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Sensory and Perceptual Factors in the Design of Driving Simulation Displays

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Abstract

The Problem. Driving simulators involve the presentation of visual information (along with other information) to examine driving skill and performance. In order to optimize driving skill and performance, simulator displays should be designed in accordance with the sensory and perceptual capabilities of the driver. ***Role of Driving Simulators.*** The effect of different ways of displaying visual information on drivers' performance in a driving simulator is itself the object of study. ***Key Results of Driving Simulator Studies.*** Driving simulator studies have indicated the types of visual information important for performing a variety of tasks. These types include sensory factors (acuity, contrast, luminance, and motion) and perceptual factors (texture, optical flow, depth and distance information, and cue conflicts). Relevant results from psychophysics studies are discussed that can be used to optimize the presentation of visual information for driving tasks. In addition, minimum standards are proposed to optimize research and training using simulators. Finally, both the role of visual factors that can contribute to simulator sickness and the role of procedures that can be used to minimize risk of simulator sickness are also discussed. ***Scenarios and Dependent Variables.*** Simulator scenarios that are highly dependent on visual factors include steering, collision detection and avoidance, car following, braking, speed regulation, and the identification/recognition of targets (i.e., roadway signs, pedestrians, traffic lights). ***Platform Specificity and Equipment Limitations.*** The present chapter will discuss how differences in the platforms and equipment in driving simulators determine what visual information is displayed, which in turn has an impact on driving performance.

8.1 Introduction

A primary goal of driving simulation research is to understand performance under conditions where visual information is manipulated or controlled to perform a specific task. The presentation of visual stimuli in a simulator is an approximation of the information available in real-world driving. For example, the resolution available in a simulator when viewing roadway signs is considerably lower than the resolution available under similar conditions in real-world driving. Luminance levels of daytime visual displays are below the luminance available under real-world conditions. A critical assumption of driving simulation research is that the presentation of visual information in the simulator is sufficiently rendered to minimize any differences between performance on the driving task under investigation in the simulator and performance on the same task in real-world driving. Any violation of this assumption can lead to incorrect generalizations from performance on the simulator task to performance in real-world driving, and may have a negative impact on the design of new technologies to improve driving safety or the use of simulators for training.

It is unlikely that simulators can have fidelity equivalent to real-world vision. For example, perceiving detail in real-world vision is limited by the resolution of the photoreceptor lattice in the retina. In contrast, perceiving detail in driving simulation displays is limited by the resolution of the monitor or projection system, which is considerably lower than resolution in real-world vision. This limitation as well as others (i.e., contrast, motion, texture, etc.) raises several pertinent questions regarding simulator design and the external validity of simulators for understanding driving skill and performance. Do these limitations represent a problem for driving simulation research? If optimal fidelity cannot be obtained then what minimum standards should be used to optimize external validity? Is it necessary to use simulators with the highest fidelity? Finally, what is the potential impact on performance when minimum conditions are not used?

The purpose of this chapter is to address these questions. First, I will present an overview of what is known about the visual information used to perform different driving tasks, including discussions of both the sensory information (e.g., spatial resolution, temporal resolution, luminance, and contrast) and perceptual information (e.g., perception of motion, perception of a 3D scene, egocentric distances and depth). Second I will discuss why limitations in the capabilities of driving simulators make it likely that the *sensory information* presented in simulated driving tasks is oftentimes inadequate and can lead drivers to perform a task in ways than are different from what they might do in the real world. Third, I will take up a similar discussion of the how limitations in the capabilities of driving simulators can make it likely that the *perceptual information* a driver is using differs from what might be used in the real world. Fourth, I will discuss perceptual conflicts that can exist in driving simulators and the potential impact such conflicts can have on driving performance. Finally, I will discuss the relationship between fidelity issues in simulators and the incidence of simulator sickness.

8.2 Visual Factors and Driving Tasks

Driving is a skill that is critically dependent on visual information. As we drive our visual system extracts information from the surrounding scene that we use to perform different tasks (steering control, braking, etc.). Understanding what visual information is used to perform these tasks is critical to determining what information should be present in a driving simulator. These tasks can be categorized, for the sake of convenience, into the following performance issues: identification/recognition of targets, steering control, collision detection and avoidance, braking, car following and speed regulation. This list is based on the types of tasks that have been studied in driving research and is not intended to be an exhaustive list. But it does provide a basis from which we can evaluate what is known from research regarding the information used to perform the tasks and the sensory and perceptual information used to perform the tasks. A thorough review of the visual information used to perform these tasks is beyond the scope of the present chapter. However, the review in the present chapter will focus on those issues likely to be of relevance for optimal design of driving simulation displays.

8.2.1 Detection/Recognition of Targets

In this section, the detection and recognition of targets such as roadway signs will be discussed. An extensive body of literature exists concerning the design of signs for optimal legibility on roadways (e.g., Kline & Fuchs, 1993; Mori & Abdel Halim, 1981; Shinar & Dori, 1983). A detailed review of this literature is beyond the scope of this chapter. However, the research literature on signage and driving has primarily focused on issues of font type, size, and contrast. In simulation displays, the visibility of signage is limited by the display resolution, luminance and contrast of the monitor/projection system.

Most simulation displays operate with a resolution of 1024 by 768 and include anti-aliasing (algorithms to blend features across pixels to avoid jagged edges). Lower resolution settings result in greater pixilation of the image, resulting in a decreased ability to see signage detail at increased simulated distances. The degree of pixilation will depend on the size of the display, the viewing distance from the driver to the screen, and the simulated distance of the character in the simulation.

8.2.2 Steering Control

Research on steering control suggests that drivers use two different types of visual information. One source of information is optical flow—the perspective transformation of the visual world during motion of the observer. An extensive body of literature has examined the usefulness of optical flow for determining the instantaneous direction of observer motion (e.g., Gibson, 1966; Warren, Morris, & Kalish, 1988; Dyre & Andersen, 1997). Optical flow is characterized by the collection of velocity vectors projected to the retina. In terms of driving simulation displays, accurate depiction of optical flow will be determined by the spatial resolution of the display (a lower resolution results in less precision in specific local velocity information) and the temporal resolution of the display (lower temporal resolution results in less accuracy in the magnitude of specific local velocity information). The second source of information used by drivers is a representation of the 3D driving scene. Recent research (Hahn, Andersen, & Saidpour, 2003) showed that observers use static scene information in determining the instantaneous direction of heading. More recently, Andersen and Enriquez (2006b) showed that static scene information is based on an allocentric representation of landmarks in the scene (egocentric distances between the driver and landmarks or features in the scene). Optimal information for driving simulation displays would involve the presentation of a sufficient number of landmarks in the driving scene and the availability of rich visual information for determining egocentric distance. Indeed, studies have found asymptotic performance in car following when nine landmarks were present (Andersen & Saidpour, 1999). Other studies (Land & Lee, 1994) have shown that the visibility of the curvature of the 3D roadway is used for steering along a curved path. Their results suggest that observers use the tangent of the curve to estimate the future path of the driver's vehicle. This research suggests that visibility of the roadway is important in steering along a curved path.

8.2.3 Collision Detection and Avoidance

Detection and avoidance of collision is a complex and varied task. The range of conditions is quite varied when one considers all possible combinations (constant and changing velocity; linear and curvilinear paths) of moving objects and a moving vehicle. Furthermore, a related topic that has received considerable focus in the driving literature is determining the time-to-contact (TTC) of an impending collision. Studies examining time-to-contact (Lee, 1976; Tresilian, 1991; Wann, 1996) as well as collision detection (Andersen & Kim, 2001; Andersen & Enriquez, 2006a) have shown that the ability to detect collisions is based on optical expansion (i.e., approaching objects increase in size over time).

Research has also examined the optical information for detecting collisions for different trajectories of motion. Consider the case of an approaching object on a linear trajectory. If the object is on a collision path with the driver the bearing will be constant, whereas if the object is not on a collision path (i.e., will pass by the driver) the bearing will vary over time. If the approaching object is on a circular trajectory then an object on a collision path will have a constant rate of bearing change whereas if the object is not on a collision path the rate of bearing change will vary. Previous studies have demonstrated sensitivity of drivers to use constant bearing information for detecting linear path collision events (Andersen & Kim, 2001; Andersen & Enriquez, 2006a) and constant rate of bearing change for detecting circular path collision events (Ni & Andersen, 2008).

Optical expansion is one type of optical flow information (Koenderink, 1986) and involves the perception of motion. Optimal information for the perception of motion would be determined by the spatial and temporal information in the display. Bearing information (the projected position of an object in the visual field) would be determined by the spatial resolution of the display. Change in bearing (change in the projected position of an object in the visual field) would be determined by the projected velocity of the object in the display. Thus, optimal presentation of these information sources in driving simulation displays would be based on the spatial and temporal resolution of the displays.

8.2.4 Braking

Previous research on optical information for braking suggests that drivers use two different information sources. As noted earlier, previous studies have examined time-to-contact judgments in driving (Lee, 1976, 1980; Schiff, Oldak, & Shaw, 1992; DeLucia, Bleckley, Meyers, & Bush, 2003). Time-to-contact information is specified by the inverse rate of expansion of the approaching object. Lee (1976) also showed that the time derivative of TTC information can be used for regulating braking behavior. Several studies have shown that drivers use this information for braking (see Andersen & Sauer, 2004, for a review). Other studies have shown that drivers use egocentric distance information (Andersen, Cisneros, Saidpour, & Atchley, 1999, 2000). Because braking involves the use of expansion information (which is dependent on the perception of motion) it also is dependent on spatial and temporal information.

8.2.5 Speed Regulation

To date, only one study has examined the visual information that is used for the perception of vehicle speed. Larish and Flach (1990) examined the ability of human subjects to perceive the speed of self motion. They used a magnitude estimation methodology in which subjects rated the perceived speed of forward motion. Their results indicate that observers use global optical flow rate (the rate at which optical texture passes a particular location in the visual field). These results indicate that scene texture is a necessary source of information for determining vehicle speed, as well as spatial and temporal information for the perception of motion.

Other studies have also suggested the important role of texture in the perception of speed. Nguyen-Tri and Faubert (2007) found evidence that texture and motion interact in order to determine speed. Manser and Hancock (2007) found that variations in the texture pattern of a simulated tunnel wall during driving could result in variations in driver speed in a simulator. They found that drivers increased speed when the width of the texture pattern was decreased, and decreased speed when the width was increased. These results are consistent with earlier studies by Denton, which found that decreasing the spacing of horizontal lines across a roadway resulted in decreased speed of approach to a traffic circle (Denton, 1980).

In most real-world settings, texture is present at several different levels of scale. For example, consider a roadway consisting of concrete sections. At one level of scale, the expansion joints between the concrete sections represent a pattern of texture. At a smaller level of scale, the spacing of gravel within the concrete section represents a different level of scale (see Gibson, 1979 for a discussion). An important limitation in driving simulation displays is that texture is presented at one level of scale, or a subset of the possible levels of texture scale present in real-world scenes. This limitation may have a profound impact on performance and may represent a problem in relating driving simulation to real-world driving. For example, the limited texture in simulated 3D scenes has been shown to result in a compression of the perceived space along the depth axis (Andersen & Braunstein, 1998a). This finding suggests that limited texture in driving simulation scenes will lead to a misperception of distances in the scene, which will likely impact driving tasks such as collision detection and avoidance.

8.2.6 Car Following

Research on the visual information used to car follow (successfully maintain a fixed distance behind a lead vehicle) has examined visual angle and change in visual angle (associated with expansion or contraction of the rear-end of the lead vehicle). In a series of experiments Andersen and Sauer (2007) examined car following performance to variations in lead vehicle speed defined by sinusoidal and ramp function profiles. Based on this research they proposed a model based on visual angle (used to assess a desired following distance) and change in visual angle (used to estimate instantaneous change in relative speed between the driver and lead vehicle). Data from real-world car following performance was tested using model parameters determined from driving simulation studies. The results indicated that the model was highly predictive of car following performance under real-world driving conditions. Indeed, for real-world driving data the DVA model accounted for 10% more variability in driving speed and 35% more variability in distance headway.

The review of previous research on driving suggests that several different sources of information are important for performing the variety of tasks involved in driving. These information sources can be categorized as sensory information (spatial resolution, temporal resolution, luminance, and contrast) and perceptual information (perception of motion, perception of a 3D scene, egocentric distances and depth). In the next sections we will discuss sensory and perceptual issues in the design of simulation displays. We will discuss those factors important for the driving tasks discussed above, as well as perceptual factors normally not considered in driving simulation displays which can have important consequences for performance.

8.3 Sensory Issues in Simulator Research

Sensory information is important for several aspects of driving performance. For example, reduced visibility due to decreased luminance (present during night driving) or decreased contrast (present during driving in fog) has been shown to be associated with increased risk of a crash (Evans, 2004). Given the role of sensory information in driving tasks an important issue is whether the reduced fidelity of driving simulation scenes, as compared to real-world driving scenes, might have an impact on performance in driving tasks in a simulator. In the next sections we will consider this issue for spatial resolution, temporal resolution, luminance, and contrast.

8.3.1 Spatial Resolution

As introduced earlier the display resolution of a computer monitor or projection system falls well below the actual spatial resolution of the visual system. Under optimal luminance and contrast conditions, the spatial resolution of the visual system, assessed using sine wave grating patterns, is approximately 60 cycles per degree, or 0.016 degrees visual angle (Campbell & Robson, 1968). In contrast, consider a driving simulation display projected to a 60 degree by 40 degree visual angle. If the display resolution is 1024 by 780 (a resolution common for most driving simulators) then the dimensions of a single pixel will be 0.058 by 0.051 degrees visual angle. Thus, the driving simulation display has a resolution that is nearly four times lower the optimal resolution of the visual system.

There are three possible effects of decreased resolution of simulation displays on driving performance. One effect is that the lower resolution of simulation displays will result in decreased visibility of targets that are located at greater distances in the simulation. To illustrate this effect, consider the visibility of a roadway stop sign with 33 cm high lettering. In addition, assume that a minimum of 4 pixels is needed to depict the vertical dimension of the letter S in the word "stop". Under these conditions the sign would be detectable at a distance of 93.7 m. If we apply the same conditions to real-world vision (assuming 4 times the minimum resolution of 0.016 degrees) the sign would be visible at a distance of 295 m. Under most driving conditions the effects of the difference in maximum distance visibility would be negligible. However, this difference does become relevant when considering driving conditions at higher speeds. For example, consider a driving speed of 40 km/h. We can calculate the amount of time a driver has to read the sign by determining how many seconds of driving time it takes to pass the sign given the maximum distance that it can be seen. We will refer to this value as the *distance reading time*. At a vehicle speed of 40 km/h the distance reading time for the driving simulation display is 7.7 seconds whereas in real-world driving the reading time is 24.4 seconds. One would expect that both of these reading times are more than adequate to read the sign regardless of the tasks being performed by the driver. Now consider the reading time when the driving speed is 105 km/h. The distance reading time for the driving simulation display is 2.9 seconds whereas the distance reading time for real-world driving is 9.3 seconds. These reading times suggest that at highway speeds the reduced distance reading time may be problematic for drivers in the simulator, particularly if the driver is engaged in performing multiple tasks or if the driving scene is highly cluttered with other stimuli which might distract the driver. The point of these calculations is not to argue specific limitations in driving simulation displays. The actual distance reading times can vary across simulator displays (e.g., variations in visual angle, size of signage, etc.). The point of these calculations is to demonstrate, with a specific set of parameters (display resolution, visual angles, at signage size), the difference between driving simulation displays, real-world vision conditions, and the potential effects on performance.

A second effect concerns the precision of information for the perception of motion. The perception of motion involves the spatial displacement of information over time (Braddick, 1974). A reduction in spatial resolution will result in a reduction in the accuracy with which motion is specified. This reduction can alter the perceived motion of objects in the driving scene as well as the perception of the direction and speed of the driver's vehicle. Although this issue should typically not be a problem in most simulation displays with resolutions of at least 1024 by 780, it does become an issue when the viewing distance to the screen or monitor is reduced. For example, consider a 1024 by 780 projected image viewed at a distance of 2 meters and subtending a horizontal visual angle of 60 degrees. Under these conditions the horizontal extent of a pixel is 0.058 degrees visual angle. Reducing the distance to 1 meter to produce a larger visual angle of the display will result in a projected horizontal extent of the display of 73.8 degrees. Under these conditions the horizontal extent of a pixel is 0.072 degrees. This represents a 23% reduction in the display resolution (in projected visual angle) which will result in less accurate information for the spatial displacement of motion.

A third effect concerns the visibility of simulation display pixels. As noted above, under optimal viewing conditions there is an approximately fourfold decrease in resolution for simulation displays as compared to real-world viewing conditions. Since the minimum visual angle in a simulation display is well above the threshold of human vision, then the individual pixels of a display may be visible. Anti-aliasing algorithms (image processing procedures which average luminance across pixels) are used in simulation displays to reduce the visibility of individual pixels and minimize the appearance of jagged edges for diagonal lines. Despite the use of anti-aliasing algorithms some degree of pixilation is visible in simulation displays. The problem with pixel visibility is that it provides a texture cue that is inconsistent with the 3D simulation of the driving scene. More specifically, the size of pixels is approximately uniform in the vertical and horizontal dimensions. As a result, the pixels represent a texture pattern that the image is frontal parallel and the driving scene has no depth. However, this information contradicts the motion and pictorial cues in the display which specify that the driving scene extends into 3D space. Information of this type has been referred to in the literature as a flatness cue (e.g., Eby & Braunstein, 1995). One effect of flatness cues is to compress the perceived depth of the scene. Gogel (1954) found that the perceived depth of adjacent objects was compressed to the average depth across a scene. He referred to this effect as the adjacency principle and found that the use of this principle by human observers resulted in misperceived distance (Gogel, 1972), size (Gogel, 1998), and speed (Gogel, 1982) of objects in a scene. As a result the egocentric distances of objects in the scene (i.e., other vehicles, signs, pedestrians, crosswalks, etc.) will appear closer than the distances that are simulated. The compression of visual space may have a profound effect on driving performance.

8.3.2 Temporal Resolution

The primary issue of temporal resolution and driving simulation concerns the effects of the refresh rate of the display and the perception of motion. Previous research has shown that the perception of motion declines when the presentation rate of individual frames is slower than one every 40 msec (Baker & Braddick, 1985). In terms of the refresh rate of the display this rate translates to 25 frames per second. Most research on depth perception and motion perception uses a minimum refresh rate of 30 frames per second. These studies suggest that the refresh rate should not fall below 30 frames per second.

More problematic, however, is the relationship between refresh rate in the simulation and simulation display detail. Simulation research necessarily involves real-time computations for producing closed loop control. As a result, the computer is performing calculations in real-time based on control inputs and the rendering of the 3D graphics presented in the display. The amount of computation (number of calculations per unit time) can vary according to several factors including the complexity of the driving scene and complexity of the simulation of vehicle dynamics. More specifically, the greater the amount of detail to be presented in the display (e.g., number of buildings, texturing, objects, moving vehicles, etc.) the greater the number of calculations that must be performed. The variation in the number of calculations can have a profound effect on the refresh rate of the display, resulting in a display refresh that varies over time. The change in refresh rate over time can dramatically alter the perception of motion that is simulated. For example, if the refresh rate changes from 30 frames per second to 10 frames per second, the change in temporal information can dramatically alter the perception of motion. Given the 25 frames per second limit (Baker & Braddick, 1985) this type of variation will lead to a perception of smooth motion at the high frame rate to a perception of jittery motion or no motion at the low frame rate. Thus, the smoothness of the perception of motion will vary as the frame rate changes over time. The variation in smoothness of motion is often perceived as a variation in velocity that is not simulated in the driving scenario but is an artifact of the variation in frame rate (Palmisano, Burke, & Allison, 2003). This change in velocity can have a profound effect on driving performance in the simulator. Indeed, variations in perceived velocity that are not consistent with the simulation (e.g., accelerations or decelerations of driver responses) may be a leading cause of simulator sickness (Palmisano, Bonato, Bubka, & Folder, 2007; Bonato, Bubka, & Palmisano, 2006).

A simple solution to this problem is to set minimum temporal rates for the simulation. Variations in the refresh rate above

30 frames per second are less likely to be detected by the human visual system because all motion above 30 frames per second is perceived as smooth motion (Baker & Braddick, 1985). However, frame rates that fall below 25 are likely to be perceived as jittery motion. These findings suggest that all simulation studies should have the refresh rate set to a value no lower than 30 frames per second (a value well above the 25 frames per second limit).

8.3.3 Luminance and Contrast

Visual displays in simulators have luminance and contrast levels well below luminance and contrast in real-world vision. For example, consider the levels of luminance that are optimal for normal human vision. Campbell and Robson (1968) found the greatest sensitivity to variations in contrast occurred for stimuli with average luminance of 500 cd/m^2. Luminance levels under the best conditions in simulators are approximately 50 cd/m^2. In general, these differences should not result in performance differences between real-world and simulator driving. However, the lower luminance levels can limit the ability of simulators to create problematic conditions for drivers such as glare (e.g., McGregor & Chaparro, 2005; Wood, Tyrell, & Carberry, 2005) or the range of luminance present under fog conditions (e.g., Broughton, Switzer, & Scott, 2007; Buchner, Brandt, Bell, & Weise, 2006).

8.4 Perceptual Issues in Simulator Displays

8.4.1 Motion and Optic Flow

Of all the sources of visual information used in driving probably no single source is as important as the perception of motion and optic flow. As reviewed above, most driving tasks require the perception of motion and recovery of information from optical flow (i.e., optical expansion). Problems can occur in simulation displays for the perception of motion and optical flow when the spatial and temporal resolution is low. A reduction in the spatial resolution of a display will result in less precision of the information present to a driver in specifying the direction of local display velocity. Similarly, a reduction of temporal resolution (display refresh) can result in jittery motion than can lead to misperceived magnitude of local velocity information. These reductions can have a significant effect on perceiving optical flow information important in driving. For example, a severe reduction in spatial and temporal rates may lead to decreased ability to determine the rate of expansion—information important for determining the time to an impending collision.

As noted earlier, temporal limitations in simulators can be addressed if the display refresh rate is maintained at 30 frames per second. Spatial limitations only become an issue for performance if the display resolution is low or if the viewing distance from the driver to the monitor or screen is small. Previous research on motion perception have typically used viewing distances of one meter or more with display resolutions of 1024 by 780 or higher. This suggests that problematic display resolution may only occur with very low-fidelity simulators or with simulator displays viewed at close distances (less than one meter).

8.4.2 3D Texture

The primary limitation of texture in simulation displays, compared to real-world vision, is the relationship between texture and scale. In real-world scenes, texture occurs at several different levels of scale. For example, consider a roadway scene of an urban area containing city blocks with buildings. In this scene there are several different scales of texture. One level of texture is available from the repeated pattern of the buildings located along the roadway. A second level of texture is available from the pattern of windows on a building. A third level of texture is available from the materials used for the exterior of the building (e.g., granite or concrete). Thus, in real-world driving scenes information is available from several types of texture at different levels of scale.

Often in computer simulations the levels of texturing are limited. For example, texture information might be available from the first or second level listed above (e.g., pattern of buildings or windows on a building) but may not include the more detailed texture from the third level. The decision to include different levels of texture is often determined in part by the computational requirements to incorporate multiple levels of texture in the driving scene and its impact on the refresh rate of the display.

The point of raising this issue is to argue that: (1) current driving simulation scenes do not include the full range of texture information available from a real-world scene; and (2) the potential impact of including a limited range of texture on driving performance in a simulator is unclear. The limited range of texture scale in simulators may have an impact on driving performance. For example, previous research has shown the edge rate (the number of texture units that pass a location in the visual field per unit time) is used to determine speed of forward motion (Larish & Flach, 1990) and has suggested that edge rate information is important in driving tasks such as car following (Andersen, Sauer, & Saidpour, 2004). What is not known is the effect of multiple levels of texture scale on edge rate information. An important issue for future research will be to determine the role of different levels of texturing scale on driving performance.

8.4.3 Stereopsis/Binocular Disparity

Several studies have suggested the importance of egocentric distance information for driving performance. For example, Andersen, Cisneros, Saidpour and Atchley (1999, 2000) suggested that drivers use distance information to regulate braking behavior. One source of information for distance perception is stereopsis or binocular disparity. Stereopsis provides information about distance as a result of each eye receiving a unique view of the world. The difference in relative positions in the projections to each eye is used to determine distance. Previous research has found that disparity information is effective at specifying depth for distances of up to 100 meters (see Cutting & Vishton, 1995, for a review).

The importance of binocular disparity information on driving simulation displays is twofold. First, most driving simulation research does not include binocular information. An extensive body of literature has shown the role of binocular information in perceiving depth information when other sources of depth information (e.g., texture, motion, pictorials cues) are present (see Howard & Rogers, 2002, for a detailed review). The problem is that when disparity information is not present it may affect the use of these information sources for distance perception. The lack of disparity information may have a profound effect for some driving tasks. For example, the perception of motion in depth is important for recovering time-to-contact information for an impending collision. Previous research has shown that disparity information interacts with motion information (expansion) to produce the most accurate estimates of time-to-contact (see Gray & Regan, 2004, for a review). If disparity information is not present then time-to-contact estimates are less accurate (Gray & Regan, 1998). Indeed, studies have found a decrease in accuracy (when comparing monocular with monocular and binocular information) in estimating time-to-contact of between 30 to 50% (Cavallo & Laurent, 1988; Heuer, 1993). Thus driving performance that includes time-to-contact will not match the performance in real-world driving when disparity information is present. A similar problem exists when estimating the speed of approaching objects. Harris and Watananiuk (1995) found greater accuracy in estimating speed of approach when disparity information was present. Thus, the lack of disparity information in a driving simulator may have a profound effect on drivers' estimates of the speed of approaching objects.

A more serious problem exists in driving simulators when disparity information is absent. The driver views the simulator display (either monitor or projection screen) with both eyes. Under these conditions the disparity information to the eyes is consistent with a flat surface (i.e., the screen or monitor). But the simulation is specifying that the driving scene is three-dimensional. Thus, disparity information when viewing with both eyes provides conflicting information for depth and distance that is depicted from motion and pictorial cues. Since disparity is useful for distances of up to 100 meters this problem exists for any simulation display where the distance between the driver and display (either projection screen or monitor) is less than 100 meters—a limit violated in every driving simulator.

There are no straightforward solutions to this issue. Although stereo systems exist that can be utilized in driving simulation displays, the most common apparatus involves shutter glasses that must be worn by the driver. This can be problematic if the driver wears prescription glasses. Furthermore, shutter glasses can diminish the apparent brightness of the display (at any given moment one lens is filtered and thus dark; when the visual system fuses information from both eyes it averages the dark image with the visible light image of the screen, thus reducing overall luminance of the fused image). Driving simulation research should be conducted with an understanding that conflicting disparity information might impact driving performance.

8.4.4 Eye Convergence and Accommodation

Convergence refers to the change in the optical angle between the two eyes to bring an object into focus. The feedback from the muscles in the eyes provides feedback regarding egocentric distance. Accommodation refers to the change in the optical focus of the lens to bring an object into focus. The muscle feedback to change the shape of the lens to alter focus also provides information for egocentric distance. Convergence can provide depth information for distances of up to 10 meters (Cutting & Vishton, 1995). Accommodation can provide depth information for distances of up to 2 meters (Cutting & Vishton, 1995). Both convergence and accommodation can provide information to a driver that they are viewing a flat screen rather than a 3D display. The presence of this conflicting information can compress the perceived distance when viewing a display. For example, Andersen and Braunstein (1998b) found that accommodation reduced the perception of the intervals in depth in a computer-generated scene. Since convergence can provide information of a flat screen for distances up to 10 meters it is a potential problem for viewing most driving simulation displays (the notable exception is large dome simulators). This problem is also present in head-mounted display systems, which include binocular disparity and defocus the image to limit accommodation information, but cannot alter the angular eye position from convergence. Since accommodation provides distance information for displays up to 2 meters, viewing any projection system or monitor at distances closer than 2 meters can result in flatness information from accommodation.

False flatness information from accommodation can be reduced or removed using optical techniques. For example, a Fresnel lens system can be used to reduce accommodative focus. A related technique often utilized in flight simulation displays is to use parabolic mirrors for projecting the display to the pilot. A final method for removing accommodative focus is to use a large plano-convex lens (Andersen & Braunstein, 1998b).

8.4.5 Flatness Cues

The review of the issues discussed above indicates that there are a number of visual information sources that can provide conflicting information for the perception of a 3D scene. These include disparity, convergence, accommodation and visibility of display/image pixels. In addition to these perceptual conflicts the visibility of the frame of the display or projection screen can serve as a cue to flatness. Previous research (Eby & Braunstein, 1995) found that the presence of a surrounding rectangular frame resulted in a compression of depth of a 3D scene. The compression of depth occurred regardless of whether the 3D scene was viewed in a darkened room or in a fully illuminated room. Many driving simulation displays are presented with the frame of the monitor or projection screen visible. As a result, in driving, if a task involves the use of depth information, it will be altered because of the compression of perceived space along the depth axis. The presence of this information may limit the conclusions that can be reached from simulations studies. To avoid this problem simulation displays should be presented such that the surrounding frame of the display is occluded from the driver's view.

8.5 Visual Displays and Simulator Sickness

A serious problem with driving simulators, as well as other types of simulator, is that exposure to visual stimuli can result in simulator sickness. The incidence of simulator sickness is quite common and occurs regardless of whether the simulator has a fixed base (the simulator platform remains stationary) or variable base (the platform is allowed to move to simulate g-forces and roll, pitch and yaw). Simulator sickness has occurred with displays that are presented on a monitor, projection system or head-mounted system. Reason and Brand (1975) proposed that motion sickness was the result of perceptual conflicts between different sensory systems. This theory, often referred to as the cue conflict theory, is relevant to simulator sickness because of fidelity differences between different types of sensory information in a simulator. The type of motion and accelerations/decelerations that can be presented visually is virtually unlimited because motion can be adequately presented in visual displays. However, vestibular and kinesthetic information is severely limited in a simulator. Fixed-based simulators provide little or no information regarding motion and accelerations and decelerations. Variable-based simulators cannot precisely reproduce all the information available during motion under real-world conditions. Thus, a conflict exists between the visual information and kinesthetic and vestibular information. To better predict conditions that result in simulator sickness one needs to consider the different types of information available from different sensory systems for the perception of observer motion. The visual system can provide information for constant speed, changing speed, constant direction, and changing direction (see Watanabe, 1998, for a detailed review). In contrast, the vestibular system can only provide information for changing speed and changing direction (see Mergner, Rumberger, & Becker, 1996). This difference suggests that any simulated conditions in which a change in direction or a change in speed can occur are conditions that might result in simulator sickness.

One might assume that the conflict would be greater in a fixed-based simulator, but several studies suggest that the incidence of simulator sickness is much higher in variable-based simulators (see Hettinger, Berbaum, Kennedy, & Dunlap, 1990). This finding suggests that no input from vestibular/kinesthetic information in a fixed-based simulator is preferable to information that is a low-fidelity replication of physical movement of a driver in a variable base simulator.

8.5.1 Sensory Conflicts and Simulator Sickness

The Reason and Brand theory of motion sickness suggests that conflicts across different sensory modalities (e.g., vision and the vestibular system) produce sickness. However, the specific conditions that result in simulator sickness are not known, nor is there a well accepted theory that predicts the conditions under which simulator sickness occurs. Despite the lack of a theory of simulator sickness, there are several well-known conditions that, if present, increase the likelihood of simulator sickness. In the next sections we will review the conditions known to increase the likelihood of simulator sickness.

8.5.2 Display Field of View

One of the most common conditions that can result in simulator sickness is a visual display with a large field of view. The increased incidence of simulator sickness with a large field of view suggests that stimulation of the peripheral visual field is critical. Previous research has shown that motion in the peripheral visual field is important for producing vection—the perception of observer motion through space (see Andersen, 1986). Although stimulation of a small area of the central visual field (15 degrees) is sufficient to produce vection (as well as motion sickness; Andersen & Braunstein, 1985) it is likely that motion in the periphery leads to a more compelling impression of vection (Andersen, 1986). The compelling impression of vection—that the observer/driver is in motion—contradicts the vestibular and kinesthetic information in a simulator. This conflict would thus increase the likelihood of simulator sickness.

Any conditions which increase the magnitude of the conflict will increase the likelihood of simulator sickness. For example, any driver motion involving a curved path will not be accompanied by appropriate stimulation of the vestibular system that the driver is physically moving along a curved path. Indeed, previous research (Mourant, Rengarajan, Cox, Lin, & Jaeger, 2007) has found greater simulator sickness when driving curved as compared to straight roadways. The increased incidence of simulator sickness on curved roadways suggests that minimizing the frequency of large changes in vehicle path (e.g., right or left hand turns) should be considered in designing scenarios for driving research in order to reduce the likelihood of simulator sickness.

8.5.3 Simulator Design Eye

A common cause of simulator sickness is an inconsistency between the simulated projection point in the computer model of the 3D driving scene (referred to in computer graphics as the simulator design eye) and the viewpoint of the driver relative to the monitor/projection screen (see Hettinger et al., 1987). This inconsistency is due to differences in the perspective of the computer simulation and the perspective of the driver's viewpoint to the display, which result in severe distortions of the driving scene when viewed. In the computer simulation, perspective is determined by the geometry of a simulated eye point relative to an image plane (i.e., the ratio of the distance between the eye point and the image plane to the distance between the eye point and the ground). The inconsistency occurs when the geometry of the driver to the display does not match the geometry in the simulation of the eye point to the image plane. When the geometry is inconsistent the driver's view is incorrect, resulting in considerable distortion of the 3D world.

8.5.4 Display Alignment

Finally, an additional cause of simulator sickness is misalignment of multiple displays (see Hettinger et al., 1987, for a discussion). Simulators that present a wide field of view will often use multiple screens or monitors to produce a large visual angle. Each screen/monitor is presenting a different view of the simulated scene. If these displays are not correctly aligned the visual system will infer that the misalignment is a change in viewpoint. To illustrate this issue, consider a horizon line presented across three projection screens. If one of the screens is misaligned relative to the other screens the horizon line will not appear as a single line across the screens. Instead, the horizon line in the misaligned display will appear above or below the horizon line in an adjacent display. When a driver is scanning across the three displays the misalignment across the displays will be perceived as a sudden change in viewpoint. The change in viewpoint will not be consistent with the simulation, and thus will result in simulator sickness. To avoid this problem screens and monitors in simulators must be properly aligned.

8.6 Summary

Driving is a skill that is heavily dependent on visual information that is processed and responded to by the driver. The goal of this chapter was to discuss the limitations of visual displays used in simulators and how these limitations might impact driving research. To understand these limitations it is important to note that the types of visual information used in driving will vary according to the type of driving task. For example, the information used in car following will be different to the information used in detecting and avoiding a collision. In this chapter I have reviewed the visual information (both sensory and perceptual) used to perform different driving tasks including detection/recognition of targets, steering control, collision detection and performance, braking, speed regulation, and car following.

Driving simulators present visual information that is an approximation of the information present under real-world driving conditions. For example, in a simulator visual motion is presented using a series of discrete presentations of static images whereas in real-world driving visual motion is a continuous projection of spatial displacement over time. The impact of simulator limitations in presenting visual information can have a serious effect on driving performance. For example, if the presentation rate or display refresh falls below 30 Hz the perceived motion of the driver and of objects in the scene will be altered. In this chapter I have reviewed the potential impact of spatial resolution, temporal resolution, luminance, contrast, texture, stereopsis, convergence and accommodation on driving performance in a simulator. An additional concern often not considered in simulator research is the presence of flatness cues that can alter the perceived depth of the driving scene. Finally, visual factors that can increase the incidence of simulator sickness and how these factors can be minimized or eliminated are discussed.

Driving simulators are an important tool for understanding driving skill and performance. Simulators allow researchers to examine performance issues that otherwise would not be possible using real-world driving (e.g., collision detection and avoidance). Understanding the limitations discussed in this chapter and the methods available to minimize or remove these limitations should lead to better use of simulators in driving research.

Key Points

- Driving performance is highly dependent on visual information.
- Different driving tasks (e.g., steering control, car following, collision detection and avoidance) involve different sources of visual information. Driving simulation displays should be designed to optimize the presentation of these information sources.
- Sensory issues that can impact performance in driving simulators include spatial resolution, temporal resolution, luminance, and contrast.
- Perceptual issues that can impact performance in driving simulators include motion, optic flow, texture, and stereopsis.
- A serious issue often overlooked in driving simulation is the presence of flatness cues from conflicting perceptual information (e.g., stereopsis, accommodation, convergence) or the visibility of the frame of the display.
- Factors that result in simulator sickness are quite varied and include sensory conflicts, a wide field of view, improper position of the driver given the simulation, and display misalignment.

Keywords: Driving Tasks, Simulator Display Design, Simulator Sickness, Visual Perception

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