between geographic and TSD ER cue types.

In terms of mean speed performance, TSD ER cues had a significant effect on speed choice during both the comfortable speed and half speed tasks. This was expected because these main effects were also significant during both Experiments 2 and 3. The results found the same relationships between TSD ER cues and comfortable speed choice as were found during Experiment 2: driving alongside traffic moving at a rate that was faster than the participant produced faster comfortable driving speeds and half speeds; driving alongside traffic moving at a slower rate was associated with slower comfortable and half speeds; and driving alongside traffic moving at the same rate was associated with speeds in between the other two conditions. It is therefore concluded that proximal TSD ER information strongly affects egospeed perception regardless of geographic ER cue presence.

There was a main effect for geographic ER cue presence on mean speed during the half speed task, and a similar non-significant trend during the comfortable speed task. Speeds were slower in the presence of geographic ER cues (Experiment 3) compared to speeds when ER cues were absent (Experiment 2). It was hypothesized after Experiment 2 that the addition of geographic ER cues beyond the TSD ER cues would provide drivers with the ability to take advantage of visceral and cognitively-mediated comparisons of speed, resulting in faster perceived egospeed and slower produced speeds overall. The interaction results suggest that the geographic ER cues had a weak effect on egospeed perception regardless of the direction of TSD ER cues that were also present. It is therefore concluded that distant geographic ER information may have an effect on egospeed perception regardless of TSD ER cue presence. Practically, this conclusion suggests that using speed countermeasures, such as transverse road striping or applying a frequent ER pattern to passed-objects, can have a speed reduction affect on drivers regardless of the traffic that is occluding portions of that pattern.

Target ratios were similar to those in Experiments 1 and 2 in that the comfortable speed ratio was close to 1.0 and drivers' speed during the half-speed task was on average 36 percent faster than their target speed. Although it was hypothesized from the results of Experiments 2 and 3 that the half speed target ratio would be closer to the average ratio while geographic ER cues were present compared to the average while TSD ER cues were present, there was no main effect for geographic ER cues. This suggests that ER cue type may not have played a large role in drivers' ability to produce accurate C2 and half speeds relative to their C1 speed. This also provides more supporting evidence for the hypothesis that speed production behavior does not have a linear relationship with estimated speed, such that half of an estimated speed does not appear to be equivalent to half of a produced speed.

There was a significant main effect for TSD ER condition on the reliability ratio during the comfortable speed task. Reliability ratios while experiencing the faster TSD ER cues were significantly lower than those while experiencing the slower TSD ER cue condition. Post hoc observation suggests that drivers' ability to maintain speed was also more stable during the faster speeds (comfortable speed tasks) than during the slower speeds (half speed task) regardless of the presence of near geographic ER cues. Therefore, TSD ER cues once again had a stronger effect on egospeed perception in comparison to geographic ER cues, as was expected by the TSD ER cues' greater proximity. Drivers also did not change their comfortable speed choice over time (speed drift ratio) based on either geographic or TSD ER cue types. In addition, there was no effect for drivers' ratings of ease, which suggests that differences between the geographic and TSD ER cues were not related to perceived differences in drivers maintaining their comfortable and half speeds. This may also suggest that drivers were using more direct perceptual mechanisms and were not aware that the ER cues were affecting their perceived egospeed.

The MRM has been reliable in identifying differences between comfortable and half speed choices resulting from the presentation of geographic and TSD ER cues. Overall, this methodology found few differences between these ER cue conditions on the target ratio, speed drift ratio, reliability ratio, and ease rating measures. The half speed target ratio may only have utility for quantifying the extent that drivers overproduce these speeds. The lack of differences for the speed drift and reliability ratios suggests that drivers are relatively good at maintaining consistent target speeds within a virtual environment. Furthermore, significant differences between mean produced speeds may suggest that changing a driver's perceived egospeed does not make the task of maintaining a comfortable speed more difficult or easy. Alternatively it may suggest that drivers are largely unaware of the effects of ER cues on perceived egospeed, especially in instances where those cues are not in conspicuous disagreement with each other, as was evidenced by the significant effect for the opposing ER cue pair for ease ratings between Experiments 2 and 3.

DISCUSSION

The purpose of this research was to examine three questions: (1) Will speed production be affected by the presence of ER cues from objects at near and far distances from the road? (2) Will speed production be affected by ER cues moving at similar, faster, or slower speeds than the observer's speed (e.g., vehicles traveling in adjacent lanes)? (3) Will differences in speed production found while experiencing geographic or traffic ER change when they are experienced at the same time? Each of the research questions will now be addressed in light of the results from this research. The MRM was used to answer these questions by examining performance on comfortable and half speed maintenance tasks; performance of relative judgments about speed (target ratio); speed consistency performance over the course of the task (speed drift ratio, reliability ratio); and judgments of task difficulty (ease rating). A summary of all significant ER cue comparisons can be found in Table 22 for mean speed and in Table 23 for the non-mean speed measures.

Table 22. Summary of significant comparisons for mean speed by ER comparison and task.

ER Comparison	Comfortable Speed	Half Speed
1. Geographic Presence	no ER > near	(no ER > near)
1. Geographic Distance	far > near	far > near
2. Traffic Speed Direction (TSD)	faster > same faster > slower same > slower	faster > same faster > slower
3. Cue Pairs	opposing > agreeing (occluding > agreeing)	opposing > agreeing
2. Geographic Presence x 3. Traffic Speed Direction	faster > same faster > slower same > slower	no ER > near faster > same faster > slower same > slower

Note: Parentheses “( )” denote an effect that approached significance.

Table 23. Summary of significant comparisons for non-mean speed comparisons by ER comparison and task.

ER Comparison	Target Ratio	Speed Drift Ratio	Reliability Ratio	Ease Rating
1. Geographic Presence	-	-	-	-
1. Geographic Distance	H: (far > near)	C: (for near: C1 < C2)	-	-
2. Traffic Speed Direction (TSD)	-	C: (faster > same) C: (faster > slower)	C: faster < slower	-
3. Cue Pairs	-	-	H: (opposing > agreeing) H: (occluding > agreeing)	C: (opposing < occluding)
2. Geographic Presence x 3. Traffic Speed Direction	-	-	C: faster < slower	C: (for faster: no ER > near [opposing])

Note: Parentheses "( )" denote an effect that approached significance. "C" denotes effects for the comfortable speed task. "H" denotes effects for the half speed task.

Will Speed Production be Affected by the Presence of ER Cues from Objects at Near and Far Distances from the Road?

Experiment 1 examined the effects of the presence and observed distance of geographic ER cues. The presence of near geographic ER cues led to slower speeds in comparison to conditions when ER cues were not present. This effect was in the expected direction: drivers were able to use the geographic ER cues to better inform their egospeed perception by using a combination of direct and indirect perceptual mechanisms. In fact, there were slightly fewer participants who were excluded due to reaching the maximum speed during the near condition compared to the no ER condition (10 percent compared to 13 percent, respectively; see Table 24). This suggests that it may have been easier to unknowingly reach the maximum speed when they could not refer to ER cues within the environment. Geographic ER cue presence also effectively reduced mean half speeds (and showed a trend for comfortable speeds) when TSD ER cues were present during Experiment 3 (near geographic ER) in comparison to Experiment 2 when they were not present (no ER). Together these results show that drivers use geographic ER cues to make slower and more consistent speed choices. The lack of difference between ease ratings also suggests that drivers are likely to perceive these cues using direct perceptual mechanisms (i.e., viscerally: immediately and unconsciously), which may explain why they do not report these differences in produced speed to be more difficult to maintain.

Table 24. Valid tasks that were excluded due to driving at maximum speed.

	All Tasks Completed	
ER Cue Type	Count	Percent
Geographic Cues		
No ER	8	13%
Far	7	11
Near	6	10
TSD Cues		
Faster	20	27
Same	18	24
Slower	7	9
Cue Pairs		
Opposing	9	14
Occluding	6	9
Agreeing	0	0

Near ER cues had a significantly stronger effect at reducing speeds than did the far cues, as was expected by previous research that found optical information to be more influential when it is located at closer distances to the observer (DeLucia, 2008; specifically within the context of driving, see also van der Horst & de Ridder, 2007; Manser & Hancock, 2007). This was observed in the results of Experiment 1 where the presence of far geographic ER cues did not lead to a difference in speed compared to the no ER condition. Because the ER cues provided by far objects were further away, drivers had less information to inform their speed choice, resulting in slightly greater difficulty when attempting to reduce their speed by half compared to when they viewed the near objects. This was suggested by the target ratio data where near cues produced speeds marginally closer to the target half speed (33 percent above target) compared to instances where far cues were present (39 percent above target). This follows from DeLucia's framework for motion perception (2008) in that objects located at shorter distances are more inclined to activate direct, visceral perceptual mechanisms, thereby increasing the strength of their perceived egospeed and reducing their produced speed. When coupled with cues are at greater distances, drivers may also take advantage of indirect, cognitively-mediated perceptual processes resulting in increased egospeed perception and reduced produced speeds.

Although there was a significant difference between no ER and near ER cue conditions during the comfortable speed task, this comparison only approached significance during the half speed task (while traveling at slower speeds). This post hoc finding also agrees with DeLucia's framework in that tasks involving faster motion cues are expected to activate more direct perceptual mechanisms in addition to the cues processed by indirect perceptual mechanisms from cues at greater distances. As described in the previous paragraph, drivers will have more accurate egospeed perception when a combination of direct, visceral perceptual processes with indirect, cognitively-mediated perceptual processes. This may explain why past on-road research (Recarte & Nunes, 1996; Conchillo et al., 2006) found observers to be more accurate at estimating their egospeed while traveling at faster speeds. Within the context of this experiment, the result of having more accurate egospeed perception was a reduction in speed.

This difference between objects at far and near distances may have potentially resulted from an increased perception of risk from driving too fast for the current conditions. Because the objects at the far distance subtended the same visual angle as the near objects but only appeared to be placed at further distances from the driver, it does not seem plausible that drivers maintained slower speeds to be cautious for fear of colliding with either of these object types, especially since there were no significant differences between the geographic ER cues on the reliability ratios or ease ratings. This lack of difference for task ease suggests instead that drivers were unaware of their increased perception of egospeed. This would be more likely if drivers processed additional cues directly as was expected to be the case during the near geographic ER condition.

Finally, there was tentative evidence that the near objects were more effective at helping drivers maintain a consistent speed over the course of the C1 task compared to the C2 task (speed drift ratio) when these were the only ER cues present (Experiment 1). Similar to results of van der Horst & de Ridder (2007), this would suggest that the near geographic ER cues may be more effective when first encountered and that the effectiveness as a cue was diminished over the length of exposure. This effect may have been diminished by the method of sampling that was necessitated by the study design—namely that the first 40 seconds of the speed tasks were not examined due to potential contamination from participants signaling their comfortable or half speeds prematurely. This necessary (yet unfortunate) data exclusion may also be why the comfortable speed target ratio was not associated with any strong differences between speeds during the C1 and C2 tasks (mean target ratio was 1.0). In addition, the interaction analysis found that geographic ER cues did not produce any differences in speed ratio while TSD ER cues were present.

In summary, the presence of the near geographic ER cue condition produced slower speeds than the no ER cue condition. The distance at which the ER cues were located also made a difference in that near cues produced slower speeds than the far cues. These findings suggest that drivers are able to use near geographic ER cues to improve their egospeed judgments, although there was some weak evidence that these cues may become attenuated over the course of longer exposures. Traffic safety practitioners wishing to reduce driver speeds can use geographic ER cues most effectively by placing them at a closer distance to the driver to maximize the subtended visual angle of the cue.

Will Speed Production be Affected by Traffic ER Cues Moving at Similar, Faster, or Slower Speeds?

During Experiment 2, this research examined the effects of traffic speed direction (TSD) ER cues. It was clear that participants' mean speed was linked to traffic speed: When traffic was moving faster, the participant also chose faster comfortable speeds, and when traffic was moving slower, participants chose moderate-to-slower comfortable speeds. This effect was in the expected direction and may suggest that drivers relied heavily on the TSD ER cues because they were the strongest visual cues available to them. In fact, there were notably more participants who were excluded due to reaching the maximum speed during the faster and same TSD ER cue conditions (27 and 24 percent, respectively; see Table 24) compared to the slower TSD ER cue condition (9 percent) or any other ER cue condition in Experiments 1 and 3 (Table 24. It may have been easier to unknowingly reach the maximum speed during the faster and same TSD ER conditions due to the strength of these ER cues. The compelling effect of TSD ER cues was also maintained when they were presented together with the geographic ER cues (Experiment 3), in that the significant main effect for TSD ER cues was found during the interaction analysis. These results conform to DeLucia's framework for motion perception (2008) which suggested that cues viewed at a close distance would have a strong influence on motion perception by activating direct perceptual mechanisms. Because these direct mechanisms serve visually guided actions viscerally, drivers were expected to be influenced by these cues without realizing they were producing different speeds.

The direction of TSD ER cues had an additional effect on the reliability of drivers' speed. While driving amongst the faster TSD ER cues during Experiment 2, participants had lower reliability ratios for their comfortable speed compared to their performance while driving amongst the slower TSD ER cues. Trends in the speed drift ratios also suggested that while producing a comfortable speed and experiencing the faster TSD ER cues, drivers increased their speed over the course of the exposure more than while experiencing either the same or slower TSD ER cues. The faster TSD ER cues, which presented a consistent contracting ER cue, may have caused drivers to continually perceive that their egospeed was slower than it actually was, resulting in gradual increases in produced speed. It is interesting to note that the opposite effect did not occur to the same extent under expanding, slower TSD ER cue conditions, even though mean comfortable speeds were slower during the slower TSD ER cue condition. This may suggest that contracting ER cues that are in opposition to the driver's forward path of travel (expanding optic flow) have a stronger effect on perceptions of egospeed. The likelihood of this effect is further supported by the analysis of the interaction between geographic ER cue presence and TSD ER cues, which suggested that faster TSD ER cues may produce lower reliability regardless of the geographic ER cues present. Therefore, the combination of opposing ER cues (contracting TSD ER paired with expanding near geographic ER) may have a stronger influence on egospeed perception overall.

One might hypothesize that either faster or slower TSD ER cues would lead drivers to have an increased perception of risk due to the continuous feeling of driving slower or faster than surrounding traffic (during the faster and slower TSD ER cue conditions, respectively). Although there were no differences observed in the ease ratings between these TSD ER cue conditions during Experiment 2, the differences observed in mean comfortable speeds were due to the TSD ER cues activating visceral (unconscious, immediate) direct perceptual mechanisms that resulted in changes to their speed performance rather than conscious choices based on perceptions of anxiety. These changes may have also been exaggerated by an increased perception of risk, although it was beyond the scope of the current research to differentiate between the effects of perceived risk and egospeed perception.

Similar to when they experienced geographic ER cues, the speed at which participants traveled (i.e., comfortable versus half speed) may have played a role in their egospeed perception. This was suggested by the significant difference between same and slower TSD ER cue conditions observed during the comfortable speed task that was not significant during the half speed task (when drivers were traveling at slower speeds). Once again, similar trends have been found in speed estimation research in the real world (Recarte & Nunes, 1996; Conchillo et al., 2006) and ER cues may have had a stronger effect on egospeed perception at higher speeds (Denton's ER, equation 2). Because all three TSD ER cues subtended the same visual angle, differences between the ER cue conditions must have been due to differences in traffic speed direction ER cues.

DeLucia's framework would also suggest that faster-moving cues would strongly influence drivers' egospeed judgments (direct perceptual mechanisms) when no other salient references were present that allow for cognitively-mediated perception. Therefore it follows that the faster TSD ER cues not only had a more pronounced effect on egospeed perception but this effect may be stronger at faster speeds.

Admittedly, the governed upper speed limit in the driving simulator makes it difficult to draw any specific conclusions relating to behavior at faster speeds. However, it is expected that the relationship between TSD ER cues and speed behavior at higher speeds has a non-linear trend due to Weber's law (i.e., positive correlation between speed and the strength of visual stimuli necessary to perceive differences in speed magnitude) and the visual fidelity loss that is inherent at faster rates of travel. This non-linear trend was indicated by drivers consistently producing faster half speeds compared to the target half speed during all three experiments. The hypothesis that half of an estimated speed is not equivalent to half of a produced speed could be answered with additional data from additional speed ratios (e.g., having participants drive at twice their comfortable speed).

In summary, slower TSD ER cues led drivers to perceive they were driving faster, resulting in moderate-to-slower produced speeds. Conversely, faster TSD ER speed cues led drivers to perceive they were driving slower, resulting in faster produced speeds. Faster ER cues had a strong, continuous influence on egospeed perception which resulted in lower variability and upward speed drifts during the course of each task. It may also be the case that the ER cues from the faster TSD ER cues had a stronger effect on egospeed perception at faster speeds (i.e., during the comfortable speed task) than did same or slower TSD ER cues because they are in opposition to any geographic cues from the environment. This may also have resulted from the drivers maintaining faster speeds during the faster TSD ER cue condition. Therefore, traffic safety practitioners wishing to reduce driver speeds may find greater benefits by applying some form of expanding ER (slower TSD) cues in situations where drivers are already traveling at faster speeds.

Will Differences in Speed Production During Geographic or Traffic ER Change When They Are Experienced at the Same time?

During Experiment 3, this research examined the effects pairing geographic and TSD ER cues by examining the effect of ER cue pairs on speed production. These results suggest that drivers are using a combination of direct and indirect perceptual mechanisms to achieve a more accurate representation of egospeed. Because the direct mechanisms serve visually guided actions by providing an unconscious and immediate visceral reference, drivers were expected to be influenced by the TSD ER cues without realizing they were producing different speeds. However, the geographic ER cues were expected to help drivers by providing an additional, cognitively-mediated influence which could be integrated to improve egospeed perception.

When ER cues were in agreement (i.e., expanding, slower TSD ER appeared to move in the same direction as the expanding, near geographic ER cues) the participants chose slower comfortable speeds compared to when the ER cues were occluding or in opposition to geographic ER cues. As also found in laboratory studies of expansion and contracting flow rate (Gray & Regan, 2000), when drivers observed two separate sources of expanding ER information, drivers perceived they were traveling at a faster egospeed and reduced their speeds to a greater extent than when one cue was occluding the other or when the cues were providing opposing (contracting) information. In addition, there were no participants excluded due to reaching the maximum speed during the agreeing ER cue pair condition compared to during the opposing and occluding ER cue pair conditions (14 and 9 percent, respectively; see Table 24), making this the only condition from all three experiments where no drivers reached the maximum speed. This suggests that the agreeing ER cue pair provided a set of cues that made it easier for drivers to maintain a slower speed throughout the trial.

One might hypothesize that either faster or slower TSD ER cues would lead drivers to have an increased perception of risk due to the continuous feeling of driving slower or faster than surrounding traffic (during the faster and slower TSD ER cue conditions, respectively). This effect was expected to be stronger in Experiment 3 compared to Experiment 2 due to the addition of the geographic ER cues. There is weak evidence to support this hypothesis in that drivers reported it was marginally easier to drive with the occluding ER cue pairs than with the opposing ER cue pairs. When occluding ER cue pair objects were present in the driving environment, we observed that drivers perceived the geographic ER cues as moving past them at a faster rate, leading to a perception of faster egospeed and resulting in marginally slower speeds compared to those during the opposing ER cue pair condition. Overall, the collective lack of significant differences among ER cue conditions suggests that the effects of ER cues are focused at the perceptual level and not a result of conscious processing of anxiety or threat from visual cues as would be expected from using direct perceptual mechanisms.

It was also expected that the presence of geographic ER cues (Experiment 3) would have resulted in drivers improving their perception of egospeed in comparison to conditions when they were not present (Experiment 2) due to the ability to make egospeed judgments based on two references to immediate, direct cues (and potentially using them as weak cognitively-mediated reference cues as well). Improved perception of egospeed was expected to result in drivers producing similar speeds across the TSD ER conditions, an effect that was explored in the interaction analysis between the presence of geographic ER cues and TSD ER cues. The interaction analysis found that the presence of near geographic ER cues produced slower half speeds but did not have a significant effect on mean comfortable speeds (although the trend suggests speeds were lower). Although the presence of geographic ER cues was found to significantly affect speed choice while presented alone (Experiment 1), presenting both cue types together may have been more influential.

These results add insight to the findings of past on-road research (Conchillo et al., 2006) where observers were found to be less accurate at estimating their egospeed when in the presence of ambient traffic. The experimenters did not control for traffic type, so it was unknown whether the ER cues from traffic may have provided information similar to opposing, occluding, or agreeing ER cue pairs. In the current study, the combination of geographic ER cues and TSD ER cues did not result in any interaction effects, although the ER cue pairs did have an influence on drivers' egospeed perception that was different from viewing either cue type alone. The agreeing ER cue pair led drivers to perceive they were driving faster, resulting in slower produced speeds. This is in contrast to when geographic ER cues were occluded or in opposition to the TSD ER cues where these ER cue pairs reduced the accuracy of egospeed perception and resulted in faster speeds. These findings add to the previous discussion on the effect of TSD ER cues. It was hypothesized that the faster TSD ER cues had a stronger effect on egospeed perception at faster speeds than did same or slower TSD ER cues because they were in opposition to the geographic ER cues from the surrounding environment. The addition of geographic ER cues was most influential while driving at slower speeds (half speed task), suggesting that these cues may not be as effective at informing egospeed perception while TSD ER cues are present and while drivers are traveling at faster speeds. Overall, when the expanding geographic ER cues were in agreement with the expanding and TSD ER cues in the agreeing ER cue pair condition, they had a stronger effect on informing egospeed perception than when these cues were occluding or in opposition to each other—an effect which resulted in faster produced speeds.

For traffic safety practitioners, these findings suggest that the perceived speed of more proximal ER sources, such as traffic, may have a stronger influence on egospeed perception than more distant geographic ER cues. Also, a driver’s perception of egospeed can be improved by enhancing optic flow with additional, expanding (agreeing) ER cues. In general, geographic ER cues may be more effective at curbing unsafe speeds on roads where drivers travel at slower speeds. Overall, speed reduction may be realized by using geographic cues to affect the speed of drivers who are closer to those cues (e.g., drivers in outside lanes of a highway) resulting in speed reduction for other traffic more distant from those cues within the traffic stream (e.g., inside lanes of highway). This type of complex interaction between drivers would need further exploration before concrete recommendations could be made on the net speed reduction of traffic streams. That said, the evidence here suggests that adding geographic ER cues will reduce speeds regardless of the TSD ER cues present. Therefore, the addition of ER cues similar to those presented in the geographic ER cue condition would be an effective method to reduce unsafe speeds regardless of the traffic conditions.

Effectiveness of the Modified Ratio Method

The main purpose of proposing and using the MRM involving target speeds was to mitigate the potential inherent limitations of using a virtual driving environment. Specifically, drivers are more accustomed to driving in a real-world environment where they experience visual, audio, proprioceptive, and tactile stimulation at a higher level of fidelity. No driving simulation will ever be able to completely replicate the experiences of driving on a real-world road, including the sensations relating to accelerating, decelerating, turning, and maintaining various speeds. The use of the comfortable speed, half speed, and returning to comfortable speed tasks allowed for the measurement of additional measures relating to what speeds drivers felt were comfortable (mean comfortable and half speeds); their ability to make relative judgments about their speed (target ratio); their ability to maintain a consistent speed over the course of the task (speed drift ratio, reliability ratio); and their judgment of task difficulty (ease rating). The effectiveness of the MRM towards each of these four aims will now be explored.

The MRM was sensitive to differences in drivers' mean speed while experiencing different ER cues. The mean driving speed measure for both comfortable and half speed tasks was consistently sensitive enough to identify differences between ER cues for the geographic presence, geographic distance, traffic speed direction, and the cue pair comparisons. This suggests that the length of time which drivers were given for each task (180 seconds) and the sample time segment (i.e., from the 40th second though the 180th second) were sufficient to observe differences between these conditions. Furthermore, comparing results of the half speed task to that of the comfortable speed task (post hoc) allowed for a high-level examination of how overall net speed (i.e., faster versus slower) may affect speed choice differently during each of the ER comparisons. Therefore, if it is the goal of future research to determine differences between sets of ER cues, the MRM would be effective as it was applied in these experiments. If the remaining questions are not of interest or if shorter experimental sessions are necessitated, an adequate amount of data from just a single comfortable speed task per each ER condition could be collected (i.e., have participants complete just C1). One caveat to this option is that higher frequency ER cues may cause speed drift effects when initially presented, as was found during the presence of the near geographic ER cues during Experiment 1. This effect was not observed when the lower ER frequency TSD ER cues were present during Experiments 2 and 3. Therefore, it is advised that future studies conduct preliminary testing to check for similar effects before using all three MSM speed maintenance tasks instead of examining only C1.

Next, it is unclear that the MRM was effective at identifying drivers' abilities to make relative judgments about their speed. During all conditions, drivers consistently drove faster than their target half speed, but were able to easily reproduce their comfortable speeds during C2. This leads to one of two conclusions. First, it may have been more difficult for drivers to discern their half speed than it was for them to estimate their comfortable speed within the virtual environment. Drivers may have made their best guess while still being grossly inaccurate at producing a half speed. This may also suggest that speed production behavior may not have a linear relationship with estimated speed, such that (as seen in the results of all three experiments) half of an estimated speed does not appear to be equivalent to half of a produced speed. Second, drivers may not have been able to conceptualize the task of driving at half of their comfortable speed. This is a possibility because there are no equivalent real-world situations to this task. Also, if this were to be asked of them in typical driving conditions, they could use the information from the speedometer (especially the ratio information from a dial display). For these reasons, the practical merits of the target ratio comparisons are unclear for future research applications except for the purpose of further defining the relationship between estimated speed and speed production at ratio speeds.

Third, the length of each speed task was established to collect a sufficient amount of data to examine whether drivers could maintain a consistent speed over the course of the task. The purpose of the task length was also to determine whether the ER cues would cause them to change their speed (speed drift ratio, target ratios) or have increased variability (reliability ratio) over time, as might be expected when a driver's speed is recalibrated after exposure to optic flow or ER cues. In terms of the speed drift ratio, there were only a few trends relating to the change in speed over the course of a task. This suggests the ER cues used during these experiments did not cause drivers to change their speed over time. However, it may also be the case that focusing on the sample time segment (from the 40th second to the 180th second) resulted in the removal of data that would be relevant to drawing this conclusion (i.e., performance during the first 40 seconds). This removal was shown to be necessary due to variance in participant speed behavior, which may suggest that using a measure of consistency as a performance metric may not be appropriate within the MRM. Alternatively, the sample time segment might not have been long enough to establish a concrete change in speed behavior over time. Therefore, if the goal of future research is to examine speed change over time, it is suggested that the period of time examined be lengthened to see whether differences between ER cues emerge. Further exploration of driver behavior at the time that drivers indicated they reached their target speed would also shed some light on this response, on their initial speed behavior, and on whether the conservative exclusion of the initial 40 seconds is appropriate in all circumstances.

Similarly, the reliability ratio identified differences between traffic speed direction (TSD) ER cues for the comfortable speed task (Experiment 2 and geographic cue presence by TSD interaction analyses) and trends between ER cue pairs during the half speed task. The initial intentions for using this measure were that it would be more robust than taking the outright variability in speed because it accounts for the mean speed performance during that task. This would allow for more standardized comparisons across ER cue conditions, especially in cases where there was a significant difference between mean speed choices. The results for reliability ratio suggest that there was a relationship between TSD ER speed cues that was mitigated by the mean speed of the driver. The strongest effects for reliability ratio occurred between conditions featuring contracting, faster TSD ER cues and expanding, slower TSD ER cues. The results of the interaction analysis found that whether or not geographic ER was present, drivers viewing the contracting cues had lower variability than drivers viewing expanding cues.

During Experiments 2 and 3, the conditions with faster TSD ER cues (faster TSD ER and opposing ER cue pair conditions) also had significantly faster mean speeds than did conditions with slower TSD ER cues (slower TSD ER and agreeing ER cue pair conditions). Collectively, this evidence suggests that while maintaining faster speeds drivers made less speed corrections, and may suggest that drivers had less difficulty completing this task compared to while driving at slower speeds. However, this finding may also result from drivers being unable to accurately perceive ER cues while traveling at faster speeds or being unable to differentiate speed differences while traveling at faster speeds (as per Weber's law). Therefore, the reliability ratio should be interpreted with caution for assessments using the MRM as there may be a number of causal factors influencing differences between ER cue conditions.

Finally, in terms of measuring drivers' subjective ratings of task ease, this methodology was inadequate at consistently finding differences between ER cue conditions. One conclusion that may be drawn from this is that drivers do not conceptualize differences between ER cue conditions in terms of being easier or difficult than other conditions. The evidence did suggest that drivers were using visceral, direct perceptual mechanisms (at least partially) and therefore perceived these ER cues without much cognitive-mediation. This conclusion has interesting implications for practitioners who would like to reduce the speed of drivers on a road by using ER cues. Specifically drivers are typically not consciously aware that speed calming measures are present and therefore these applications may be effective at reducing speeds without causing increases in the perceived driving difficulty or in negative reaction against the speed calming measure.

There are two methodological factors that may explain why differences were not observed in the ease rating data. First, the ease ratings were collected after each drive rather than immediately after each task. Drivers may have incorrectly rated their ease during the tasks due to forgetting how difficult it was or allowing comparisons between the comfortable and half speed tasks to temper their actual ratings. Second, drivers were asked to rate both comfortable speed tasks together in a single rating. This may have skewed their rating if one comfortable speed task was thought of as more difficult than the other. These ratings are valuable, and it is recommended that such ratings be collected in future implementations of the MRM. However, it is recommended that these ratings be collected immediately after each task is completed and before beginning the next task (e.g., after C1 is completed but before starting H).

Potential Limitations and Remaining Questions

Although this research attempted to address the major experimental limitations and confounds, some questions remain that warrant discussion. These questions mainly relate to future studies examining ER cues within the MRM. In addition, the known limitations to the study methodology are also discussed.

The first question relates to the nature of the TSD ER cues. A key difference between the geographic ER cues and TSD ER cues was that drivers had the ability to affect the relative speed of ER while experiencing the geographic ER cues, but were unable to affect the relative speed while experiencing the TSD ER cues. The consistent TSD ER cues were implemented such that participants would experience the consistent

ER patterns throughout each task of the experimental drives. During Experiment 2 the observed trends in participants excluded, due to driving at the maximum speed, and the reliability ratio data both suggest that drivers adjusted their speeds upward over the course of the drive while being passed by faster TSD ER cues. This suggests that drivers who are surrounded by traffic moving at a faster speed may have been increasing their speed in an attempt to match or pass the ambient traffic. However, no matter how the driver sped up or slowed down, the ambient traffic would always move at faster, similar, or slower speeds than the participant (it moved at a "consistent speed"). In contrast, participants could affect and change the ER they experienced from geographic ER cues by accelerating or decelerating to different speeds. That said, it stands to reason that participants might perform differently if they were given a similar level of control over the TSD ER cues as well. To explore this difference, a supplemental experiment was conducted after Experiments 1, 2, and 3 to examine the effects of TSD ER cues that were not continually shadowing the participant speed but remained at the same speed throughout the task; in other words, traffic speed was set equal to the participant's speed at the time they indicated reaching their target speed and the traffic remained at this "initial speed" throughout the task. This was intended to examine whether allowing participants the ability to pass or be passed would affect their comfortable speed choice over the course of each task.

The methods and results of this analysis are presented in Appendix G. The lack of main effects for all metrics on all comparisons and interactions between speed type (consistent, initial) and task type (comfortable speed, half speed) suggested that participants performed the comfortable speed and half speed tasks similarly regardless of speed type. The initial speed type did not produce half speeds that were any more accurate than did the continuous speed type. Overall mean speeds during the initial speed type were slightly slower than those during the continuous speed type, but these differences were not significant. It was also expected that the speed drift ratio measure between the two speed types would be affected by the differences in TSD ER cue conditions. This was because the continuous speed type influences driver speed over the course of the task compared to the initial speed type. The initial speed type essentially became stable (similar to the same TSD ER condition) for all three initial speed type ER conditions once the participant matched that speed. The data supported this hypothesis because the initial speed type ER cues did not produce an effect for speed drift. This was not surprising because there were also no significant differences for the speed drift measure during Experiments 2 or 3, both of which used the continuous speed type. Overall, the findings from the supplementary study suggest that giving participants the ability to overcome the TSD ER cues by using the initial speed type traffic conditions would have no effect upon the direction and a minimal effect upon the strength of the comparisons between TSD ER cues.

The next question was whether having more realistic traffic patterns would affect egospeed perception and comfortable speed production. Typically when one drives down the center of three lanes on a highway, similar to the road used during this experiment, the convention is (and sometimes law dictates) that vehicles in the lane to the left of an observer’s vehicle will move at a faster rate, and vehicles in the lane to the right will move slower (within countries where vehicles drive on the right side of the road). This bidirectional traffic stream would be equivalent to having the faster TSD ER cues on the left side of the driver while having slower TSD ER cues on the right. The results of the current studies showed that the opposing ER cue pair was associated with faster speeds and may have caused drivers to have more variability and uncertainty in selecting a comfortable speed (reliability ratio) than in instances where the TSD ER cues agreed with each other (agreeing ER cue pair). During bidirectional TSD ER cues, drivers would observe contracting cues on the left side of their vehicle and expanding cues on the right side in addition to any expanding geographic ER cues in the environment. In addition, the cues on the left side of the vehicle would be slightly more proximal to the driver's point of view than cues on the right side, thus strengthening the effect of the faster TSD ER cues. Therefore it is hypothesized that a bidirectional TSD ER cue set would have similar effects on comfortable speed choice as the opposing ER cue pair (i.e., contracting faster TSD ER cues and expanding geographic ER cues), resulting in faster produced speeds. However, this effect would be slightly mitigated by the agreeing ER cue pair to the right of the driver. The effects of this "disagreement" in ER cue pair information may also lead to additional weakening of the driver's overall perceived egospeed, similar to viewing geographic ER and TSD ER cues simultaneously during the opposing ER cue pair condition. If this were the case, it would follow that a bidirectional TSD ER cue pattern is one reason drivers currently drive too fast for conditions on roadways in the real world.

The third question that emerged was that of lane choice, namely that drivers were instructed to remain in the center lane at all times for these experiments. The purpose of remaining in the center lane was to standardize the driver's location on the road and thereby standardize their viewing distance to the ER cues. To explore the possibility of changing the lane in which the participants drive would also serve to explore new interactions between the ER cues. For example, a driver observing near geographic ER cues would produce a slower mean comfortable speed while driving in the left lane as compared to driving in the right lane. This difference would be similar to the difference between the near and far geographic ER conditions in the current experiments in that driving in the left lane would make the roadside objects appear slightly closer to the driver who is seated on the left hand side of the vehicle (again, within countries that drive on the right side of the road); whereas driving in the right lane may not have as strong of an effect on egospeed because the driver is further from the geographic ER cues on the roadside to the right.

An interesting interaction to explore relating to this and the bidirectional TSD ER cues would be to examine comfortable speeds while the driver is in the right or left lane and the driver has TSD ER cues solely to the left or the right. As with the example pertaining to the lane of travel, there would be stronger effects of the ER cues when the vehicles are on the left side of the car due to proximity of those TSD ER cues to the driver. This hypothesis is supported by the results from these experiments where proximity had a direct relationship with egospeed perception. Furthermore, an interaction between these single-side TSD ER cues and geographic ER cues would also resemble the effects seen during the ER cue pairs comparisons, except that, in this example, comparisons could be made by juxtaposing geographic and TSD ER cues that are both at equal distances from the driver against each other to see if one type of ER cue would dominate or if placement on the right or left side of the driver would affect egospeed perception. It is predicted that the TSD ER cues might have a stronger influence on egospeed perception and comfortable speed choice because other moving vehicles might be perceived as a greater threat to the driver.

Although the use of a simulated environment was justified because it was the only practical way to implement these ER stimuli in a uniform matter, the limitations of using a virtual environment still hold. Driving in a simulated driving environment does not provide a participant with the same level of fidelity and risk that driving in the real world would. Drivers might also react differently to the stimuli if they were driving in their own vehicles, on typical roads, and during normal driving conditions in the real world. Therefore, the results presented here represent relative but not absolute behavioral patterns of egospeed estimation and production. In this way, observed differences in produced speed generated from exposure to ER stimuli would be expected in the same direction in the real world, but not at the same magnitude.

Included with the limitation of using a simulated environment is the criterion to exclude any participant who approached the upper limit of speed. Twenty-nine participants over all three experiments were excluded due to this criterion, representing 25.4 percent of all participants who completed the experimental procedures (N = 114, including 72 valid participants and 13 who were excluded for other reasons). Because this may represent an unusually high number of exclusions and may be considered a limitation of this study, the available non-driving performance data (e.g., demographic, vision screening, mental effort scale) were examined in an effort to identify characteristics of the speed-exclusion group that may have led drivers to speed faster than the final sample. Pearson Chi-Square tests did not show any significant differences between the final sample and the speed-excluded participants in terms of age, sex, visual acuity, or failure to see at least one peripheral eccentricity screening cue (all $p > .05$). A 2 (exclusion) x 3 (ER cue type) ANOVA per each experiment also failed to show significant differences between the speed-excluded and final-sample participants on overall mental effort (averaging all six scales of the NASA-RTLX measure; all $p > .05$). Because the speed-performance data is invalidated due to the speed limitation, little else can be determined about these speed-excluded participants beyond this data, so no strong conclusions can be drawn from this data. For future studies using the MRM as it was proposed here, it is recommended that other measures of personality (e.g., sensation seeking) or driving history (e.g., speeding tickets) are included in order to explore differences such as these. In addition, the MRM procedures may need to be modified so that drivers do not reach the upper speed limitation within the simulated environment. One recommendation based on the results for the current study would be to include a benign set of geographic ER cues within the environment for all conditions in addition to any experimental ER cues.

Another potential limitation might have been the presentation of the brick texture on the geographic ER and TSD ER cues. A uniform brick texture was used on all ER cue types, but the appearance of this texture may have been perceived differently at different distances within the simulated environment. The texture was designed to present a realistic brick pattern relative to the distance at which it was observed. Because the size of the far objects, near objects, and cars was established to subtend the same total visual angles (height and width), the visually-subtended angle of each brick on the pattern would therefore be different in size; for example a brick viewed at 3.7 m (e.g., brick pattern on the cars) would subtend a larger visual angle than a brick viewed at 9.2 m (e.g., brick on the near geographic ER objects). As a result of this, the difference in texture frequency of texture patterns may have had an unintended effect on egospeed perception (Manser & Hancock, 2007). Future studies could examine this effect by modifying the pattern on the ER stimuli elements to subtend a uniform pattern, or by using a texture-free pattern.

CONCLUSIONS

The MRM was shown to be a viable methodology to observe differences in comfortable speed production during various visual ER cues. The strength of this methodology is in the standardized collection of data on comfortable speeds and the ability to observe speed maintenance at both faster (comfortable) and slower (half) speeds. The MRM as proposed was not successful in capturing speed drift over the course of a single task, which may be an indication that the ER conditions do not change behavior over time in this way. Alternatively, the time segments observed may have been too short to capture these speed drift differences. Overall, the MRM could easily be used to reliably measure differences in speed choice between any combination of ER cues—providing additional information for future potential safety countermeasures.

The results of these experiments suggest that ER cues have a statistically significant effect on drivers' perceptions of egospeed as observed through produced comfortable speeds in a virtual driving environment. The presence of ER cues, especially at closer distances, had the effect of assisting drivers at choosing slower comfortable speeds by increasing their awareness of their egospeed. For this reason, a road design could potentially include near geographic ER cues to decrease the speed of traffic overall. Speed reductions may be realized regardless of the presence or actions of other traffic, making this an effective speed reduction application for many circumstances.

Drivers' comfortable speed choice was also subject to the speed of other vehicles on the road. Drivers tended to choose comfortable speeds that were similar to those of the traffic around them. Therefore it may be necessary to reduce the speed of all traffic on the road, or perhaps to affect some drivers by adding geographic ER cues to the environment and hope that resulting reductions in speed affect the speed choice of other drivers. This could also be accomplished by strengthening enforcement efforts in areas where multiple-lane traffic streams are typically allowed to go unchecked. Automated enforcement and ticketing technologies could lead to a more widespread culture of speed consciousness wherein slower traffic speeds of some vehicles on a particular road could influence other drivers' perceptions traffic speed rather than the threat of punishment.

When geographic ER cues were present in the environment and traffic was moving slower than the participant driver, the combined effect of both ER cues resulted in slower net speeds. Specifically, the expanding of ER cues from optic flow was perceived to be in agreement with the expanding ER from traffic. This pair of ER cues had a strong influence on perceived egospeed because these two cues were in agreement and provided the driver with visceral references of their speed. The combination of cues may also have been salient enough to elicit cognitively-mediated perceptual mechanisms, which would further assist the driver in making accurate egospeed judgments. In this instance, drivers would not only be affected by their direct perception of ER cues but also by the confirmatory evidence from geographic cues which made them more consciously aware of their speed (through indirect perceptual mechanisms). As a result, drivers perceived that they were traveling faster than when the traffic cues were contracting and working against the optic flow expansion cues. These types of conditions exist on real-world roads today where there are sometimes vast speed differentials between neighboring lanes. Although this study found that such conditions might lead to speed reductions, designing a road to have such conditions could lead to a higher crash rate due to the danger of vehicles passing between slower and faster moving traffic lanes (Bowie & Walz, 1994). Instead, a more viable solution would be to focus efforts on speed reduction enforcement or increasing the saliency of geographic ER cues, resulting in an overall reduction in crashes by promoting a traffic culture that values slower speeds. Of these two, increasing the presence of geographic ER cues would produce speed reductions by using more direct perceptual mechanisms. The benefit of using these cues would be to reduce driver speeds without increasing drivers' awareness that they are changing their behaviors and also avoiding any negativity they may have against such speed countermeasures.

REFERENCES

Aarts, L., & van Schagen, I. (2006). Driving speed and the risk of road crashes: A review. *Accident Analysis and Prevention, 38,* 215-24.

Bertamini, M., Jones, L.A., Spooner, A., & Hecht, H. (2005). Boundary extension: The role of magnification, object size, context, and binocular information. *Journal of Experimental Psychology: Human Perception and Performance, 31*(6), 1288-1307.

Blakemore, M.R. & Snowden, R.J. (1999). The effect of contrast upon perceived speed: a general phenomenon? *Perception*, *28*, 33-48.

Bowie, N.N., & Walz, M. (1994). Data analysis of the speed-related crash issue. *Auto and Traffic Safety, 2,* 31-38.

Chihak, B. (2007). *Naturalistic stopping: Exploring the stopping behavior of drivers at intersections*. (Doctoral dissertation). University of Minnesota, Minneapolis, MN, USA. Publication number AAT 3258718.

Conchillo, A., Recarte, M.A., Nunes, L., & Ruiz, T. (2006). Comparing speed estimations from a moving vehicle in different traffic scenarios: Absence versus presence of traffic flow. *The Spanish Journal of Psychology*, *9*(1), 32-37.

Corkle, J., Giese, J.L., & Marti, M.M. (2002). Investigating the effectiveness of traffic calming strategies on driver behavior, traffic flow and speed. Mn/DOT contract 74330, Report No. MN/RC – 2002-02. SRF Consulting Group, Inc, Minneapolis, MN.

Cutting, J.E., & Vishton, P.M. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In W. Epstein & S. Rogers (Eds.), *Perception of space and motion* (2nd ed., pp. 69-117). San Diego, CA: Academic Press. As cited in DeLucia, 2008.

DeLucia, P.R. (2008). Critical roles for distance, task, and motion in space perception: Initial conceptual framework and practical implications. *Human Factors, 50*(5), 811-820. DOI 10.1518/001872008X312297.

DeLucia, P.R., & Meyer, L.E. (1999). Judgments about the time to contact between two objects during simulated self-motion. *Journal of Experimental Psychology: Human Perception and Performance*, *25*(6), 1813-1833.

Denton, G.G. (1976). The influence of adaptation on subjective velocity for an observer in a simulated rectilinear motion. *Ergonomics, 19*, 409-430.

Denton, G.G. (1980). The influence of visual pattern on perceived speed. *Perception*, *9*, 393-402.

Distler, H., & Bulthoff, H.H. (1996). Velocity perception in 3-D environments. *Perception*, *25*, Supplement, 58.

Elvik, R. (2005). Speed and road safety: Synthesis of evidence from evaluation studies. *Transportation Research Record, 1908*: 59-69.

Ewing, R., & Dumbaugh, E. (2009). The built environment and traffic safety: A review of empirical evidence. *Journal of Planning Literature, 23*(4), 347-367.

Hesketh, B., & Godley, S.T. (2002). A comparison of time estimations in driving with target-only in motion, self-only in motion, and self-and-target in motion. *Ecological Psychology, 14*(3), 111-125.

Gibson, J.J., & Crooks, L. (1938). A theoretical field-analysis of automobile-driving. *American Journal of Psychology*, *51*, 435-471.

Gibson, J.J. (1966). The senses considered as perceptual systems. Boston: Houghton Mifflin.

Godley, S.T., Triggs, T.J., & Fildes, B.N. (2000). Speed reduction mechanisms of transverse lines. *Transportation Human Factors, 2*(4), 297-312.

Godley, S.T., Triggs, T.J., & Fildes, B.N. (2002). Driving simulator validation for speed research. *Accident Analysis and Prevention*, *34,* 589-600.

Goodale, M.A., & Milner, A.D. (2005). *Sight unseen: An exploration of conscious and unconscious vision*. Oxford, UK: Oxford University Press. As cited in DeLucia, 2008.

Gray, R., Macuga, K., & Regan, D. (2004). Long range interaction between object-motion and self-motion in the perception of movement in depth. *Vision Research*, *44*, 179-195.

Gray, R., & Regan, D. (2000). Risky driving behavior: A consequence of motion adaptation for visually guided motor action. *Journal of Experimental Psychology: Human Perception and Performance*, *26*(6), 1721-1732.

Hancock, P.A., & Manser, M.P. (1997). Time-to-contact: more than tau alone. *Ecological Psychology*, *9*(4), 265-297.

Hollands, J.G., Tanaka, T., & Dyre, B.P. (2002). Understanding bias in proportion production. *Journal of Experimental Psychology, 28*(3), 563-574.

Horberry, T., Anderson, J., Regan, M.A., Triggs, T.J., & Brown, J. (2006). Driver distraction: The effects of concurrent in-vehicle tasks, road environment complexity and age on driving performance. *Accident Analysis and Prevention*, *38*, 185-191.

van der Horst, R., de Ridder, S. (2007). Influence of roadside infrastructure on driving behavior. Transportation Research Record: Journal of the Transportation Research Board, No. 2018. Transportation Research Board of the National Academies, Washington, D.C., pp. 36-44. DOI: 10.3141/2018-06.

Johnson, W.W., & Awe, C.A. (1994). The selective use of functional optical variables in the control of forward speed. Ames Research Center, Moffett Field, CA. OMB No. 0704-0188.

Kaiser, M.K., & Mowafy, L. (1993). Optical specification of time to passage: Observers' sensitivity to global tau. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 1028-1040.

Kaiser, M.K., Proffitt, D.R., Whelan, S.M., & Hecht, H. (1992). The influence of animation on dynamical judgments. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 669-690.

Larish, J.F., & Flach, J.M. (1990). Sources of optical information useful for perception of speed of rectilinear self-motion. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(2), 295-302.

Leibowitz, H. (1985). Grade-crossing accidents and human factors engineering. *American Scientist*, *73*, 558-562.

Lewis-Evans, B., & Charlton, S. (2006). Explicit and implicit processes in behavioural adaptation to road width. *Accident Analysis and Prevention*, *38*, 610-617.

Manser, M.P. (1997). *Time-to-contact: An examination of research methodology, age, sex, and internal timing mechanism.* (Doctoral dissertation). University of Minnesota, Minneapolis, MN, USA. Publication number AAT 9721633, ISBN 97805913033610.

Manser, M.P., & Hancock, P.A., (1996). Influence of approach angle on estimates of time-to-contact. *Ecological Psychology*, *8*(1), 71-99.

Manser, M.P., & Hancock, P.A., (2007). The influence of perceptual speed regulation on speed perception, choice, and control: tunnel wall characteristics and influences. *Accident Analysis and Prevention*, *39*, 69-78.

Matthews, M.L. (1978). A field study of the effects of drivers' adaptation to automobile velocity. *Human Factors*, *20*, 709-716.

McCloskey, M., & Kohl, D. (1983). Naïve physics: The curvilinear impetus principle and its role in interactions with moving objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *9*(1), 146-156.

McCloskey, M., Washburn, A., & Felch, L. (1983). Intuitive physics: The straight-down belief and its origin. Jo*urnal of Experimental Psychology: Learning, Memory, and Cognition*, *9*(4), 636-649.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S. H., Pick, H. L, Jr, & Warren, W. H. (2007). Visual flow influences gait transition speed and preferred walking speed. *Experimental Brain Research*, *181*, 221-228.

Mohler, B. J., Thompson, W. B., Creem-Regehr, S., H., Willemsen, P., Pick, H. L, Jr., & and Rieser, J. J. (2007). Calibration of Locomotion due to Visual Motion in a

Treadmill-based Virtual Environment. *ACM Transactions on Applied Perception*, *4*(1), article 4, 1-16.

National Highway Traffic Safety Administration (2001). *Traffic safety facts 2001-rural/urban comparison*. Report No. DOT HS-809 524. US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), National Center for Statistics and Analysis, Washington, DC.

National Highway Traffic Safety Administration (2007). *Traffic safety facts: speeding.* Report no. DOT HS 810 814. US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), Washington, DC.

National Highway Traffic Safety Administration (2008a). *Traffic safety facts: 2006 data, overview.* Report no. DOT HS 810 809. US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), Washington, DC. Updated March 2008.

National Highway Traffic Safety Administration (2008b). *Traffic safety facts: 2007 Data, Overview.* Report no. DOT HS 810 993. US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), Washington, DC.

National Highway Traffic Safety Administration (2009). *Traffic safety facts: 2008 Data, Overview.* Report no. DOT HS 811 162. US Department of Transportation, National Highway Traffic Safety Administration (NHTSA), Washington, DC.

Owen, D. (1990). Perception and control of change in self-motion: A functional approach to the study of information and skill. In R. Warren & A. Wertheim (Eds.), Perception and control of self-motion (pp. 289-326). Hillsdale, NJ: Lawrence Erlbaum Associates.

Owen, D.H., Wolpert, L., & Warren, R. (1984). Effects of optical flow acceleration, edge acceleration, and viewing time on the perception of egospeed acceleration. In D.H. Owen (Ed.), *Optical flow and texture variables useful in detecting decelerating and accelerating self-motion* (AFHRL-TP-84-4, pp. 79-133). Williams AFB, AZ: Air Force Human Resources Laboratory . (NTIS No. AD-A148 718). As cited in Owen, 1990.

Proffitt, D.R. (1999). Naïve physics. In R.A. Wilson & F.C. Keil (Eds.), The MIT encyclopedia of the cognitive sciences (pp. 577-579). Cambridge, MA: MIT Press.

Proffitt, D.R., Stefanucci, J., Banton, T., & Epstein, W. (2003). The role of effort in perceiving distance. *Psychological Science*, *14*(2), 106-112.

Rakauskas, M.E. (2009). A speed production methodology for the assessment of perceived egospeed. *The 53rd Annual Meeting of the Human Factors and Ergonomics Society*. San Antonio, TX, USA, October.

Recarte, M.A., & Nunes L.M. (1996). Perception of speed in an automobile: Estimation and production. *Journal of Experimental Psychology: Applied*, *2*(4), 291-304.

Regan, D., & Gray, R. (2000). Visually guided collision avoidance and collision achievement. *Trends in Cognitive Sciences*, *4*(3), 99– 107.

Scallen, S., & Carmody, J. (1999). Investigating the effects of roadway design on driver behavior: Applications for Minnesota highway design. Mn/DOT contract 74708, TOC # 28, Report No. MN/RC – 1999-10. Human Factors Research Laboratory, University of Minnesota.

Schiff, W., & Oldak, R. (1990). Accuracy of judging time-to-arrival: Effects of modality, trajectory, and sex. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 303-316.

Shared-Space (2007). Shared space: Room for everyone, a new vision for public spaces. Fryslan Province, PO Box 20120, 8900 HM Leeuwarden, The Netherlands. Accessed May 2007, http://www.shared-space.org/files/18445/SharedSpace_Eng.pdf

Shinar, D., Rockwell, T.H., & Malecki, J. (1980). The effects of changes in driver perception on rural curve negotiation. *Ergonomics, 23*, 263-275.

Snowden, R.J. (1997). Perceived speed: effects of field size and background texture. *Investigative Ophthalmology and Visual Science*, *38*(4), S1167.

Snowden, R.J., Stimpson, N., & Ruddle, R.A. (1998). Speed perception fogs up as visibility drops. *Nature*, *392*(2), April, 450.

Stetson, C., Fiesta, M.P., & Eagleman, D.M. (2007). Does Time Really Slow Down during a Frightening Event? PLoS ONE 2(12): e1295. doi:10.1371/journal.pone.0001295

Sun, H.J., Lee, A.J., Campos, J.L., Chan, G.S.W., & Zhang, D.H. (2003). Multisensory integration in speed estimation during self-motion. *CyberPsychology and Behavior*, *6*(5), 509-518.

Theeuwes, J. & Godhelp, H. (1995). Self-explaining roads. *Safety Science*, *19*, 217-225.

Tornros, J. (1998). Driving behaviour in a real and a simulated road tunnel- a validation study. *Accident Analysis and Prevention*, *30*(4), 497-503.

Triggs T. (1986). Speed estimation. In G.A. Peters, & B.J. Peters (Eds.), 1986 *Supplement to Automotive Engineering and Litigation, Volume 1*. Garland Law Publishing, New York, NY, pp. 95-124.

Warren, R. (1976). The perception of egomotion. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 448-456.

Warren, R. (1982, October). Optical transformations during movement: Review of the optical concomitants of egospeed. (Final technical report for Grant No. AFOSR-81-0108). Columbus, OH: Ohio State University, Department of Psychology, Aviation Psychology Laboratory. As cited in Larish & Flach, 1990.

Warren, R. (1990). Preliminary questions for the study of egomotion. In R. Warren, & A.H. Wertheim (Eds.), *Perception and Control of Self-Motion*. Lawrence Erlbaum Associates, Hillsdale, New Jersey, 3-10.

Witmer, B., & Sadowski, W.J. Jr. (1998). Nonvisually guided locomotion to a previously viewed target in real and virtual environments. *Human Factors*, *40*, 478–488.

APPENDIX A: STUDY OVERVIEW

At this time we require that you turn off your cell phone.
The purpose of this study is to examine the effect of visual information on speed perception while driving.

The study will involve a vision test, questionnaires, and driving in the driving simulator. You must follow the instructions given to you by the experimenter and those automatically triggered in the driving simulator through the speakers.

You will have a practice drive in order to familiarize yourself with the simulator before beginning the actual experimental drives. You should drive as you would normally in the real world. Your task will be to follow the lead vehicle at a close but safe distance. Safe driving should be your first priority at all times.

After the practice drive, you will be asked to drive on a highway environment a number of times. During these drives, you will be instructed to drive at a number of different speeds without the use of the speedometer. In addition to driving safely as you normally would, your task will be to maintain these speeds until you are instructed to stop or change speed.

After each set of drives, you will exit the simulator and answer questions on the computer and out loud.

Do you have any questions about the study before we begin?

APPENDIX B: PARTICIPANT CONSENT FORM

CONSENT FORM

Effects of Environmental Cues on Perceived speed While Driving

You are invited to be in a research study to examine the effects of environmental cues on driving performance. You were selected as a possible participant because you responded to our ads requesting participants and were found to be a suitable participant for this study. We ask that you read this form carefully and ask any questions you may have before agreeing to be in the study.

This study is being conducted by Michael Rakauskas who is a graduate student in the Psychology CAB Program at the University of Minnesota.

Background Information:

The purpose of this study is to investigate how drivers speed performance may be affected while viewing different environmental cues.

Procedures:

If you agree to be in this study, we will ask you to complete a number of drives in our driving simulator and answer questionnaires regarding these driving experience. This session is estimated to last approximately three hours.

Risks and Benefits of Being in the Study:

There are no direct benefits to you for participating in this study. A risk for participation is that a small percentage of individuals may experience motion sickness while driving in the simulator. If you begin to experience this, notify us and we will stop the study. Note: you are free to withdraw from the study at any time if you do not wish to continue.

Compensation:

You will either receive 1 Psychology REP point per half hour of your participation or a payment of $30 for participation, as agreed upon during the screening process prior to participation. Participants may not receive both types of credit.

Confidentiality:

The records of this study will be kept private. Your name will not be associated with any of the data collected today. In any sort of report we might publish, we will not include any information that will make it possible to identify you or other participants. Research records are stored securely in locked offices and only researchers on this study will have access to the data collected.

Research Results:

The results of this research will be published at the end of the study. If you are interested in obtaining this information, please visit our website (listed at the bottom of this form) for more information.

Voluntary Nature of the Study:

Participation in this study is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University of Minnesota. If you decide to participate, you are free to not answer any question or withdraw at any time without affecting those relationships.

Voluntary Nature of the Study:

Participation in this study is voluntary. Your decision whether or not to participate will not affect your current or future relations with the University of Minnesota. If you decide to participate, you are free to not answer any question or withdraw at any time without affecting those relationships.

Contacts and Questions:

You may ask any questions you have now. If you have questions later, **you are encouraged** to contact Mick Rakauskas by mail at 1101 Mechanical Engineering, 111 Church St SE, Minneapolis, MN, 55455, by phone at 612-624-4614, or by email at mickr@me.umn.edu.

If you have any questions or concerns regarding this study and would like to talk to someone other than the researcher(s), **you are encouraged** to contact the University of Minnesota's Research Subjects' Advocate Line, D528 Mayo, 420 Delaware St. Southeast, Minneapolis, Minnesota 55455; (612) 625-1650.

You will be given a copy of this information to keep for your records.

Statement of Consent: I have read the above information. I have asked questions and have received answers. I consent to participate in the study

Signature:_______________________________________ Date: ___________________

Signature of Investigator:___________________________ Date: ___________________

APPENDIX C: EGOSPEED INSTRUCTIONS

You should drive as you would normally in the real world. **Safe driving should be your first priority at all times.**

In a moment, you will complete a practice drive. The purpose of this drive is to familiarize you with a speed maintenance task and to give you practice maintaining a consistent speed in the simulator.

During this drive, you will first be asked to accelerate to a **speed you feel comfortable driving at**. Once you think you have reached this speed, you should indicate using the left turn signal and then maintain this speed until you are instructed to stop. It is important that you attempt to maintain a consistent speed throughout this time. It is also important that this speed is <u>**not**</u> **the fastest speed you feel comfortable driving at**. You should aim for a speed you would feel comfortable maintaining while driving in similar conditions in the real world.

After a time, you will be asked to decelerate to a **speed that is half as fast as your comfortable speed**. Again, once you have reached this speed, you should indicate using the left turn signal and then maintain this speed until you are instructed to stop. Again, it is important that you attempt to maintain a consistent speed throughout this time.

You will then be asked to accelerate back to the **comfortable speed that you originally chose to drive at**. Just as you have done with the other speed, you should indicate using the left turn signal when you have reached this speed, and then maintain this speed until you are instructed to stop.

After all three segments, you will be asked to stop the vehicle and exit from the simulator to complete a short questionnaire on the computer.

If you have any questions or concerns, please ask them now. If you are now ready to proceed, please let the experimenter know and we will begin.

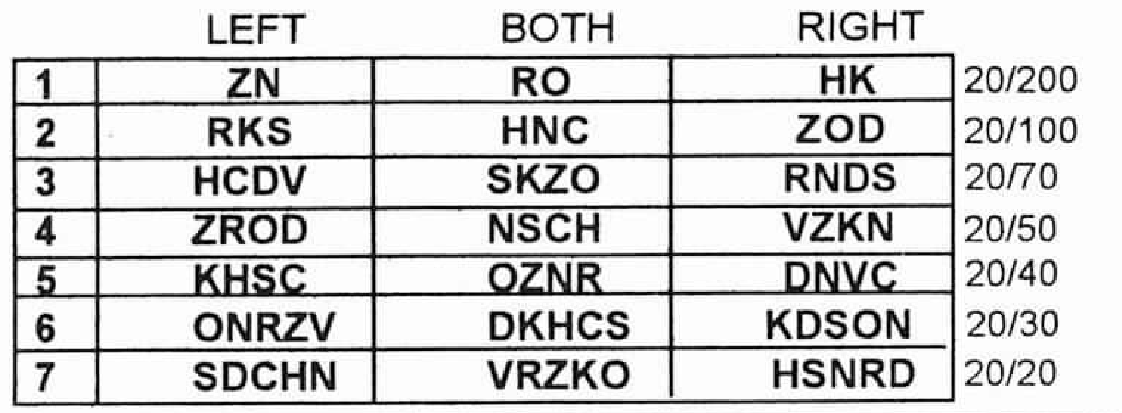
APPENDIX D: EXPERIMENTER NOTE SHEET- EXPERIMENT 1

Participant ID:________________________________

Month: ______________ Day: ____________ Start Time: ____________

Acuity testing, surveys & general notes

Dial = Far #2



	LEFT	BOTH	RIGHT	
1	ZN	RO	HK	20/200
2	RKS	HNC	ZOD	20/100
3	HCDV	SKZO	RNDS	20/70
4	ZROD	NSCH	VZKN	20/50
5	KHSC	OZNR	DNVC	20/40
6	ONRZV	DKHCS	KDSON	20/30
7	SDCHN	VRZKO	HSNRD	20/20

Instruction 1: “Tell me the number of the lowest row you can see clearly”

Instruction 2: “Please read as many letters as you can from [row above that row]”

Mark through misidentified letters.

Repeat instruction 2 for the row above the one they selected until they are all correct or only misidentify one letter per row *circle* the acuity for that row (e.g. “20/20”).

Dial = Far #1

Instruction: “You should now see a road scene. Please focus on the dot on the horizon and tell me whenever you see a yellow light in your peripheral vision.”

Press each of the noted buttons HARD for a 2 second count, then release.

After all 4 presses, *mark* the lights they indicate having seen.

Left		**Right**
☐	85	☐
☐	70	☐
☐	55	☐
☐	Nasal 35	☐

Wearing:

☐ No Eyewear
☐ Glasses
☐ Contact Lenses

Practice Drive (Mick-Practice)

PEx ease _________ _________

Experimental Scenario Set 1 - Egospeed Far Near

	c	h
B mean	_____._____	_____._____
B st dev	_____._____	_____._____
P mean	_____._____	_____._____
5 kph	________%	________%
10 kph	________%	________%
P ease	_________	_________
Ex ease	_________	_________

Experimental Scenario Set 2 - Egospeed Far Near

	c	h
B mean	_____._____	_____._____
B st dev	_____._____	_____._____
P mean	_____._____	_____._____
5 kph	________%	________%
10 kph	________%	________%
P ease	_________	_________
Ex ease	_________	_________

Experimental Scenario Set 3 - Egospeed Far Near

	c	h
B mean	_____._____	_____._____
B st dev	_____._____	_____._____
P mean	_____._____	_____._____
5 kph	________%	________%
10 kph	________%	________%
P ease	_________	_________
Ex ease	_________	_________

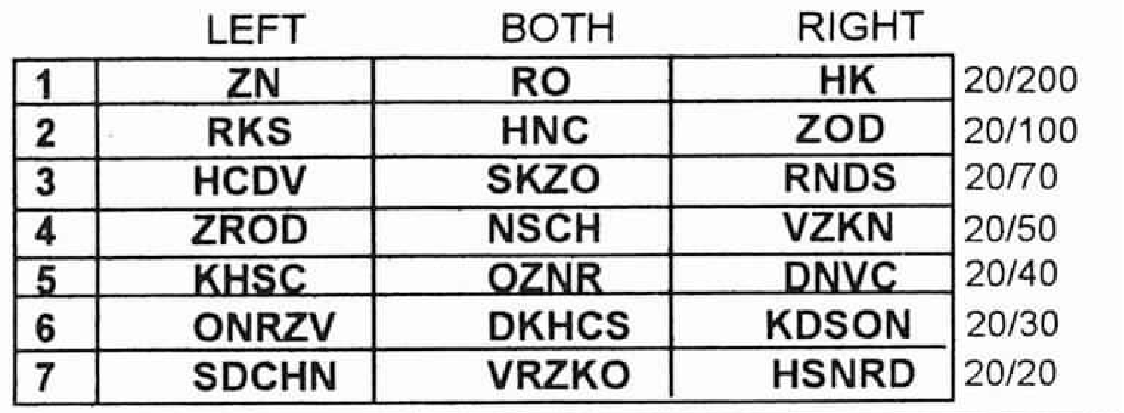
APPENDIX E: EXPERIMENTER NOTE SHEET- EXPERIMENTS 2 AND 3

Participant ID: P______________________________.

Month: ________________ Day: ______________ Start Time: _____________

Acuity testing, surveys & general notes

Dial = Far #2



	LEFT	BOTH	RIGHT	
1	ZN	RO	HK	20/200
2	RKS	HNC	ZOD	20/100
3	HCDV	SKZO	RNDS	20/70
4	ZROD	NSCH	VZKN	20/50
5	KHSC	OZNR	DNVC	20/40
6	ONRZV	DKHCS	KDSON	20/30
7	SDCHN	VRZKO	HSNRD	20/20

Instruction 1: “Tell me the number of the lowest row you can see clearly”

Instruction 2: “Please read as many letters as you can from [row above that row]”

Mark through misidentified letters.

Repeat instruction 2 for the row above the one they selected until they are all correct or only misidentify one letter per row *circle* the acuity for that row (e.g. “20/20”).

Dial = Far #1

Instruction: “You should now see a road scene. Please focus on the dot on the horizon and tell me whenever you see a yellow light in your peripheral vision.”

Press each of the noted buttons HARD for a 2 second count, then release.

After all 4 presses, *mark* the lights they indicate having seen.

Left		**Right**
☐	85	☐
☐	70	☐
☐	55	☐
☐	Nasal 35	☐

Wearing:

☐ No Eyewear

☐ Glasses

☐ Contact Lenses

Practice Drive (Egospeed-Driving Practice)

Acquisition Drive (Egospeed-PracticeLonger)

PEx ease ________ ________

Experimental Scenario Set 1 -			Slower	Stable/Same	Faster
	c	h			
B mean	____.____	____.____			
P mean	____.____	____.____			
10 mph	_______%	_______%			
P ease	________	________			
Ex ease	________	________			

Experimental Scenario Set 2 -			Slower	Stable/Same	Faster
	c	h			
B mean	____.____	____.____			
P mean	____.____	____.____			
10 mph	_______%	_______%			
P ease	________	________			
Ex ease	________	________			

Experimental Scenario Set 3 -			Slower	Stable/Same	Faster
	c	h			
B mean	____.____	____.____			
P mean	____.____	____.____			
10 mph	_______%	_______%			
P ease	________	________			
Ex ease	________	________			

How fast do you think your last comfortable speed was? ________ / 50

APPENDIX F: EASE RATINGS SCALE

During this drive,
how easy was it to maintain your…

Comfortable Speed

Difficult Easy

1 — 2 — 3 — 4 — 5 — 6 — 7

Half Speed

Difficult Easy

1 — 2 — 3 — 4 — 5 — 6 — 7

APPENDIX G: CONTINUOUS VS. INITIAL TSD ER CUES

Methods

Participants

Fourteen participants completed the experimental protocol, of which one participant's data were lost due to a computer error. Three participants were excluded for having a mean speed above 138 km/h during at least one experimental condition; in total there were 6 instances (25 percent of all valid trials run, *n* = 6) of reaching the maximum speed during the initial-faster (being passed) TSD ER cue condition, none during the initial-same TSD ER cue condition, and 1 (4 percent of all valid trials run, *n* = 1) during the initial-slower (passing) TSD ER cue condition.

The final participant sample consisted of 10 participants (6 female, 4 male, *M* = 20.2 yrs, *SD* = 1.6, *Range* = 18–23) who experienced all the ER cue conditions in a counterbalanced order to minimize any effects of presentation order. Participants were recruited from the University of Minnesota campus and those recruited from the psychology volunteer pool received course credit for their participation.

Apparatus

The driving simulator's physical setup and functionality were consistent with those described for Experiments 1, 2, and 3.

Edge Rate Condition: Initial Traffic Speed Cues

The methodology and TSD ER cue conditions were the same as in Experiment 2 (similar to conditions d, e, and f in Table 1). However, to examine the effect of Initial TSD ER cues on comfortable speed choice, ambient traffic traveled at faster, same, and slower speeds only until the participant indicated that they had reached their comfortable speed. At that point, the traffic maintained that speed and the participant could effectively drive faster or slower than the traffic by changing their own speed. When the participant was asked to change their speed (i.e., from C1 to H, or from H to C2) the traffic resumed the faster, same, or slower TSD ER profile.

It was hypothesized that drivers experiencing the consistent TSD ER cues (Experiment 2) would have larger differences in comfortable speed choice when compared to drivers experiencing the Initial TSD ER cues. Because this supplementary experiment involved fewer participants, it was expected that differences between the two experiments would be difficult to identify within this limited context. Therefore, this comparison is meant to provide a suggestion towards the direction of any effects for ER cue effectance on comfortable speed choice.

Results

Analyses

A 2 x 3 x 2 mixed-model ANOVA was performed to examine the effects of speed Type (Consistent [Experiment 2], Initial [supplementary Experiment]) on Traffic speed from TSD ER cues (faster, same, slower speed traffic) and comfortable speed task type (C1, C2). A separate 2 x 3 mixed-model ANOVA was performed to examine the effects of the speed Type and TSD ER cues on half speed performance. Because this was an exploratory analysis with unbalanced samples, the main effect for speed type and the interaction between this and TSD ER cues are most relevant and are the only results discussed below. Follow-up tests for significant interactions were examined using paired-samples *t* tests to compare the consistent to initial speed types under each TSD ER cue condition separately. Differences between means were considered significant at the α = .05 level for all main effects and a Bonferroni-corrected significance level of α = .017 (family-wise error rate of α = .05divided by 3, the number of follow-up tests) for each of the pair-wise follow-up effects for cue type. Main effects at the α = .06 level and follow-up effects at the α = .027 level were considered to approach significance and are noted in the Discussion because they may indicate potential trends in the data.

Mean results for the comfortable speed and half speed performance measures for the Supplemental Experiment are presented in Table 25, and means from Experiment 2 are presented in Tables 7 through 11. Mean results for the comfortable speed and half speed performance measures across the Supplemental Experiment and Experiment 2 are presented in Table 26.

Table 25. Mean (SD) results for all comfortable speed and half speed performance measures during the Supplemental Experiment.

Initial-TSD ER	Mean Speed (km/h)		Target Ratio	Speed Drift Ratio		Reliability Ratio		Ease Rating
	C1	C2	C2 / C1	C1	C2	C1	C2	C [a]
Faster	114 (20)	112 (18)	0.997 (.067)	1.006 (.016)	1.004 (.022)	0.011 (.008)	0.014 (.006)	5.5 (1.4)
Same	106 (20)	106 (19)	1.011 (.086)	0.997 (.009)	0.999 (.014)	0.010 (.004)	0.012 (.007)	5.8 (1.0)
Slower	99 (31)	98 (31)	0.988 (.079)	0.994 (.017)	1.006 (.022)	0.012 (.011)	0.020 (.017)	5.8 (1.2)
	H		H / (C1*0.5)	H		H		H
Faster	74 (14)		1.310 (.201)	1.006 (.026)		0.037 (.031)		4.8 (1.5)
Same	71 (16)		1.347 (.173)	1.005 (.024)		0.026 (.014)		5.0 (1.1)
Slower	64 (25)		1.272 (.254)	1.030 (.036)		0.039 (.032)		4.7 (1.5)

[a] Ease ratings were asked in terms of comfortable speed in general and pertain to both C1 and C2 collectively.

Table 26. Mean (SD) results for all comfortable speed and half speed performance measures across Experiment 2 and the Supplemental Experiment.

ER Cue Type	Mean Speed (km/h)		Target Ratio	Speed Drift Ratio		Reliability Ratio		Ease Rating
	C1	C2	C2 / C1	C1	C2	C1	C2	C [a]
Speed Type								
Consistent	110 (32)	110 (33)	0.998 (.076)	1.000 (.034)	1.000 (.034)	0.018 (.017)	0.018 (.017)	5.8 (1.5)
Initial	106 (32)	106 (33)	0.999 (.077)	0.999 (.033)	1.003 (.033)	0.011 (.016)	0.015 (.022)	5.7 (1.5)
TSD Cues								
Faster	*116 (21)*	*114 (18)*	*0.988 (.053)*	*1.007 (.018)*	*1.012 (.029)*	*0.012 (.009)*	*0.015 (.013)*	*5.6 (1.0)*
Same	*109 (19)*	*108 (20)*	*0.994 (.076)*	*0.998 (.027)*	*0.994 (.020)*	*0.017 (.014)*	*0.014 (.012)*	*5.8 (0.9)*
Slower	*102 (23)*	*103 (22)*	*1.011 (.082)*	*0.995 (.036)*	*0.997 (.039)*	*0.020 (.018)*	*0.022 (.019)*	*5.9 (1.0)*
	H		H / (C1*0.5)	H		H		H
Speed Type								
Consistent	78 (30)		1.410 (.339)	0.999 (.051)		0.040 (.042)		4.6 (2.1)
Initial	69 (30)		1.310 (.340)	1.014 (.049)		0.034 (.049)		4.8 (2.1)
TSD Cues								
Faster	*81 (18)*		*1.405 (.212)*	*1.010 (.070)*		*0.037 (.036)*		*4.9 (1.4)*
Same	*75 (17)*		*1.383 (.214)*	*0.993 (.057)*		*0.039 (.035)*		*4.6 (1.3)*
Slower	*70 (22)*		*1.353 (.227)*	*1.007 (.042)*		*0.038 (.034)*		*4.6 (1.4)*

[a] Ease ratings were asked in terms of comfortable speed in general and pertain to both C1 and C2 collectively.

Note that the main effects for Traffic ER cues are in *italics* to emphasize that they represent unbalanced samples across the two experiments.

Mean Speed

For comfortable speed performance, the main effects for speed Type ($F(1,32) = 0.30, p > .05$), task type ($F(1,32) = 1.68, p > .05$), and the speed type by TSD ER cue interaction ($F(2,64) = 0.35, p > .05$) were not significant. For half speed performance, the main effect for speed Type ($F(1,32) = 0.30, p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 0.61, p > .05$) were not significant.

Target Ratio

For comfortable speed target ratio (C2 / C1), the main effects for speed Type ($F(1,32) < 0.01, p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 1.29, p > .05$) were not significant. For half speed target ratio (H / (C1 / 2)), the main effect for speed Type ($F(1,32) = 1.85, p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 1.13, p > .05$) were not significant. The mean target ratio for both speed Type conditions collectively found that drivers' second comfortable speed was on average exactly the same ($M = 1.0$) as their first comfortable speed, and their half speed was on average 36 percent higher than the target half speed (i.e., half of their C1 mean speed).

Speed Drift Ratio

For comfortable speed drift ratio, the main effects for speed Type ($F(1,32) = 0.02, p > .05$), task type ($F(1,32) = 0.31, p > .05$), and the speed Type by TSD ER cue interaction ($F(2,64) = 0.57, p > .05$) were not significant. For half speed drift ratio, the main effect for traffic speed direction Type ($F(1,32) = 1.92$, $p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 0.70$, $p > .05$) were not significant.

Reliability Ratio

For comfortable speed drift ratio, the main effects for speed Type ($F(1,32) = 2.01$, $p > .05$), task type ($F(1,32) = 0.72$, $p > .05$), and the speed Type by TSD ER cue interaction ($F(2,64) = 0.82$, $p > .05$) were not significant. For half reliability ratio, the main effect for speed Type ($F(1,32) = 0.28$, $p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 1.83$, $p > .05$) were not significant.

Ease of Maintaining Target Speeds

The main effects for speed Type ($F(1,32) = 0.07$, $p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 0.21$, $p > .05$) were not significant. For subjective ease of maintaining half speed, the main effect for speed Type ($F(1,32) = 0.18$, $p > .05$) and the speed Type by TSD ER cue interaction ($F(2,64) = 1.01$, $p > .05$) were not significant.