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

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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

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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

Section 2.4.2 below), which together lasted approximately one hour. The participants were then exposed to a 3D stereoscopic environment for a maximum of 20 min (see Section 2.5 below). Finally, participants filled out questionnaires designed to assess the motion sickness symptoms and visual and physical discomfort experienced during and after the exposure to the 3D stereoscopic environment. For example questionnaire questions see Section 2.6 below.

2.3. Apparatus

2.3.1. Computer

All non-3D stereoscopic visual tasks were performed on a Quad Core Intel Mac Pro with an NVIDIA Quadro 4000 GPU, running Matlab and the Psychophysics Toolbox [36,37]. Visual stimuli were presented on a 54.6 cm × 33.8 cm LCD display (Planar SA2311W, 120 Hz, 1920 × 1080 pixels) at a viewing distance of 85 cm for the stereovision tasks and 59 cm for the remainder of the tasks. For the stereovision tasks, participants wore active stereo shutter glasses (NVIDIA 3D 2, 60 Hz/eye), through which they viewed the LCD display. When viewed through the shutter glasses the luminance of a white stimulus was 5.62 cd/m^2, mid gray was 3.48 cd/m^2, and black was 0.01 cd/m^2.

2.3.2. 3D stereoscopic stimuli

All 3D stereoscopic movies were presented using the Oculus Rift Developer Kit (DK1), a head-mounted display with an 18 cm LCD screen (60 Hz, 1280 × 800 pixels [640 × 800 pixels per eye], FOV = 90 degrees horizontal/110 degrees vertical), and a built in head tracker (1000 Hz absolute 3DOF orientation). We note though that head movements will not affect the movies, and thus the display environment should not be considered a full virtual reality environment.

2.4. Visual performance task battery

2.4.1. Stereovision tasks

Participants performed four tasks designed to measure their static and dynamic stereovision. Each block took approximately 5 min to complete and consisted of 100 trials. See Fig. 1 for schematics of the different stimuli. Movies illustrating the stereo stimuli used in this experiment are included in the Supplementary materials.

2.4.1.1. Static Stimulus. For the static 3D stimulus, participants fixated the center of the screen while two arrays of randomly positioned black and white dots (128 dots total) were presented simultaneously above and below fixation for 1 s on a mid-gray background. Each array extended from 0.5 to 6 degrees of visual angle above and below fixation and was 13 degrees wide (Fig. 1A). On each trial one of the arrays was randomly selected to appear behind the plane of fixation (farther away), while the other array was presented in front of it (nearer). Each plane was presented with ±0.125 degrees of binocular disparity relative to the fixation plane, such that the total disparity difference between the two planes was .25 degrees. To help participants maintain vergence and fixation, a fixation point and a 1/*f* (pink) noise pattern was presented in the spatial surround. In addition, a Nonius cross was presented around the fixation point to help participants monitor any potential vergence failures. Participants used the up or down keys to indicate which dot array (top or bottom) appeared nearer. The disparity range was chosen to maximize inter-individual variability across all stereovision tasks. The results of pilot testing indicated that this disparity range produced a small but generally perceptible sense of depth given the relatively short 1 s presentation time.

2.4.1.2. Dynamic Stimulus. We assessed sensitivity to 3D motion using three versions of a dynamic 3D stimulus in which specific cues to 3D motion (changes in disparity and inter-ocular velocity) could be isolated. In all stimuli, configuration of the display was similar to that described above for the static condition (extent, size and distribution), with the exception that the planes specified by the two dot arrays moved, indicating opposite directions of motion-in-depth (towards and away from the observer). On the first frame of each trial, one of the arrays was randomly selected to appear behind the plane of fixation while the other array was presented in front of it (at 0.125 degrees of crossed/uncrossed binocular disparity). The arrays moved in opposite directions in depth at a speed of 0.25 degrees/second for one second, so that the array that started 0.125 degrees in front of the plane of fixation receded to 0.125 degrees behind the plane of fixation (and vice versa for the opposite array). Participants reported which dot array appeared to move towards them.

2.4.1.2.1. Changing disparity cue stimulus. To isolate the changing disparity cue to motion-in-depth (i.e. to remove inter-ocular velocity differences), dots were randomly repositioned at each screen refresh interval with a new disparity value. At each refresh, the dot disparity was increased/decreased (depending on the direction of motion in depth of the given array) so that the disparity of the dots changed at a rate of 0.25 degrees/second. In this stimulus, dots do not have an inter-ocular velocity difference since they are randomly repositioned at each screen refresh, but as a whole the dots define a plane that moves through depth. Accuracy in this task thus provides a measure of sensitivity to qualitative changes in stimulus disparity over time.

2.4.1.2.2. Inter-ocular velocity difference cue stimulus. To isolate the inter-ocular velocity difference cue (i.e. to attenuate information about changes in disparity), dots were given opposite contrast in each eye (i.e. black in one eye, white in the other). While this does not entirely remove information about changes in disparity (changing disparity is a necessary correlate of IOVD, but not vice versa), anti-correlation of stereo image pairs has been shown to significantly reduce the ability to use disparity information to perceive depth [38–40]. Accuracy in this task provides a measure of sensitivity to the differential direction of movement of a stimulus in each eye.

2.4.1.2.3. All cues stimulus. The all cues 3D task block contained static disparity, changing disparity as well as inter-ocular velocity cues, consistent with what would be present in natural viewing conditions. This task provides a general measure of sensitivity to the direction of motion in depth of a stimulus.

Prior to beginning the experiment, participants completed 20 practice trials of the "all cues" 3D motion condition, with feedback on whether or not they answered correctly (high tone for correct, low tone for incorrect). Participants always completed the all cues stimulus block first; the order in which participants completed the other three conditions was counterbalanced between participants.

2.4.2. General vision tasks

As noted above, our a priori hypothesis was that differences in stereomotion sensitivity would be directly related to experienced stereo 3D display discomfort. The tasks below were thus designed to rule out confounds related to simple visual abilities (e.g. visual acuity or speed of processing) as well as confounds related to motivation/effort (e.g. that individuals who tried harder during the task battery experienced more fatigue and thus experienced greater subsequent discomfort). See Fig. 2 for schematics of these stimuli.

2.4.2.1. Onset timing. A stimulus onset asynchrony (SOA) task was used to measure participants' speed of visual processing. During each trial, participants fixated a central point (a 1° white rectangle against a mid gray background) while two circles (diameter of 1°)

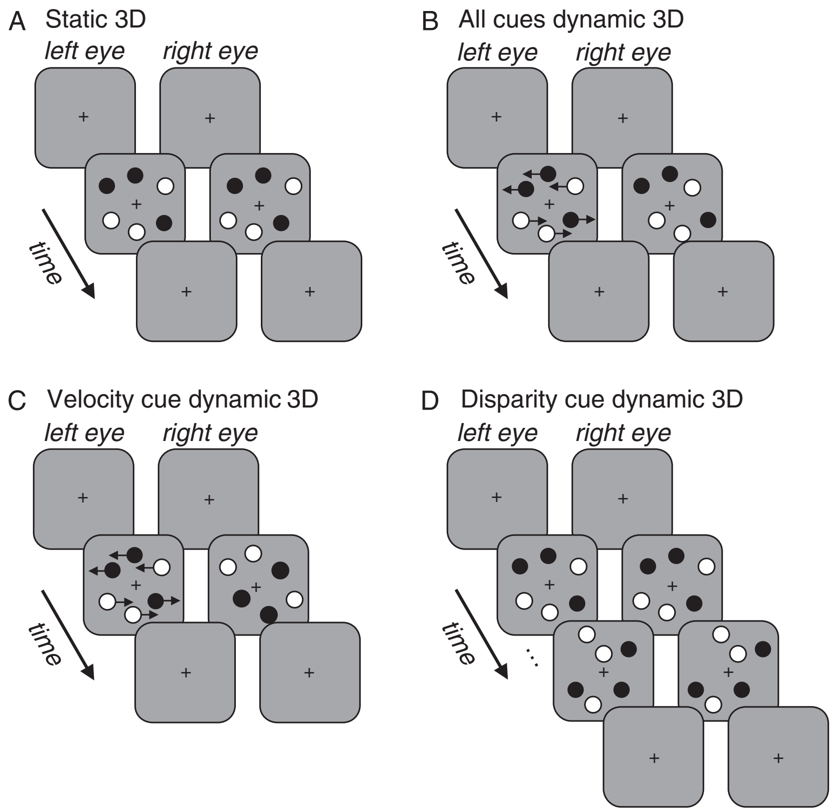

Fig. 1. Schematic of the 3D perceptual tasks. (A) Static 3D tasks tested static disparity perception. (B) Full-cue dynamic 3D tasks tested both interocular velocity differences and changing disparity perception. (C) Velocity-cue dynamic 3D tasks tested ability to use velocity differences in the two eyes to infer the motion through depth of random dots. (D) Disparity-cue dynamic 3D tasks tested ability to use changing disparity to infer the motion in depth of random dot displays. For the static task, participants indicated which panel of dots appeared in front of the plane of fixation. For the dynamic tasks, participants indicated which panel of dots appeared to move towards them. The two panels of dots always moved in opposite directions (dynamic tasks) or were situated in planes opposite of fixation (static). Left and right eye information was segregated via stereo shutter glasses. Movies illustrating these stereo stimuli are included in the Supplementary materials.

appeared at slightly different times 5° above and below the fixation point. We varied the onset differences between 5 ms and 340 ms. Participants reported which circle appeared first using the up and down arrow keys on a standard keyboard. After each trial, participants received feedback about whether or not they responded correctly. A short (~30 s) practice was completed before the task. The main task took roughly 5 min to complete and consisted of 12 trials per onset speed (for a total of 60 trials). For data analysis purposes, performance on the task was reduced to the linear slope of the fit of the participant's performance across the five SOA levels.

2.4.2.2. Simple discrimination. A simple discrimination task was used as a second measure of the participants' speed of visual processing. During each trial, as participants fixated the center of the screen, either a white square or circle would appear (subtending 2° of visual angle). Participants were instructed to respond as fast as they could whether a circle or a square appeared using the left and right arrow keys (left for square, right for circle) on a standard keyboard. After each trial, participants were told whether or not they responded correctly as well as their reaction time. Mean response time was used as the measure of simple discrimination abilities. A short (~30 s) practice was completed before the experimental task. The task took roughly 4 min to complete and consisted of 120 trials.

2.4.2.3. Acuity. A tumbling E task was used to measure participants' visual acuity at 5° and 15° of eccentricity (measured in separate blocks), which provides a measure of peripheral acuity. During the task, an "E" appeared either to the left or right of fixation at which point the participant responded which direction the E was facing using the arrow keys (4 cardinal directions). After each trial, the participant received feedback as to whether or not they answered correctly. The stimulus size was controlled via a 3:1 staircase (i.e. after three correct responses the stimulus was reduced in size, after one incorrect response the stimulus was increased in size). The stimulus was changed by 50% during the first 20 trials, by 30% for the next 20 trials, and by 20% for the final 40 trials (80 trials in total). The task at each eccentricity (5° and 15°) took roughly 4 min. A short practice (~30 s) was completed before the experimental Tumbling E task (at 5 degrees).

2.5. Exposure to 3D stereoscopic videos

Participants were exposed to, at most, four stereo 3D videos, totaling 20 min in time, with an Oculus Rift (DK1). Participants watched the videos in the same order: (1) a 4 min, first-person video of a car driving through mild traffic, (2) a 3 min first-person computer-generated (CG) video of a fighter jet flying through a canyon, (3) a 5 min first-person video of a drone flying around a bridge, and (4) a 6 min first-person video of a drone flying through a parking lot. See Fig. 3 for screen shots of the four videos. Full copies of the four videos are also included in the Supplemental materials.

Participants were told they could stop or take a break at any time. Whether or not the participant stopped early, as well as their stopping time if they did, was recorded. Participants stood on a Wii balance board while they watched the videos through the Oculus

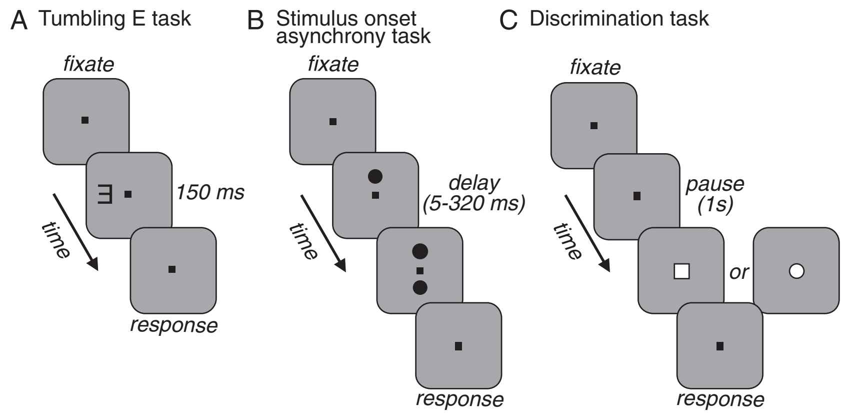

Fig. 2. Schematics of the three perceptual and processing tasks included in the battery. (A) The "Tumbling "E" task was used to test acuity outside of the fovea. The tumbling E stimulus was decreased in size after consecutive correct responses until participants could no longer perform above chance. (B) Stimulus onset asynchrony tests measured one's sensitivity to small temporal differences in the presentation times of simple stimuli. Sensitivity was quantified by the best fitting linear slope across the response times for the 5 different onset asynchronies. (C) Discrimination tasks were used to test speed of processing of simple stimuli. While fixating at the center of a gray screen, either a white square or circle appeared. The mean response time was used to quantify discrimination abilities. Participant's heads were stabilized with a chin rest while viewing stimuli on a computer screen.

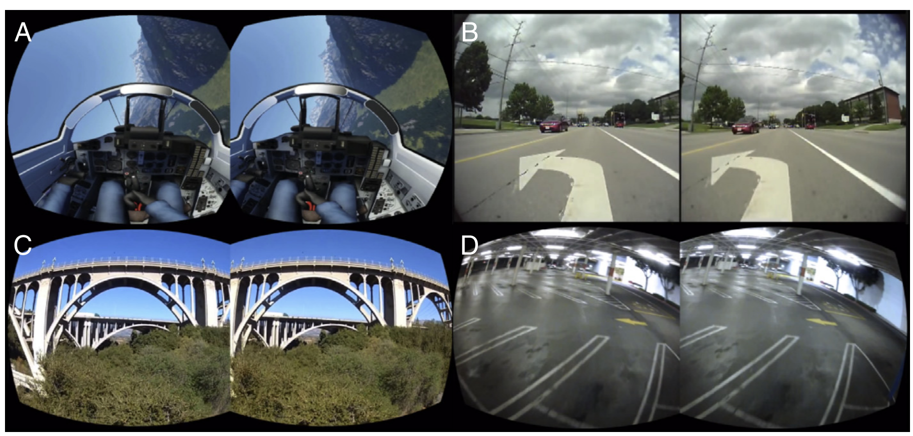

Fig. 3. Screenshots from the four 3D videos shown to the participants with an Oculus Rift head mounted virtual reality display. Participants watched (A) a first-person computer-generated (CG) video of a fighter jet flying through a canyon, (B) a ground-level video of a car driving through mild traffic, (C) a first-person video of a drone flying around a bridge, and (D) a first-person video of a drone flying through a parking lot. Videos averaged approximately 5 min in length. Full copies of these videos are included in the Supplementary materials.

Rift. Our original goal was to utilize measures of participant sway as a possible predictor of motion sickness symptoms as postural instability has been identified as a key predictor of motion sickness [41,42]. However, due to participant safety concerns (e.g. during piloting several participants had reasonably substantial balance issues), a handrail was provided to ensure that participants did not fall during the experiment. This in turn severely limited the effectiveness of such a measure. Since no significant relationships between observed sway and participant group could be observed, the results are not discussed below.

2.6. Survey measures related to discomfort

After watching the 3D stereoscopic videos, participants reported their discomfort felt during and after the videos. A motion sickness questionnaire was taken from [43]. Like many common measures in this field (e.g. the Simulator Sickness Questionnaire [44] or the Nausea Profile [45]), this questionnaire takes a multi-dimensional approach to assessing motion sickness (i.e. recognizes that there can be many independent manifestations of motion sickness). This questionnaire included 16 items on a 9-point Likert scale (e.g. "I felt sick to my stomach", "I felt like I was spinning", etc.). In addition to standard motion sickness questionnaire above, a visual and physical symptom questionnaire was also taken from [7], which included 14 items on a 5-point Likert scale (e.g. "Pulling sensation in eyes", "Blurred vision", "Back/neck/shoulder ache", etc.). The participants also filled out a questionnaire in which they reported past experience with motion sickness and experience with virtual reality/3D stereoscopic environments (see Supplementary materials). This questionnaire included 6 items on a 9-point Likert scale (e.g. "How much motion sickness do you feel riding in a car?", "How often are you exposed to virtual reality environments?", etc.).

3. Results

3.1. Data processing

Redundant or related questions on the questionnaires were averaged into six categories: (1) feelings of sickness (which included questions from the motion sickness questionnaire concerning feelings of nausea, and stomach discomfort), (2) feelings of physical distress (which included questions from the visual and physical symptom questionnaire concerning back, neck, and muscle aches), (3) feelings of psychological distress (which included questions from the visual and physical symptom questionnaire concerning feelings of unease and dizziness), (4) feelings of visual discomfort (which included questions from the visual and physical symptom questionnaire concerning feelings such as eye strain and blurred vision), (5) motion sickness history (which included questions about how prone the participant was to motion sickness in cars, boats, and roller coasters), and (6) virtual reality history (which includes questions about how often the participant had been exposed to or used VR and/or 3D stereoscopic stimuli).

3.2. Differences between "quitters" and "survivors"

The main dependent measure of interest was whether the participants completed all 20 min (4 videos) of the 3D stereoscopic exposure, or whether they experienced discomfort severe enough that they had to discontinue the experiment. The analyses below thus separate the participants into "quitters" and "survivors".

3.2.1. Basic demographic differences between quitters and survivors

Overall, 63% of participants (75% of females and 41.4% of males) quit early. While age did not significantly differ between those who quit (M_{age} = 19.04 SD_{age} = 7.47), and those who did not (M_{age} 19.04, SD_{age} = 1.48), $t(71) = 1.55$, $p = 0.124$, females were more likely to quit than males, $t(71) = 2.78$, $p = 0.007$; see Fig. 4.

3.2.2. Differences in visual task performance between quitters and survivors

Consistent with our hypothesis, significant differences were seen between quitters and survivors with respect to performance in 3D visual tasks. Quitters performed significantly better than survivors in both disparity-based 3D motion tasks (quitters: M = 74% correct, SD = 20%; survivors: M = 63%, SD = 17%; $t(71) = 2.40$, $p = 0.019$), as well as in velocity-based 3D motion tasks (quitters: M = 77%, SD = 19%; survivors: M = 67%, SD = 17.8%; $t(71) = 2.23$, $p = 0.029$). Performance in the all-cues dynamic stereovision task and the static stereovision task did not differ significantly between quitters and survivors (see Fig. 5 for a summary of these differences in 3D stereovision task performance). There were no other significant differences between the groups on any of the visual performance measures (Supplementary materials) nor were there significant differences in previous media experience (including video game experience). In addition to the differences between quitters and survivors, we also observed that female participants performed significantly better on the velocity-based stereovision task (M = 79%, SD = 18%) than males (M = 70%, SD = 19%), $t(71) = 2.07$, $p = 0.042$.

3.2.3. Differences in psychological/physiological distress in quitters and survivors

Questionnaires taken after the Oculus Rift phase of the experiment indicated that quitters experienced greater levels of sickness following exposure to VR (M = 5.27, SD = 1.80) than survivors (M = 3.53, SD = 1.91), $t(68) = 3.85$, $p < 0.001$, as well as greater levels of psychological distress (M = 4.66, SD = 1.58) than survivors (M = 3.20, SD = 1.88), $t(70) = 2.48$, $p = 0.016$. Quitters also reported being more prone to motion sickness (M = 4.12, SD = 1.86) than survivors (M = 3.20, SD = 1.93), $t(71) = 2.01$, $p = 0.048$; see Supplementary materials.

3.3. Correlations between discomfort levels and stereovision performance

For a more nuanced view of the relationship between stereovision capabilities and experienced discomfort we regressed performance in the all-cues stereovision task (only those participants whose performance in this task was above 75% correct) against the various self-report measures of discomfort. We utilized this criterion because it is difficult to ascertain whether participants falling below this value were unable to perceive depth or instead had issues with attention, etc. (particularly because some of the same participants performed above chance on the static and/or cue-isolated conditions). Furthermore, given the number of trials utilized here, the expected variance around true chance performance is quite high (i.e. a participant responding truly at random could be expected to have a somewhat high range of possible scores that would not in fact be meaningful – as in a participant scoring 40% would not truly be 10% worse than one scoring 50%) making it difficult to model a linear relationship (see discussion for future directions to address this issue). Consistent with our predictions, better stereovision ability was associated with a greater amount of self-reported motion sickness ($r(25) = 0.31$, $p = 0.030$), physical discomfort in VR ($r(25) = 0.34$, $p = 0.017$), eye/vision discomfort in VR ($r(25) = 0.29$, $p = 0.046$), and psychological distress in VR ($r(24) = 0.50$, $p < 0.001$). See Fig. 6 for correlation plots between these measures.

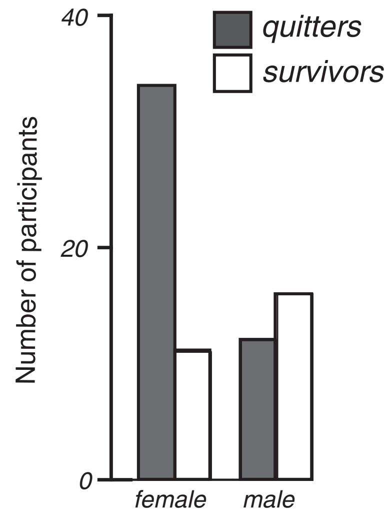

Fig. 4. Bar plot showing the number of males and females who did (quitters) and did not quit (survivors) prematurely during the 3D stereoscopic videos. Females were significantly more likely to quit early than males.

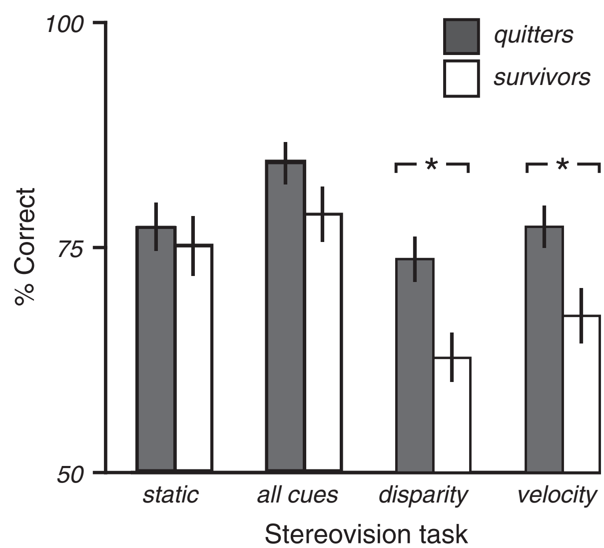

Fig. 5. Bar plot showing the differences in performance across the four 3D perceptual tasks between quitters and survivors. Quitters performed better on disparity-based 3D motion as well as velocity-based 3D motion tasks compared to survivors. $* = p < 0.05$. Error bars represent standard error of the mean.

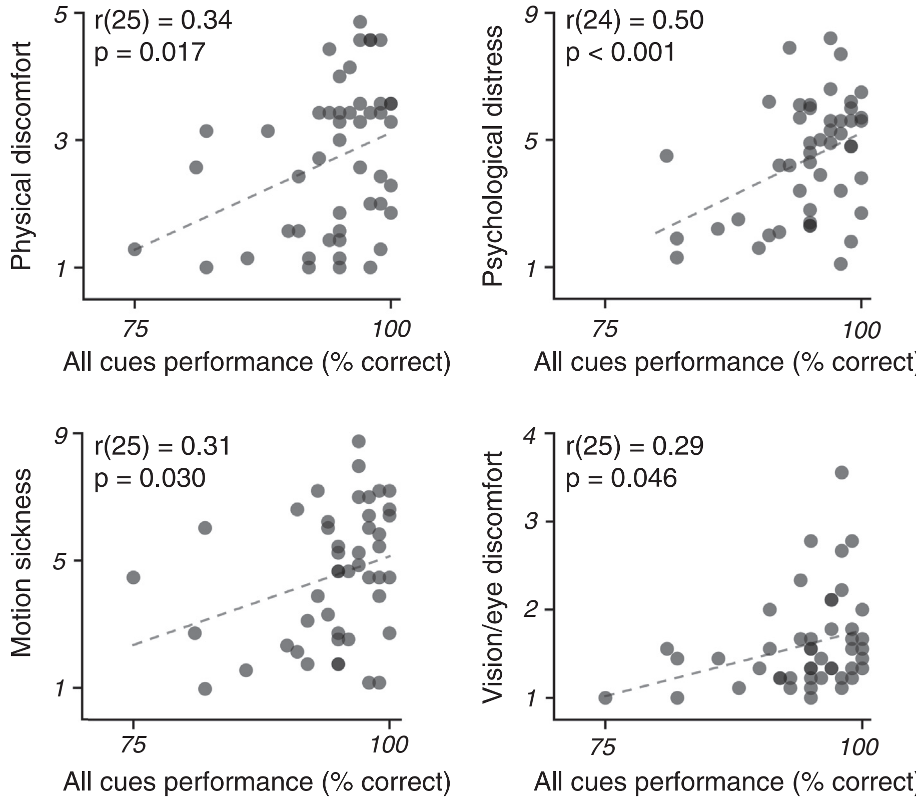

Fig. 6. Scatter plot showing correlations between performance on all-cues dynamic 3D tasks and various measures of self-reported discomfort in VR. To test our hypothesis that sensitivity to 3D motion is associated with increased likelihood of discomfort in VR, we only consider participants who performed greater than or at 75% correct on the all cues dynamic 3D task (near or above chance). We find significant correlations between performance on our dynamic 3D task and physical discomfort self reports (top left), psychological distress (top right), motion sickness (bottom left), and vision/eye discomfort (bottom right). See Section 2 for a detailed description of these measures. All self-report measures were given on a Likert scale with smaller numbers roughly corresponding to "less" and larger numbers corresponding to "more".

4. Discussion

The "cue conflict" or "sensory-rearrangement" theory of motion sickness suggests that motion sickness is experienced when sensory systems report widely different values (particularly signals related to self-motion). This theory in turn leads to the prediction that individuals who possess better base sensory abilities will be more prone to motion sickness because their systems will be better able to recognize situations in which the sensory estimates are in a state of irresolvable conflict. In line with those predictions, in the present study we found that those participants who showed high levels of performance on difficult 3D motion tasks were less likely to be able to tolerate 20 min of 3D stereoscopic video experience than those participants who performed poorly. These results lead to an interesting paradox; those who have better 3D vision, and thus would be able to take the most advantage of 3D technology, are also those who are least able to tolerate it. These effects appear to be specifically related to stereo-visual capabilities, as we found no significant differences between "survivors" and "quitters" in any other visual task (e.g. in static 3D vision, basic acuity or speed of visual processing). This is consistent with a recent study by Read and Bohr [46], which also found no link between static stereo acuity and the likelihood of experiencing discomfort during 3D viewing. Furthermore, the finding that 'quitters' did not outperform 'survivors' in any other visual task other than the two dynamic 3D tasks suggests their inability to tolerate extended VR exposure is not likely due to greater motivation or effort, better vision more broadly, or a result of fatigue.

The differences we observed between static 3D position and 3D motion assessments of binocular sensitivity might have further clinical implications. Traditionally binocular function has been assessed using static 3D stimuli (i.e. using the Randot stereo test, or TNO test for stereoscopic vision), but our results suggest that motion sickness, somewhat unsurprisingly, seems primarily related to one's 3D motion sensitivity. Development of clinical tests of 3D motion perception might be instrumental in the understanding of other dysfunctions of the visual and vestibular systems.

It is also worth noting that our experiment examined stereoacuity performance of naïve participants using a disparity value (0.25 degrees), that is larger than the threshold disparity values found in many previous psychophysical studies (e.g. [47,48]), even including studies that utilized a similarly long presentation time (e.g. [49]). Indeed, given the thresholds obtained in previous work (e.g. <1 min of arc), one might have expected ceiling level performance in all of our participants (excluding the ~4–15% that would be expected to be stereoblind). This was not what was found however. While some observers in our sample did perform at ceiling level, the performance of the majority of observers fell somewhere in between ceiling and floor levels. We believe this points to an important issue to be resolved in the literature. Many threshold values reported in psychophysical studies are based upon data from a small number of highly experienced observers (often only 2–3 observers, typically including at least one author). Perhaps it is not surprising then, that naive observers show substantially poorer performance than would be expected based on prior reports. Consistent with this, our initial piloting, which utilized disparity values based upon thresholds obtained from expert observers, resulted in floor levels of performance in the preponderance of naïve observers. It is thus essential that care be taken when attempting to assess performance across the entire population, as parameter values taken from expert observers may not be appropriate. Our final stimulus configuration was carefully chosen, based upon pilot data collected from truly naïve observers, to best capture the naturally occurring variability in stereoacuity found in the general population. This variability then allowed us to determine that performance on some stereoacuity measures, but not others, is associated with visual discomfort. We note though that even with this pilot data, some proportion of participants still showed chance level performance in some conditions. There may thus be some virtue in also obtaining threshold measures, rather than only accuracy, in the future (although this comes with the confound that participants will have different testing experiences).

The sex difference that we observed between 'survivors' and 'quitters' – with females being more likely than males to feel discomfort and prematurely stop the 3D stereoscopic video viewing task – are also consistent with previous research that found that females were more likely than males to feel adverse effects from 3D viewing [46]. In our case, we found that this was not an unspecified sex effect, but could be specifically attributed to the fact that females performed better than males in the 3D motion tasks. This particular sex effect has not been previously noted in the literature and thus is worthy of future exploration.

Future questions include what factors determine whether the discomfort associated with 3D environments persists or diminishes with experience, and if the rate at which the discomfort diminishes is related to a general propensity to learn/habituate quickly [15]. For most of the participants in the study, this was their first experience with a true VR system (as opposed to stereo 3D movies/television). It is thus unclear whether their symptoms would be reduced after repeated exposure to the VR environments. Such a reduction could occur if the brain is able to parcel out context-specific cue weightings (i.e. "when wearing 3D head mounted displays, discount conflict between accommodative and vergence cues"). Anecdotal reports again suggest that this is possible – for instance, Oculus Rift developers have also been reported to experience some initial amount of discomfort that is reduced or eliminated given sufficient experience with the environment, although this might potentially be associated with a decreased reliance on the sensory cues that make VR experiences so compelling in the first place. It would also be beneficial to better understand how these particular cues to motion in depth relate to and interact with other cues that have previously been seen to be predictive of motion sickness – for instance, sensitivity of the vestibular system to self-acceleration – as there are many cues that can conflict and thus potentially be associated with increased motion sickness [15].

The present study also suggests other potential methods for reducing 3D-associated motion sickness. One seemingly obvious method would be to increase the faithfulness with which the VR world matches the real world [26] – reducing both the number of cues that are in conflict, as well as the extent to which they are in conflict. Alternatively, in cases where cue conflict is inherent to the technological system (e.g. there will necessarily always be conflict between accommodative cues and disparity cues given that the image is projected onto a single surface), it may be possible to create additional uncertainty in those cues that are in conflict (e.g. Maiello et al. [50], who suggested the utilization of blur as a cue to depth in order to reduce the inability to binocularly fuse stimuli).

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.entcom.2016.01.001.

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