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How to Use Driving Simulators Properly: Impacts of Human Sensory and Perceptual Capabilities on Visual Fidelity

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ABSTRACT

Fidelity has been a critical concern of researchers throughout the history of driving simulation. Understanding the limits of a driving simulation system is a prerequisite for conducting valid driving simulator studies. This paper proposes a novel and interdisciplinary methodology to ensure validity of studies using driving simulators (primarily for traffic control devices and other object detection tasks) based on the visual limits of human sensory and perceptual capabilities, and the characteristics of raster graphics. This methodology decomposes the perceptual issues of a stimulus into perceptual issues of different visual properties like luminance, hue, or text of the stimulus. By systematically analyzing the mechanism of human vision in driving simulators, the perceptual principle is proposed to ensure perceivable visual details in human-in-the-loop driving simulation systems. Additionally, the graphic principle is proposed to ensure perceivable features of a target object in the virtual driving environment. Both principles quantify the minimum requirements of visual fidelity with two measurements: angular resolution and matrix dimensions. The enriched results from existing pertinent studies are analyzed and organized to yield support of both principles. This research focuses on the minimum requirements for four factors; namely the visual acuity of drivers, the specifications of display systems, the configurations of graphics systems, and the design of virtual scenarios, as well as the relationship among all these factors to assess the visual fidelity in driving simulation systems. Within the realm of human perception, this work can provide criteria for proper design, calibration, and usage of driving simulators.

1. Introduction

Driving simulation has been widely accepted as an alternative virtual environment to study topics related to vehicle driving since the late 20th Century. The development of driving simulators started in the 1960s (Fisher et al., 2011; Hutchinson, 1958). Early driving simulators were originally developed to avoid the cost of field studies and to enhance control of the driving environment as well as to make it possible to collect certain data which are difficult to measure in the field. Since then, driving simulation has become an acceptable and disputable alternative to naturalistic experiments. As a branch of virtual reality that specializes in simulating vehicles and associated traffic environments, this technology is continually improving. Advances in electronics, computer science, and mechanics have motivated and supported the development of driving simulation. Driving simulation has been widely applied in a number of fields including engineering, psychology, and medicine (Chrysler et al., 2006; Gawron and Ranney, 1988; Huang et al., 2012; McKenna et al., 2006; Moskowitz and Florentino, 2000; Strayer et al., 2006). In transportation research, many driving

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simulator studies have been conducted to research the design of transportation facilities (Bham et al., 2016; Chen et al., 2018; Dudek et al., 2006; Stephens et al., 2017; Wang et al., 2015), transportation management (Bella, 2005; Weare et al., 2016), traffic operations (Muttart et al., 2014; Ogle et al., 2015), traffic safety (Ba et al., 2017; Tang et al., 2018), and the impacts of other emerging technologies applied in transportation systems (Boriboonsomsin et al., 2016; Huang et al., 2012; Louw and Merat, 2017; Wu et al., 2018; Zhao et al., 2016; Zimmermann et al., 2018).

Research based on driving simulation has limits, as well as advantages, compared to research conducted in the real driving environment. One of the most important advantages of using driving simulation to conduct research is that it grants researchers the capability to create a specified virtual environment with all parameters being fully controllable—realistic reproduction of which would be challenging and require a great deal of resources (Kearney et al., 2006; Olstam et al., 2008; Papelis et al., 2003). Researchers can arbitrarily configure and customize the virtual environment if necessary and quantify driving experience with repeatable events or scenarios for a variety of objectives. Thus, experiments using simulation can provide much greater accessibility to all variables and measurements than can on-road experiments.

The issue of fidelity has been a continuing concern of researchers throughout the history of driving simulation. Fidelity is the extent to which driving simulation reproduces the state of driving and the driving experience in reality. In order to reproduce the driving experience as realistic as required by specified tasks, the visualization system of a driving simulator is supposed to be designed, installed, configured, and manipulated in accordance with a human's visual capability and the nature of the tasks. Only in this human-in-the-loop context can a driver's behavior be effectively identical in both the real and virtual environment. It is especially important for research surrounding traffic control devices and other objects affecting driving behavior. For example, drivers should perceive and react to signs or markings in the virtual world at a simulated distance equivalent to the real-world reaction distance. Tu et al. (2015) conducted a driving simulator study to explore the impacts of hazy weather on driver behavior by modifying visual fidelity for different weather conditions. They configured a visibility of 1000 m to simulate clear weather conditions and 80 m for hazy weather conditions. The results indicated that the visual fidelity had significant impacts on driving performance. Consideration of visual fidelity raises a number of questions in the design, calibration, and usage of driving simulators. Do drivers detect traffic control devices and other objects in the same way in a driving simulator as in reality? Is the visual fidelity of a driving simulator sufficient to support a rigorous study of those detection tasks? If not, how is the visual fidelity made sufficient?

This paper focuses on the visual fidelity of driving simulation which is one of the most significant factors that has both sensory and perceptual impacts on drivers. The research explores the limits of visual fidelity in driving simulation systems based on extensive knowledge in the fields of human factors, computer graphics, and transportation engineering. By presenting a methodology for systematically analyzing and assessing the visual fidelity of driving simulation systems, the paper reveals why and how to verify satisfactory visual fidelity in driving simulator studies and illustrates how to properly diagnosis and calibrate driving simulators within the realm of human perceptual capabilities.

2. Literature review

Based on the interdisciplinary background involved in this study, this section reviews pertinent studies in diverse areas that underlie the proposed methodology in this paper.

2.1. Resolution of human eyes

The visual information humans can obtain in either the real or the virtual driving environment is highly dependent on their vision. Visual acuity, the sharpness of vision, is used to measure the capability of humans to see fine details. It is determined by properties of the retina and sensitivity of pertinent functions of the neural system (Cline et al., 1997).

In the real world, when objects are presented in the view as seen by a human, the visual angle subtended by the minimum details of the object, which the human can sense, is the resolution of his/her eyes. Visual acuity is a function of physiological and neurological characteristics for individuals, so the resolution of eyes is different for each individual. On the other hand, it is also a function of lighting, color, and contrast, so the resolution of eyes varies with the environment as well. The maximum angular resolution of human eyes was revealed to be roughly 0.6 arc minutes per line pair or 0.3 arc minutes per pixel in good lighting conditions (Konig, 1897). A typical acuity for a human with a "good" eye is 20/20 which means the capability of resolving objects that subtend 1 arc minute (Warren, 2015).

2.2. Resolution of driving simulators

In the virtual world presented by driving simulators, the resolution of human eyes is not the only critical factor determining the minimum details of the objects a human can actually sense. There are additional critical factors including the resolution of the display devices and rendered raster graphics. The visual information obtained by human eyes is represented by raster images that consist of a series of matrices of pixels on displays. Unlike the high-precision view of human eyes in the real world, the computer-based graphics systems and display devices are inherently more discrete by several orders of magnitude. The images drivers actually sense in a driving simulator are pixelated if the resolution of the displayed graphics is lower than the resolution of human eyes.

The display resolution of a driving simulator is critical to its visual fidelity. In a virtual driving environment, the display resolution restricts the visibility of objects of relatively small dimensions or at great distances from the location of the camera. Insufficient display resolution may cause this restriction to deny the correlation between the real and corresponding virtual driving experiences