University of Tartu
Institute of Psychology

Madis Vasser
CHANGE BLINDNESS IN 3D SPACE
Master's thesis

Supervisor: Jaan Aru, PhD
Running head: CHANGE BLINDNESS IN 3D

Tartu 2015

Change Blindness in 3D space

Abstract

Change blindness, the phenomenon of not noticing big changes in a visual scene, was investigated in the present study. Subjects explored stereoscopic three dimensional (3D) environments through a virtual reality (VR) setup. A novel method that tracked the subjects head movements was used for inducing changes in the scene whenever the changing object was out of the field of view. The main research aim was to study the effect of change location (foreground or background) on change blindness. Two experiments were conducted, one in the lab (n = 50) and the other online (n = 5). Up to 25% of the changes were undetected and the mean overall search time was 27 seconds in the lab study. Results indicated significantly lower change detection success and more change cycles if the changes occurred in the background, with no differences in overall search times. It was shown that the effect of change cycles was mainly driven by subjects who used the strategy of moving their head rapidly to spot the changes. The results confirm previous studies and also show the feasibility of online VR experiments. Importance of the work and future research directions are discussed.

Keywords: Change Blindness, attention, spatial attention, virtual reality
Running head: CHANGE BLINDNESS IN 3D

Muutusepimedus kolmemõõtmelises ruumis

Kokkuvõte

Käesolevas töös uuriti muutusepimeduse fenomeni, kus vaataja ei märka suuri muutusi visuaalses stseenis. Katseisikud vaatasid stereoskoopilisi kolmemõõtmelisi (3D) keskkondi läbi virtuaalreaalsuse (VR) seadme. Muutuste esitamiseks kasutati uudset meetodit, mis jälgis katseisiku pealiigutusi ning tekitas muudatuse hetkel, kui muutuv objekt asus väljaspool vaatevälja. Töö peamiseks eesmärgiks oli uurida muutuste asukoha (esiplaan või tagaplaan) mõju muutusepimeduse avaldumisele. Läbi viidi kaks eksperimenti, üks laboritingimustes (n = 50) ja teine internetipõhiselt (n = 5). Kuni 25% muutustest jäid tuvastamata ning keskmine otsinguaeg oli laboritingimustes 27 sekundit. Tulemused näitasid oluliselt madalamat muudatuste tuvastamise edukust ning kõrgemat muudatuste tsüklite koguarvu tingimuses, kus muutus toimus tagaplaanil. Üldises otsinguajas tingimuste vahelisi erinevusi ei olnud. Leiti, et muudatuste tsüklite koguarvu kergitasid eelkõige katseisikud, kes kasutasid muutuste märkamiseks kiirete pealiigutuste strateegiat. Tulemused kinnitavad eelnevaid uuringuid ning näitavad samas internetipõhiste VR eksperimentide võimalikkust. Arutatakse ka töö olulisuse ning edaspidiste uurimissuundade üle.

Märksõnad: Muutusepimedus, tähelepanu, ruumiline tähelepanu, virtuaalreaalsus
Läbiv pealkiri: Muutusepimedus 3D ruumis

Introduction

Change blindness is the well-known phenomenon of not being able to notice relatively big changes in a scene with a visual disruption, unless the change is presented numerous times or a helpful hint is given (Simons & Rensink, 2005). The study of change blindness has led to many valuable insights about the processes and limitations of human attention. From previous works with unfamiliar 2D scenes we know that changes in the foreground are easier to detect (Mazza et al, 2005; Turatto et al, 2002) and the appearance of an object tends to be more prominent than disappearance (Cole & Liversedge, 2006). Although the role of situational context has received little study in attention research (Smilek et al, 2006), it has been shown that marginal interest changes in the foreground are harder to detect than central changes (O'Regan et al, 2000). Studies have also shown robust change blindness even in familiar and well known mental scenes (Rosielle & Scaggs, 2008).

A typical fixed change blindness protocol consists of a stimulus scene (shown usually around 500ms), an altered version of the same scene (the change, shown usually the same length of time) and a short (usually around 100-200ms) visual distraction of some kind between the two. Alternatively, a more exploratory approach has sometimes been used, where the subjects own behaviour determines the moment of the change (O'Regan et al, 2000; Suma et al, 2011). Eye movements, eyeblinks, transient full-screen masks (so-called “flicker paradigm”) or partial patterns (“mud splashes”) have all been used previously for introducing the change (Simons & Rensink, 2005). Many different types of changes have been explored with these methods. These include the abrupt appearance of a new object, the sudden disappearance of an existing object, sudden or gradual changes in color and shape, position and movement (Karacan, 2010). Various parameters have been found to affect the total search time, such as the total number of objects in the scene, their overall placement (random or in a pattern), colour, shape and how probable the change is (Gusev & Mikhaylova, 2013).

It has been shown that sufficient attention alone does not guarantee change detection. The specific aspect of an object that the observer attends to also plays an important role (Simons & Rensink, 2005). For example, the subject might attend to the colour of the object, while it is actually the shape that changes (and is therefore missed). Focusing on features or objects within the location of the change that are not actually changing are called “blank stares” (Caplovitz, 2008). In 3D applications it has been shown that change blindness can sometimes occur even while the subject is tracking a moving and changing cube with one's gaze (Triesch et al, 2003). It has been hypothesized that under some circumstances even a central aspect of a stimulus may change without being noticed. If the change occurs a sufficiently long time into the period of exploration, so that the observer has already encoded this picture element into his or her internal representation, it might make it more marginal and unlikely to be returned to (O'Regan et al, 2000). Wang and Brockmole (2003) have suggested that observers only keep track of objects in sight. Attention also seems to have a so-called “dead zone” around the main focal point. Changes in the attentional “dead zone” are relatively harder to spot (Utochkin, 2011). Different processing strategies have been suggested to explain change blindness, such as: (1) subjects rely on their first impressions of a scene, (2) the initial mental representation will be overwritten, or (3) conflicting features will be merged. (Simons, 2000).

A valuable way to study attention is by allowing participants to explore their environment (Smilek et al, 2006). With traditional display systems the sensory input is merely audio-visual and there are no means to interact with the reality presented on a passive screen (Pillai, Schmidt & Richir, 2013). Some investigators have sought to more ecologically valid experimental conditions (Smilek et al, 2006) or actually performed the experiments as field studies (Simons & Levin, 1998). As real natural environments are difficult to control experimentally and reproduce, and 2D images are lacking many real-life features, 3D virtual reality (VR) environments are sometimes preferred for cognitive psychology research (Karacan, 2010). VR environments render quasi-realistic natural scenes, giving the experimenter absolute control over all details of the scene, and allow perfect reproduction of the experimental setting between subjects (Triesch et al, 2003). This approach also gives more freedom of movement to the study subject, who is not confined to look only in a single direction since the virtual environment is projected spherically all around the person. This is important, as maximizing strict control over the subject’s behaviour might not reveal important aspects of complex systems such as human cognition and attention in the real world (Smilek et al, 2006). VR systems of today are capable of high level of immersion and the feeling of presence. Here, presence refers to the perception of one's surrounding as mediated by both automatic and controlled mental processes, an experience of a different reality (Pillai, Schmidt & Richir, 2013). High level of presence in a virtual study environment might yield stronger cognitive ethology (Smilek et al, 2006), resembling the high perceptual and computational demands present in real life behaviors (Shinoda, Hayhoe, & Shrivastava, 2001). Previous few studies of attention in VR have suffered from technological limitations, using a narrow field of view (FOV) of roughly 50 degrees (Shinoda, Hayhoe, & Shrivastava, 2001; Triesch et al, 2003). VR systems of today can overcome this limitation. Many virtual environment studies have found that a wider FOV results in more accurate distance perception and superior performance on different tasks (Arthur, 2000; Kline & Witmer, 1996; Lessels & Ruddle, 2004).

The present thesis seeks to investigate change blindness in a more natural setting by utilizing a wide FOV VR approach and a novel way of introducing changes in the scene. The changes are set to occur whenever the subject has their head turned away from the changing object. This method does not use a visual transients like the flicker or mud splash paradigms, ensuring a more comfortable and natural visual experience for the study subject. The change takes place only when completely out of the field of view, thus also eliminating the possible effect of covert attention on change blindness performance that can be present when the gaze detection paradigm is used. Based on the results of attentional blanks stares and attentional dead zones (Caplovitz et al, 2008; Turatto et al, 2002; Utochkin, 2011), we investigate the effect of distance from the viewer as a possible variable for change blindness performance. 3D environments allow us to examine actual spatial distance from the observer as a variable of change blindness, giving new insights into foreground/background effects. According to the literature on change blindness in 2D scenes (Mazza et al, 2005; Turatto et al, 2002), we predict that changes occurring in the foreground are significantly easier to detect than changes in the background.

EXPERIMENT 1

In the first experiment we studied the effects of distance to the observer on change blindness, using an offline laboratory protocol.

Materials and methods

Participants

50 study subjects (mean age 24 years, SD = 3.8, equal number of males and females) participated in the experiment. All reported having normal or corrected to normal vision. 11 subjects in the final analysis had to remove their glasses in order to participate in the experiment. Before the experiment all subjects gave written informed consent. Some participants received extra course credit for participation. The experiments were undertaken in compliance with national legislation and the Declaration of Helsinki.

Stimuli and procedure

Twelve 3D scenes of a typical livingroom setting were used in the experiment (figure 1). Three additional scenes in the beginning of the experiment were used for practice trials. The practice trials familiarized participants with the VR headset and methodology. The 12 scenes used in the experimental block were balanced so that 6 rooms had changes occurring in the foreground condition (1-3 meters from the observer in virtual space) and the other 6 rooms in the background condition (4-6 meters from the observer). These arbitrary distances were chosen from an earlier small pilot study. There was also an equal distribution of changes in the middle of the scene and in the periphery. Every room started with the location of the change in the field of view. All changes between the conditions were approximately equated with respect to their visual size and contrast (see appendix A for all the actual changes).

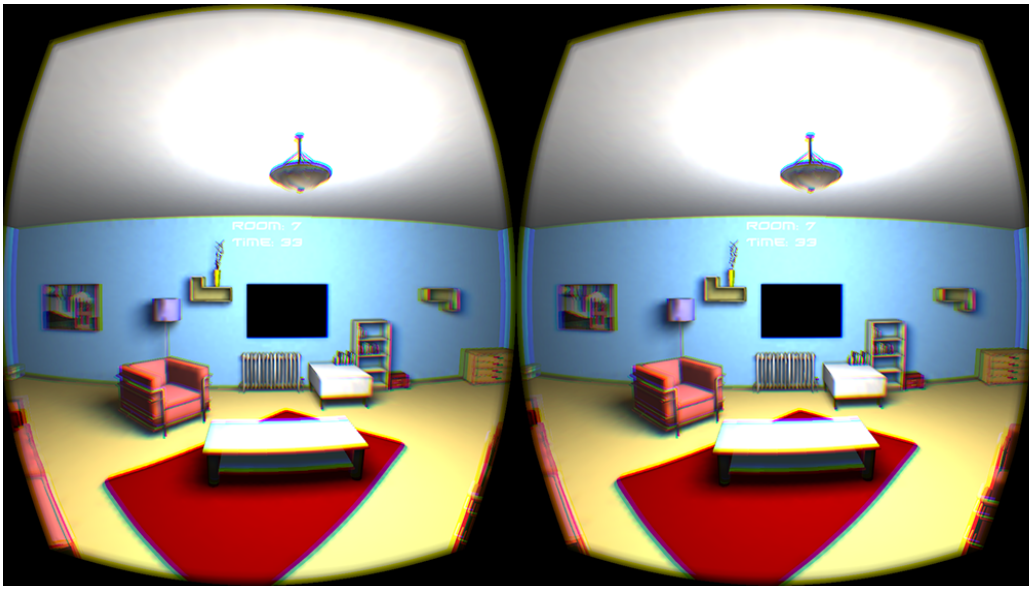


Figure 1. A typical livingroom setting used in the experiment, as seen through the stereoscopic VR headset. Images for the left and right eye, accordingly. Image warping is introduced to produce the correct output through the lenses of the VR headset.

The general category of the changing objects were held constant between different distances (e.g., furniture). All the changes were central (in a prominent place), context relevant (part of the interior), probable (easily movable if compared to real-world analogues), same colour (between foreground and background conditions). Every room contained the same amount of objects in a different layout. Also the room properties were constant. Therefore, proximity of the changing object to the observer was the only parameter manipulated. The size of the changing objects was chosen to produce a comparable retinal image between foreground and background conditions. However, since our setup also allowed the study subjects to lean approximately 10 centimeters in every direction in virtual space, the size of the retinal image varied slightly. The changing objects cycled between visible and not visible states whenever the object was out of the field of view of the headset. We did not change the room architecture during trials, as these changes might seem too improbable for the subject and thus would be extremely difficult to spot, as has been shown previously (Suma et al, 2011). Many small pilot-studies were conducted to find the optimal placement of the changing objects and to refine the study instructions given to the subjects.

The experiment was introduced to the subjects as a study of perception and attention. Study subjects were instructed to actively search for one changing object in every scene. They were explicitly told that the change would occur while they were looking elsewhere. Subjects were encouraged to press the response key as soon as they were certain they had spotted the change, after which the timer would stop and they had the chance to mark the object and confirm the selection. After that the next scene would begin. To facilitate active monitoring of the surroundings and to prevent stalling, a time limit of 60 seconds was set for each scene. Participants sat on a static chair, wearing a VR headset and headphones (for sound isolation) and holding a keyboard on their lap (for a typical setup see figure 2).

Figure 2. A study subject wearing the virtual reality goggles and headphones, with the keyboard on the lap for giving the response.

At the beginning of the experiment participants completed three practice trials with verbal and visual instructions, followed by 12 experimental trials. The 12 experimental trials included six trials with a foreground change and six trials with a background change. Experimental trials were presented in random order to minimize further practice effect on the results. After the change blindness task the subject answered a short questionnaire about their age, gender, prior experience with video games, level of nausea during the experiment and different strategies used in the task (see appendix B for the full questionnaire). The experiment lasted approximately 20 minutes.

Apparatus

The 3D environments were constructed using Unity 4.6 game engine with the help of a custom virtual reality toolbox specifically designed for this experiment (Kängsepp, 2015; Vasser et al, 2015). The following data was automatically collected for all participants in every trial: the answer (right or wrong), number of times the changing object changed states (from visible to invisible and vice versa), search time, pause time (when giving the answer) and rotational head movement data. For 16 participants the time intervals of the change cycles were also collected. The program was presented to the study subjects using the Oculus Rift Development Kit 2 virtual reality headset (Oculus VR, LLC) with a low persistence OLED display, 100 degree field of view, 75hz refresh rate and 960 x 1080 pixel resolution per eye. The system was running on a pc with Intel Core i7-4970K, MSI GeForce GTX 970 OC and RAM 8gb DDR3. The study was conducted at the University of Tartu Virtual Neuroscience Lab.

Data cleaning and analysis

Of the total subject pool of 50 participants, 46 subjects were included in the final experimental data analysis. Three subjects were excluded due to a high number (>2) of answering errors caused by misinterpretations of the instructions. One subject stopped the experiment half-way due to personal discomfort. From the remaining 552 trials, one trial was completely omitted due to corrupted data. Two of the remaining 551 trials lacked search time data due to technical reasons. Since one subject missed all of the changes in the background conditions, for some statistical tests these trials were left out of the analysis. The main within-subject independent variable in the experiment was change location, which included two conditions: foreground or background. Dependent variables were as follows: missed changes (out of time or a wrong answer), mean search time in seconds and mean number of change cycles (for trials with successful detection). From 16 subjects the time intervals between the changes were recorded. From a total of 1013 intervals 9 were removed for being over 30 seconds long - this was over half of the control time in every room and a clear sign of an outlier.

The analysis and data visualization was conducted in LibreOffice Calc and R (R Core Team, 2013). The distributions of search times and proportion of missed changes were probed for deviations from the normal distributions with the Shapiro–Wilk test. If there were deviations, the Wilcoxon signed-rank test was used instead of the t-test.

Results

The effects of change blindness were large in the present study. Subjects completely failed to identify or misidentified the changed objects in 137 of the 551 trials (24.9%). For all the successful trials, the mean search time was 26.9 seconds (SD = 14.4) and on average, the changing object changed states 4.7 times (SD = 3.9) before being spotted. Only 6.5% of study subjects (3 out of 46) managed to successfully spot all the 12 changes presented in the experiment.

First the number of errors (wrong answer or out of time trials) was examined between conditions from the sample of 551 trials. On the proportion of trials where the person failed to detect a change, with a minimum of 0 (no trials with successful detection) and the maximum of 1 (all trials with successful detection), the foreground condition yielded a mean value of 0.79 (SD = 0.17) and the background condition 0.71 (SD = 0.23). A two-tailed paired t-test assuming unequal variances revealed a statistically significant difference between the proportions of successful trials (t = 2.43, df = 45, p = 0.019). Changing objects farther away from the subject were detected less successfully as compared to the changing objects closer to the subject. All following analysis were conducted without the data from the error trials.

When comparing the amount of changes needed for successful detection on 414 trials, a significant difference was found using Wilcoxon signed rank test with continuity correction (V = 269, p = 0.037. d = 0.37). The mean amount of changes for the foreground and background conditions were 4.27 (SD = 1.86) and 5.02 (SD = 2.12), respectively. There had to be more changes for background objects so that subjects would notice them.

Search time analysis was performed on 412 trials. The mean search time for the foreground condition was 27.56 seconds (SD = 8.64) and for the background condition 27.95 seconds (SD = 8.47). The difference between the means was not statistically significant (t = -0.38, df = 44, p = 0.71). Results between conditions are also shown graphically on figure 3.

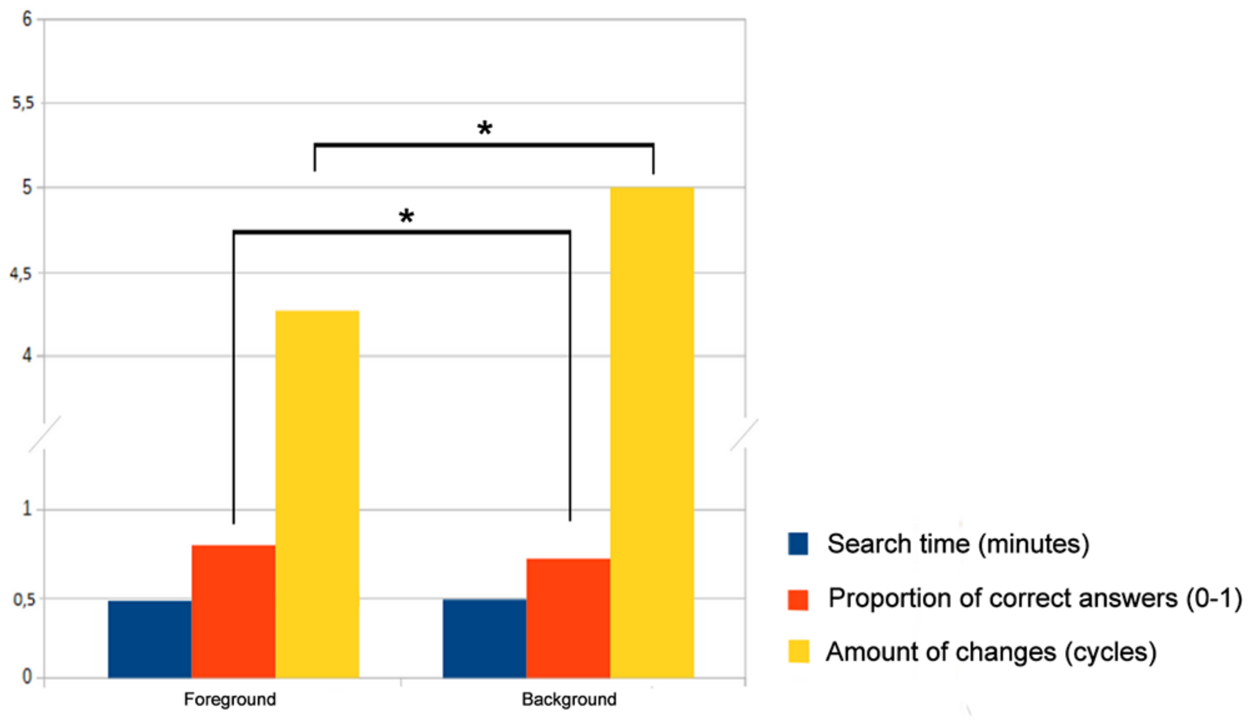


Figure 3. Summary data for the foreground and background conditions. Asterisks denote statistically significant differences ($p < 0.05$).

Subjects exhibited and reported different strategies for completing the experimental task. 95.7% of subjects tried to remember the objects in the room to spot the change. Slightly over half of the participants (56.5%) tried to check the objects one-by-one at least in some of the rooms. The same proportion of subjects developed a method of rapid head movement to detect the changes. 47.7% percent took cues from the placement of furniture to help them detect the changes. The balanced experimental plan itself was also sometimes used by 26.1% of the participants to help them guess the change location (as there were an equal number of changes in different parts of the room). Only 10.9% used special mnemonic techniques to remember the objects (e.g. remembering objects in logical sets). The slightly different appearance of shadows on the changing objects was reported by 8.7% of the study subjects.

To study the effects of various strategies on the present change blindness findings, we ran separate ANOVAs with the factors experimental condition (foreground vs background) and strategy (whether the person used or did not use one of the above mentioned strategies). When examining the proportion of successful trials, the only strategy that had a statistically significant interaction with the experimental condition was noticing the slightly different appearance of shadows on the changing objects ($F = 7.05$, $df = 44$, $p = 0.011$, ges = 0.039). The use of this strategy made foreground changes easier to spot. However, its effect on the main results was negligible as only 4 subjects made use of this strategy. Furthermore, the ANOVA still revealed a main effect of experimental condition (proportion of successfully detected foreground vs background objects, $F = 13.81$, $df = 44$, $p < 0.00$, ges = 0.073).

Comparing the effect of different strategies on the amount of changes needed for a successful detection, turning one's head rapidly was shown to significantly increase the change cycles count ($F = 15.20$, $df = 43$, $p = 0.00033$, ges = 0.20). This difference was more pronounced in the background condition as evidenced by the interaction between this strategy and the experimental condition ($F = 5.32$, $df = 43$, $p = 0.026$, ges = 0.037). This result leads to the obvious suspicion that the main finding (see above) showing that the the amount of changes before successful detection is higher for background objects could be mainly driven by subjects who used such rapid head movement strategy. Indeed, when the amount of changes needed was analysed only in the subgroup ($n = 20$) that did not use rapid head movements, no effect of distance was observed ($p > 0.3$). However, as expected, the effect of distance was strong within the group of subjects ($n = 26$) who used the strategy of rapid head movements. In this group, the detection of background objects required more changes ($V = 56$, $p = 0.01$, $d = 0.61$). Rapid head movements was also the only strategy that led to significantly shorter detection times in the foreground condition ($t = -2.29$, $df = 34$, $p = 0.028$), with an average of 5.82 seconds less required to spot the change in the foreground compared to the group without this strategy. There was an interaction between the strategy and the experimental condition for search time in successful trials ($F = 5.59$, $df = 43$, $p = 0.022$, ges = 0.031). The subjects who used rapid head movements spotted the foreground objects quicker ($t = -2.29$, $df = 34$, $p = 0.028$).

Differences between males and females were analyzed. The groups did not differ in change amounts ($t = -1.52$, $df = 38$, $p = 0.136$) but a significant difference was found in search time ($t = -2.31$, $df = 43$, $p = 0.03$. $d = 0.68$). The average for females was 30.32 seconds ($SD = 6.56$), for males it was 25.45 seconds ($SD = 7.67$). Males were quicker to spot the changing object.

After the experiment, subjects also assessed their prior experiences with computer games on a subjective 5-point scale (mean 3.24, $SD = 1.37$). The subjects were split into two groups to analyze the effects of computer game experience on change blindness, with the split point of the scale being at 3. The experienced group ($n = 23$, self-reported experience over 3 points) had an overall mean change count of 5.07 ($SD = 1.85$) and mean search time of 25.15 seconds ($SD = 7.72$). For the inexperienced group ($n = 23$, self-reported experience equal or less to 3 points) the averages were 4.17 ($SD = 1.41$) and 30.62 seconds ($SD = 6.25$), respectively. The difference in the change count was not statistically significant ($p = 0.07$), but there was a significant difference in the average values between the search times (t = -2.64, df = 42, p = 0.01. d = 0.78). As the experienced group consisted mostly (82.6%) of male participants the difference between the experienced and inexperienced groups most likely also explains the differences between males and females reported above.

The experimental apparatus prohibited some subjects to wear their prescription glasses during the experiment. To see if this affected the study results, the average proportion of right answers over the 12 rooms was calculated for the group who had to remove the glasses (n = 11). The mean proportion was 0.83 (SD = 0.16). The average for the control group was 0.72 (SD = 0.17). Removing the glasses did not negatively affect the experimental performance.

Overall the subjects reported a low level of nausea or dizziness after the experiment (M = 1.2, SD = 0.6, on a scale from 1-5).

EXPERIMENT 2

In the second experiment we collected preliminary online data by distributing the experimental program as a self-contained program on various websites related to virtual reality. The aim was to validate the feasibility of an online VR experiment.

Materials and methods

Participants

The online program was introduced as a change blindness experiment that anyone with the recommended hardware can participate. The program was distributed on three websites related to virtual reality - www.wearvr.com, forums.oculus.com and vnslab.mozello.com. The number of downloads exceeded 65 instances and data from 5 study subjects (mean age 31.4 years, SD = 7.8, all male) were collected. Participants received feedback on their performance after the experiment.

Stimuli and procedure

The stimuli was identical to that of experiment 1, with the exclusion of two rooms in the experimental block to make the study shorter in duration. We excluded one room from the foreground condition and one from the background condition. The background questionnaire was also much shorter (see appendix C). Instructions were given as an audio recording and through on-screen text. The experiment lasted approximately 15 minutes. The study protocol complied with the declaration of Helsinki.

Apparatus

The 3D environments were constructed similarly to experiment 1. All participants were asked to use the Oculus Rift Development Kit 2 virtual reality headset (Oculus VR, LLC) to conduct the experiment at their own time and place. The instructions required participants to confirm that their system was capable of running the experience at 75 frames per second. For anonymity reasons no data was collected on the PC specifications used for the experiment.

Data cleaning and analysis

Data cleaning was similar to that of experiment 1. Due to the low number of participants, only descriptive statistics were used to analyze the data.

Results

From the sample of 50 trials, participants completely failed to notice the change on 8 occasions (16%). For all the successful trials, the mean search time was 21.27 seconds (SD = 12.21) and on average, the object changed 7.24 times (SD = 4.84) before being spotted. One study subject managed to successfully spot all the 10 changes presented in the experiment. The average self-reported previous experience with computer games was 4.4 (SD = 1.34). Subjects reported a relatively low level of nausea or dizziness after the experiment (M = 2, SD = 1.2, on a scale from 1-5).

General discussion

A wide FOV VR approach with a novel change induction paradigm was used to investigate change blindness in a more natural setting. A high amount of missed changes (nearly ¼ of all trials) was observed, as previous literature with VR setup has also shown (Steinicke et al, 2010; Suma et al, 2011). However, going further than these previous works, the present results indicate that the change blindness effect persists even when the subject can freely look around in the environment (in contrast to Steinicke et al, where the scene was static) and is explicitly instructed to search for changes (in contrast to Suma et al, where the subjects were naïve). Judging by the proportion of correct identifications and number of changes needed for detection, the data analysis confirmed previous results with 2D display setups, with foreground changes being significantly easier to detect (Mazza et al, 2005; Turatto et al, 2002). For the trials with successful change detection, the response was usually not quick. With mean detections times of around 27 seconds, the object changed states on average 4.7 times before being spotted. Only 3 subjects out of 46 managed to successfully spot all the 12 big changes presented in the experiment.

There was no difference in search time between the foreground and background conditions. Previous research on this matter is sparse, as neither Mazza et al (2005) nor Turatto et al (2002) analyzed temporal data in their foreground/background paradigms. One explanation could be that the dimensions of the virtual rooms used in the present study (approximately 10 meters wide and 6 meters long) were too small to generate noticeable time differences when switching attention between the foreground and background depth planes. The result could also be attributed to our paradigm that relied on subjects head movements to induce the change in the scene. From the results we know that subjects approached the task in different ways.

Since the method used for introducing the changes in the scene was novel, background information about different pre-defined strategies was collected after the experiment. The most popular strategies were checking the objects one-by-one or turning one’s head rapidly to detect the changes, used by slightly over half of the participants. Rapid head movements had significant effects on the results, with much shorter search times in the foreground condition. However, this improvement came with the cost of more changes being needed to detect the target object. It is worth pointing out that this kind of rapid head turning produces similar visual effects to the “flicker paradigm” used widely in many two-dimensional change blindness studies (Simons & Rensink, 2005). For more natural results, future studies may want to prevent this kind of strategy use by prohibiting it in the instructions or introducing a minimum interval between the changes to render the strategy obsolete.

According to verbal comments, sometimes inattentional blindness occurred, when searching for small changes and therefore missing big ones. Many subjects who failed to detect big changes in a given room were genuinely surprised when the change was revealed after the time ran out. One participant commented: “I can’t believe how difficult it was to remember what was in the room.” This “looking without seeing” phenomena has been previously explained by the inconceivable nature of such changes in real situation, that cannot be integrated into the subjects momentary conceptual framework (O'Regan et al, 2000). It could be that the virtual environment was used as an external memory to be probed when details need to be obtained, as has been suggested previously (O'Regan et al, 2000).

Although experiment 2 had a low number of online participants, some observations can be made about the sample in comparison to the lab condition. The age of online participants was on average 7 years greater and only experienced male computer gamers participated. This can be explained by the current state of consumer VR technology that is mostly targeted to software developers. As the market expands and VR finds its way into more households, a more representative sample can be expected. Another reason for the low number of participants can be various software glitches, as the program may crash on unexpected hardware setups. Also, even though the online experiment lasted about 15 minutes, this could have been too long and repetitive for potential subjects. The sheer fact that the 5 subject completed the study successfully from anywhere in the world holds great promise for the future of online VR experiments.

The current study also has numerous shortcomings. Due to complicated methodology, some subjects may have misunderstood the instructions given prior to the experiment. Some subjects were thus quite impulsive with their responses, while others double-checked every answer before pressing the corresponding key. The amount of wrong answers was analyzed to identify and remove the participants who may have misunderstood the instructions. As the changing object could switch its visibility only when completely out of the FOV, in some cases the subject did not turn her head far enough and was thus given “misleading” information about the object (she had actually spotted the changing object, but it did not change at that particular instance as the head was simply not turned far enough). Also, since every room in the study had the same amount of objects and the objects themselves were largely same or from the same category, it was theoretically possible to count certain elements and detect if any of them was missing from the present scene. However, none of the participants reported using this strategy, sometimes stating that the experiment was too short to familiarize oneself with the objects. The location of the change could also be problematic. Since the order of the experimental rooms was completely randomized, there were sometimes situations where two consecutive rooms had the changing object at the same location (e.g in the center of the room twice in a row). This could have made the second change more salient. Another technical issue was the slight difference of shadow types between the changing and static objects due to the game engine limitations. A few subjects reported noticing something about the shadows, but none could describe exactly what it was that caught their attention. Therefore the results were probably not influenced greatly. However, future studies should eliminate these errors for even more valid results.

Conclusion

Using VR with a novel change induction paradigm allows for a natural paradigm to study human attention. It was observed that subjects often miss the relatively large changes or take a long time to find them. Changes in the foreground were detected more easily than changes in the background. Further studies should explore the effects of longer distances or different environments on change blindness performance. Preliminary results with an online paradigm showed the possibility to conduct large-scale VR field studies already in the near future.

Acknowledgments

The author expresses gratitude to Jaan Aru for excellent supervising despite (sometimes) excruciating pain, Markus Kängsepp for programming in the early hours of the morning, Renate Rutiku for emergency statistical advice, all the study subjects for being on the frontlines of science and OÜ Psühhobuss for providing the state of the art VR hardware.

References

Arthur, K. (2000). Effects of field of view on performance with head-mounted displays. PhD thesis, University of North Carolina at Chapel Hill, 2000.

Caplovitz, G. P., Fendrich, R., & Hughes, H. C. (2008). Failures to see: Attentive blank stares revealed by change blindness.*Consciousness And Cognition*, *17,* 877-886. doi:10.1016/j.concog.2007.08.006

Cole, G. G., & Liversedge, S. P. (2006). Change blindness and the primacy of object appearance. *Psychonomic Bulletin & Review 13(4),* 588-593.

Gusev, O. & Mikhaylova (2013). Effects of Stimulus Parameters and Types of Changes in Change Blindness Task. *Procedia - Social and Behavioral Sciences, 86, 10* , 598-602

Karacan, H., Cagiltay, K., & Tekman, H. G. (2010). Change detection in desktop virtual environments: An eye-tracking study.*Computers In Human Behavior*, *26*, 1305-1313. doi:10.1016/j.chb.2010.04.002

Kline, P., & Witmer, B. (1996). Distance perception in virtual environments: effects of field of view and surface texture at near distances. *Human Factors and Ergonomics Society 40th Annual Meeting,* 1112–1116.

Kängsepp, M. (2015). Virtual Reality Environment for Studying Change Blindness. Bachelor's thesis. Institute of Computer Science, University of Tartu.

Lessels, S., & Ruddle, R. A. (2004). Changes in navigational behaviour produced by a wide field of view and a high fidelity visual scene. *Eurographics Symposium on Virtual Environments*, 71–78

Mazza, V., Turatto, M., & Umiltà, C. (2005). Foreground-background segmentation and attention: A change blindness study. *Psychological Research, 69(3),* 201-210. doi:10.1007/s00426-004-0174-9

Pillai, J. S., Schmidt, C., & Richir, S. (2013). Achieving presence through evoked reality. *Frontiers In Psychology*, *4*

R Core Team (2013). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL: http://www.R-project.org/.

Rosielle, L. J., & Scaggs, W. J. (2008). What if they knocked down the library and nobody noticed? The failure to detect large changes to familiar scenes. *Memory, 16(2),* 115-124. doi:10.1080/09658210701787765

Simons, D. J. (2000). Current approaches to change blindness. *Visual Cognition, 7(1-3),* 1-15. doi:10.1080/135062800394658

Simons, D. J. Levin, D. T. (1998). Failure to detect changes to people during a real-world interaction. *Psychonomic Bulletin and Review 5 (4):* 644–649, doi:10.3758/BF03208840

Simons, D. J., & Rensink, R. A. (2005). Change blindness: past, present, and future. *Trends In Cognitive Sciences,* 916-920. doi:10.1016/j.tics.2004.11.006

Shinoda, H., Hayhoe, M. M., & Shrivastava, A. (2001). What controls attention in natural environments. *Vision Research, 41*, 3535-3545.

Smilek, D., Birmingham, E., Cameron, D., Bischof, W., & Kingstone, A. (2006). Cognitive ethology and exploring attention in real-world scenes. *Brain Research, 1080(1),* 101-119. doi:10.1016/j.brainres.2005.12.090

Steinicke, F., Bruder, G., Hinrichs, K. H., & Willemsen, P. (2010). Change blindness phenomena for stereoscopic projection systems. *IEEE Virtual Reality 2010,* 187–194

Suma, E. A., Clark, S., Finkelstein, S., Wartell, Z., Krum, D.,& Bolas, M. (2011). Leveraging Change Blindness for Redirection in Virtual Environments. *IEEE Virtual Reality 2011,* 159-166.

Triesch, J., Ballard, D. H., Hayhoe, M. M., & Sullivan, B. T. (2003). What you see is what you need. *Journal Of Vision, 3(1),* 86-94. doi:10.1167/3.1.9

Turatto, M., Angrilli, A., Mazza, V., Umiltà, C., & Driver, J. (2002). Looking without seeing the background change: Electrophysiological correlates of change detection versus change blindness. *Cognition, 84(1),* B1-B10. doi:10.1016/S0010-0277(02)00016-1

Utochkin, I. S. (2011). Hide-and-seek around the centre of interest: The dead zone of attention revealed by change blindness. *Visual Cognition*, *19*(8), 1063-1088. doi:10.1080/13506285.2011.613421

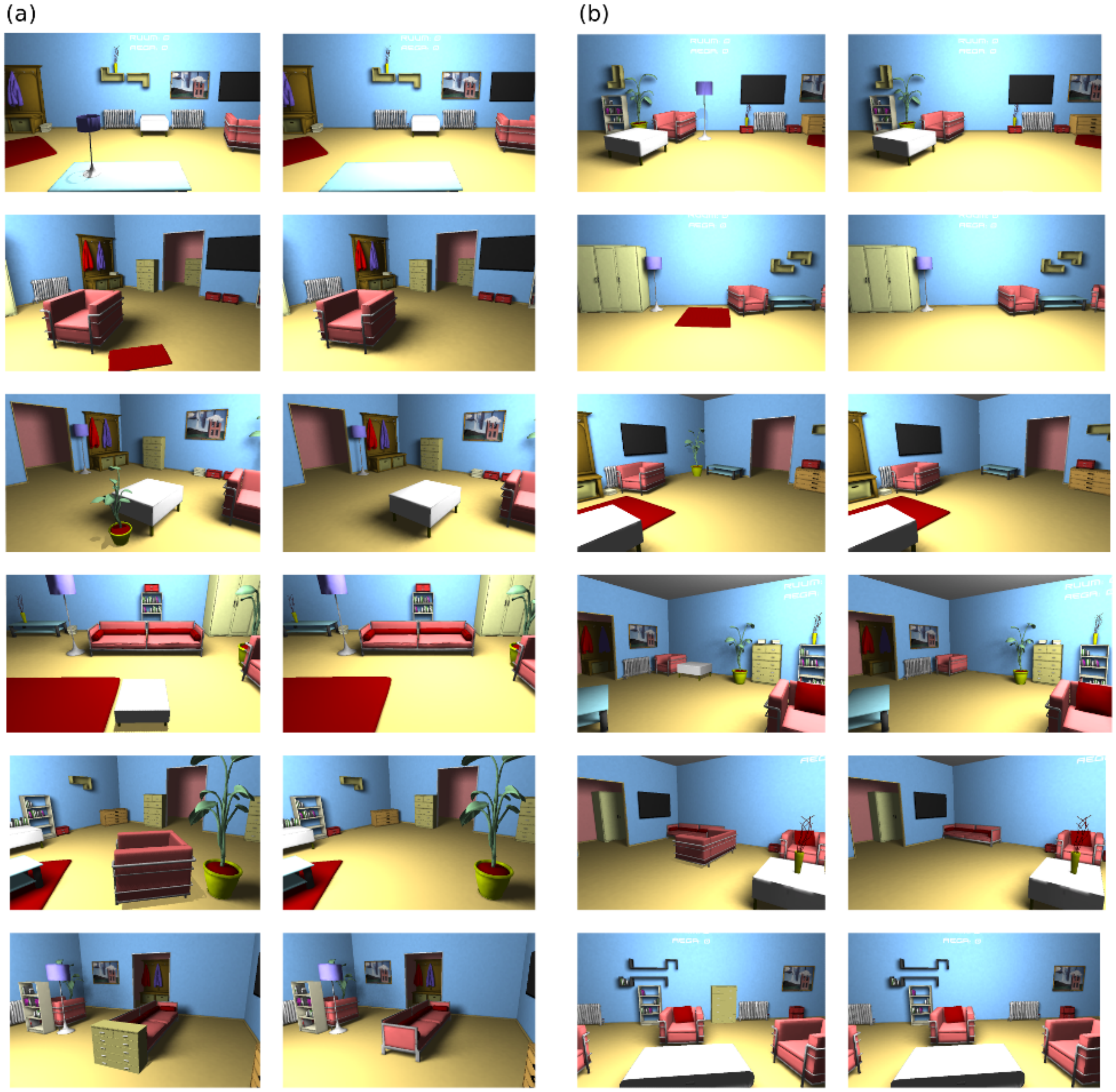
Vasser, M., Kängsepp, M., Kilvits, K., Kivisik, T. & Aru, J. (2015). Virtual Reality toolbox for experimental psychology – Research Demo. *IEEE Virtual Reality 2015,* 361 - 362

O'Regan, J. K., Rensink, R. A., & Clark, J. J. (1999). Change-blindness as a result of "mud-splashes". *Nature, 398*, 34.

O'Regan, J. K., Deubel, H., Clark, J., & Rensink, R. A. (2000). Picture changes during blinks: looking without seeing and seeing without looking. *Visual Cognition*, 7, 191–211.

Wang, R. F., & Brockmole, J. R. (2003). Simultaneous spatial updating in nested environments. *Psychonomic Bulletin & Review,* 10, 981–998.

Appendix A



Appendix A. All the changes presented in experiment 1. Foreground condition is shown in block (a), background condition in block (b).

Appendix B - questionnaire in estonian

Muutusepimedus 3D ruumis - küsimustik

Lõpp ei ole enam kaugel!

* Required

Katseisiku ID *

Sugu *

○ M
○ N

Vanus *

Silmanägemine *

○ Korras
○ Korrigeeritud

Kas eemaldasid nägemisprillid, sest need olid laiad või ebamugavad *

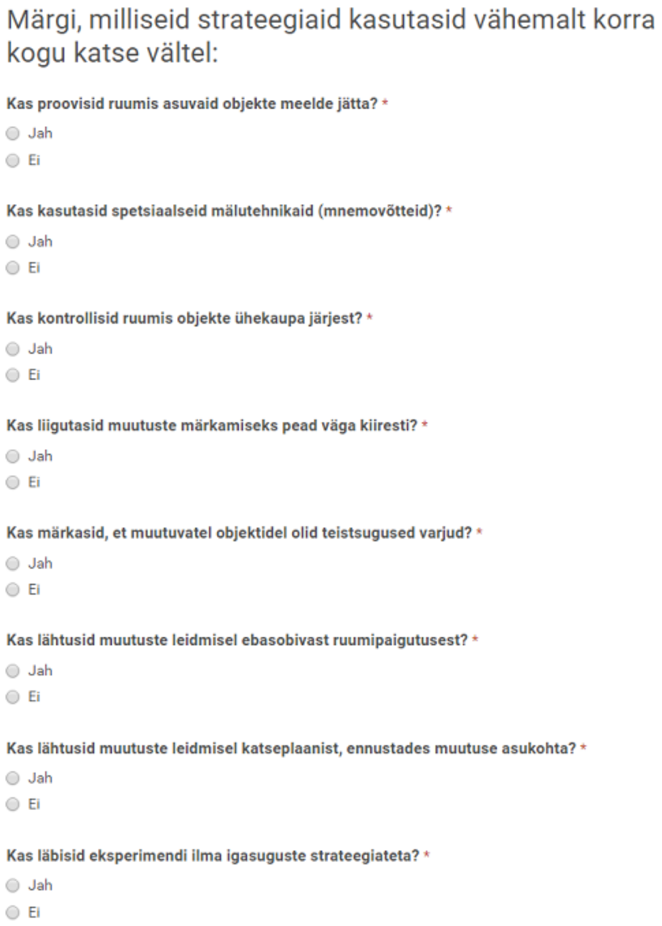
○ Ei
○ Jah

Varasem kogemus arvutimängudega *

	1	2	3	4	5	
Väga väike	○	○	○	○	○	Väga suur

Kas tundsid katse ajal peapööritust või iiveldust *

	1	2	3	4	5	
Üldse mitte	○	○	○	○	○	Väga palju



Märgi, milliseid strateegiaid kasutasid vähemalt korra kogu katse vältel:

Kas proovisid ruumis asuvaid objekte meelde jätta? *

○ Jah
○ Ei

Kas kasutasid spetsiaalseid mälutehnikaid (mnemovõtteid)? *

○ Jah
○ Ei

Kas kontrollisid ruumis objekte ühekaupa järjest? *

○ Jah
○ Ei

Kas liigutasid muutuste märkamiseks pead väga kiiresti? *

○ Jah
○ Ei

Kas märkasid, et muutuvatel objektidel olid teistsugused varjud? *

○ Jah
○ Ei

Kas lähtusid muutuste leidmisel ebasobivast ruumipaigutusest? *

○ Jah
○ Ei

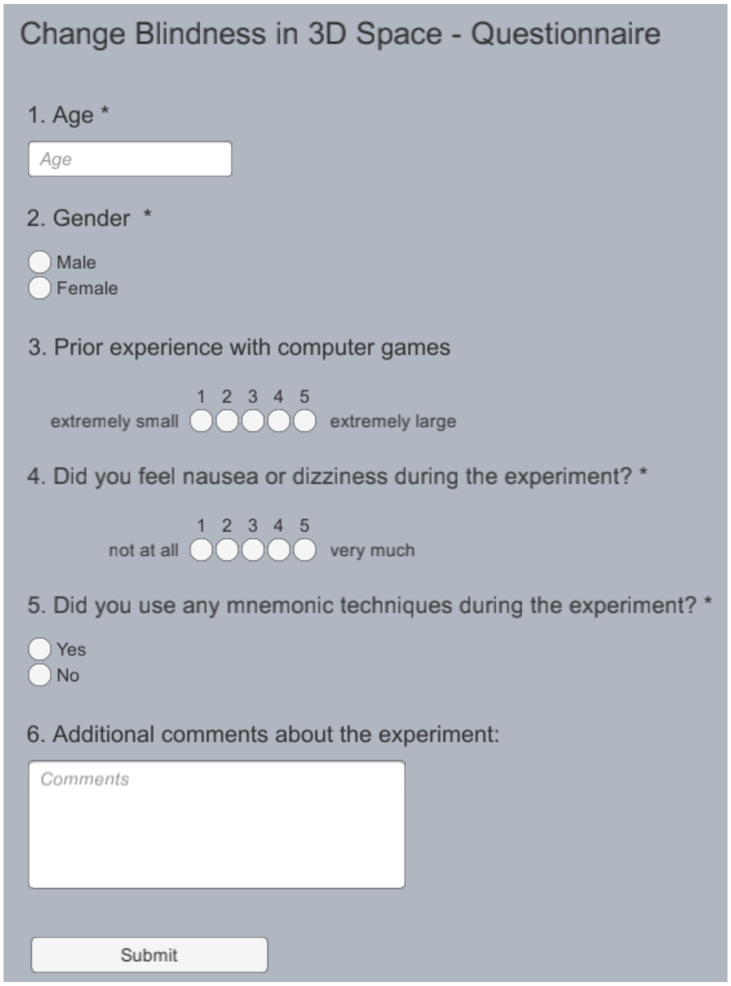
Kas lähtusid muutuste leidmisel katseplaanist, ennustades muutuse asukohta? *

○ Jah
○ Ei

Kas läbisid eksperimendi ilma igasuguste strateegiateta? *

○ Jah
○ Ei

Appendix C - questionnaire in english



Change Blindness in 3D Space - Questionnaire

1. Age *

Age

2. Gender *

○ Male
○ Female

3. Prior experience with computer games

1 2 3 4 5
extremely small ○ ○ ○ ○ ○ extremely large

4. Did you feel nausea or dizziness during the experiment? *

1 2 3 4 5
not at all ○ ○ ○ ○ ○ very much

5. Did you use any mnemonic techniques during the experiment? *

○ Yes
○ No

6. Additional comments about the experiment:

Comments

Non-exclusive licence to reproduce thesis and make thesis public

I, Madis Vasser,

1. herewith grant the University of Tartu a free permit (non-exclusive licence) to:

1.1. reproduce, for the purpose of preservation and making available to the public, including for addition to the DSpace digital archives until expiry of the term of validity of the copyright, and

1.2. make available to the public via the university's web environment, including via the DSpace digital archives, as of 10.06.2016 until expiry of the term of validity of the copyright,

CHANGE BLINDNESS IN 3D SPACE,

supervised by Jaan Aru (PhD),

2. I am aware of the fact that the author retains these rights.

3. This is to certify that granting the non-exclusive licence does not infringe the intellectual property rights or rights arising from the Personal Data Protection Act.

Tartu, 25.05.2015