Entertainment Computing 13 (2016) 1–9

Contents lists available at ScienceDirect

Entertainment Computing

journal homepage: ees.elsevier.com/entcom

Visual 3D motion acuity predicts discomfort in 3D stereoscopic environments ☆

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ARTICLE INFO

Article history:
Received 9 July 2015
Revised 30 November 2015
Accepted 9 January 2016
Available online 14 January 2016

Keywords:
Virtual reality
Simulator sickness
3D motion
Cue-conflict theory

ABSTRACT

A major hindrance in the popularization of 3D stereoscopic media is the high rate of motion sickness reported during use of VR technology. While the exact factors underlying this phenomenon are unknown, the dominant framework for explaining general motion sickness ("cue-conflict" theory) predicts that individual differences in sensory system sensitivity should be correlated with experienced discomfort (i.e. greater sensitivity will allow conflict between cues to be more easily detected). To test this hypothesis, 73 participants successfully completed a battery of tests to assess sensitivity to visual depth cues as well as a number of other basic visual functions. They then viewed a series of 3D movies using an Oculus Rift 3D head-mounted display. As predicted, individual differences, specifically in sensitivity to dynamic visual cues to depth, were correlated with experienced levels of discomfort. These results suggest a number of potential methods to reduce VR-related motion sickness in the future.

1. Introduction

Just four to five years ago, stereo 3D technology was being hailed as the next major development in entertainment media. Out of the top-twelve major box office successes in 2009, five were stereo 3D releases including *Avatar*, *Up*, and *Monsters versus Aliens* [1]. This trend was not limited to just movies. At the same time, major producers of television sets such as Toshiba, Panasonic, and Samsung were devoting significant resources in the development and marketing of stereo 3D television sets [1] and in the world of video gaming, it was predicted that the Nintendo 3DS would lead the way toward widespread use of stereo 3D in video games [2]. Yet today it appears that stereo 3D entertainment is unlikely, at least in the near future, to reach the levels of success that were previously predicted, with key creators of content, such as ESPN and the BBC, dropping their stereo 3D programming [3,4], major gaming companies failing to highlight or develop for stereo 3D [5], and some television manufacturers, such as Vizio, dropping production of stereo 3D televisions entirely [6]. While the reasons behind the current failure of stereo 3D forms of entertainment are myriad, one issue that consistently appears in both anecdotal accounts, and in the few scientific reports on the topic, is that stereo 3D environments make a significant proportion of viewers physically uncomfortable [7,8].

Such an outcome was not unexpected based upon previous scientific research. Although the utilization of digital stereo 3D technology for entertainment purposes is a reasonably new phenomenon, simulators have been incorporated in military and medical training for decades, with, perhaps not surprisingly, similar issues related to physical discomfort. In particular, users reported that virtual environments caused the experience of what has come to be called "simulator sickness" (characterized by symptoms such as nausea, headaches, and disorientation following exposure to a virtual environment [9–12]). Several proposed factors underlying susceptibility to (and likelihood of experiencing) simulator sickness have been put forward. Many of these factors have been related to the simulator hardware and display, including specific issues with graphics and visual lag, and variations in head movements and the degree of control over the visual scene [9]. Other factors have been at the level of individual differences in age (younger individuals more susceptible than older individuals), sex (females more susceptible than males), in personality factors (individuals low in extraversion, high in neuroticism, and/or high in anxiety all being more susceptible [9,13–15]). Finally, some researchers have suggested that individual differences in learning/habituation rate may also be a useful predictor of motion sickness [16]. Ultimately though, the dominant framework in the field

☆ This paper has been recommended for acceptance by William Swartout.

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http://dx.doi.org/10.1016/j.entcom.2016.01.001
1875-9521/

is the well-known "cue conflict" or "sensory-rearrangement" theory of motion sickness [17–23]. In essence, this theory posits that motion sickness occurs when sensory signals, particularly signals related to self-motion, from the various sensory systems (e.g. visual system, vestibular system, proprioceptors) are either in conflict with one another or else strongly violate expectations based on previous experience. Such mismatches frequently occur in real-world situations that evoke motion sickness as well, such as reading in a car (where the visual system, fixated upon the reading material, is not reporting self-motion, while the vestibular system does report the motion of the car) or being on a boat (where everything moves roughly in concert with the individual and thus there are few visual cues to motion, but the changes in position relative to gravity are again signaled by the vestibular system).

In the case of simulators, there are many instances of conflict both across systems and within a single system [24–26]. Many instances of conflict between systems are reasonably obvious. For instance, in a virtual video game (or a simulator), visual cues may indicate self-motion through the game environment, while the vestibular system will register no self motion since the player is in fact stationary. Conversely, when an individual is reading in a car, the visual system signals no motion (as the book that is being read is stable relative to the individual), while the vestibular system may signal self motion. Just as importantly though, instances of conflict can also arise between sub-parts of the same system (e.g. the visual system). As one simple example, consider the mismatch that can occur in simulated 3D environments between naturally correlated motor and retinal cues to motion-in-depth. In real-world environments, accommodation cues (i.e. differences in focus of the retinal images) and disparity cues (i.e. differences in object position on the two retinal images) typically provide consistent information. When an object moves toward an individual in the real world, its retinal image becomes defocused and the disparity of the information received by the two eyes changes. However, in 3D stereoscopic environments, these two depth cues are often in conflict. Disparity-based cues in a 3D stereoscopic environment may indicate that an object is approaching, however, because focus of the retinal image depends on the distance of the eye to the VR display which remains constant, this cue indicates no change in depth. Many other visual cues – such as those related to vergence angle or velocity-based cues to depth (i.e. cues based on the fact that objects moving in depth move in different directions in each eye) can also be in conflict with one another and with other retinal and motor cues. For example, in examinations of discomfort associated with non-head-mounted stereo 3D displays, researchers have found discomfort associated with motor conflicts resulting from incongruent accommodation and vergence changes [26], particularly at rapid velocities [27] although the effects appear to depend on the distance and sign of the disparity [28]. Furthermore, non-retinal and non-motor cues, such as unnatural blur and imperfect binocular projections have been shown to increase discomfort in stereo 3D displays.

Discomfort, according to cue-conflict theory, arises when the system realizes that different sensory estimates are in irresolvable conflict. This leads to the direct prediction that individual differences in motion sickness symptoms should be partially a function of individual differences in the sensitivity of an individual's sensory systems. For instance, in the case of self-motion, both the vestibular and visual system provide estimates of the degree of self-motion. If these estimates tend to be highly accurate, then the system should be easily capable of detecting situations where a mismatch has arisen. Conversely, if an individual's system provides highly error-prone and variable estimates, then mismatches are more likely to go unnoticed. There has thus been considerable work examining the relationship between motion sickness and sensory sensitivity. Much of this work has focused on the sensitivity of the vestibular system to self-motion [29,30], with the general finding that there is a small relationship between vestibular sensitivity and symptoms of motion sickness [15]. Similar work has examined individual differences in basic visual functions such as visual tracking and nystagmus as well [31]. There has been no research though that has examined inter-individual differences in sensitivity to specific motion in depth cues as predictors of motion sickness. However, the fact that younger participants are more likely to report severe motion sickness symptoms than older adults [8,9 – although see 32] is consistent with a hypothesis wherein sensitivity to these cues would play a major role, as younger adults tend to be more sensitive to disparity, accommodation, and vergence cues than older adults [33–35].

In the present study we thus aimed to identify individual differences that might underlie discomfort in 3D environments. Because many of the conflicting cues in these environments are visual in nature – and in particular are largely related to depth perception – we predicted that an individual's stereoscopic (3D) abilities would be a major predictor of discomfort. Specifically, we hypothesized that more accurate stereoscopic motion perception would be associated with greater levels of discomfort caused by stereo 3D displays. To test this hypothesis, participants underwent a set of visual measures – targeted to isolate stereovision abilities based on several visual cues. To control for the potential effects of visual acuity and speed of processing, as well as to control for potential differences in attention/motivation, participants completed an additional set of visual measures. To assess history of motion sickness and previous exposure to virtual reality and 3D stereoscopic environments, participants also completed a number of self-report questionnaires. Participants then viewed a series of 3D stereoscopic movies using the Oculus Rift virtual reality system and any discomfort that was experienced during/after the experience was assessed both by self-report questions following the task as well as by measuring the amount of time the participant could tolerate the 3D stereoscopic environment. By comparing the visual abilities and self-report measures of those who reported discomfort in the 3D stereoscopic environment and those who did not, we hoped to identify the factors most strongly associated with stereo 3D display discomfort.

2. Methods

2.1. Participants

A total of 84 individuals were recruited to participate in the study. Participants who did not complete three or more measures, or whose data on more than one measure was greater than three standard deviations from the mean, were excluded from the analysis. A total of 73 participants (28 males), aged 18 to 51 ($M_{age} = 20.47$, $SD_{age} = 6.07$), met the criteria for inclusion in the analysis. All had normal or corrected-to-normal vision. Participants were recruited from the UW Madison campus and received extra credit for introductory psychology courses as compensation. The total of 84 individuals represents all volunteers during the Fall 2013 and Spring 2014 semesters. Informed consent was obtained in accordance to the requirements of the IRB review board committee of the University of Wisconsin, Madison.

2.2. Overall design

Participants first filled out a consent form, a demographic sheet, a questionnaire concerning past experience with motion sickness and virtual reality/3D stereoscopic environments, and a video game and media usage survey. Participants then completed several tasks measuring various aspects of visual performance (see