Change Blindness Phenomena for Stereoscopic Projection Systems

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ABSTRACT

In visual perception, change blindness describes the phenomenon that persons viewing a visual scene may apparently fail to detect significant changes in that scene. These phenomena have been observed in both computer generated imagery and real-world scenes. Several studies have demonstrated that change blindness effects occur primarily during visual disruptions such as blinks or saccadic eye movements. However, until now the influence of stereoscopic vision on change blindness has not been studied thoroughly in the context of visual perception research.

In this paper we introduce change blindness techniques for stereoscopic projection systems, providing the ability to substantially modify a virtual scene in a manner that is difficult for observers to perceive. We evaluate techniques for passive and active stereoscopic viewing and compare the results to those of monoscopic viewing conditions. For stereoscopic viewing conditions, we found that change blindness phenomena occur with the same magnitude as in monoscopic viewing conditions. Furthermore, we have evaluated the potential of the presented techniques for allowing abrupt, and yet significant, changes of a stereoscopically displayed virtual reality environment.

Keywords: Visual perception, stereoscopic viewing, change blindness

1 INTRODUCTION

Visual attention describes how humans prioritize information in their visual field of view to process complex visual scenes in order to detect, identify, localize and track objects [16, 26]. This allows our visual system to handle subsets of the visual input sequentially by focusing attention to salient locations [8, 26]. In this context, *inattentional blindness* describes the phenomenon that human observers fail to notice objects that are in their view due to the circumstance that they focus on other parts of the visual scene [11]. In such situations, modifications to certain objects can literally go unnoticed when the visual attention is not focused on them. *Change blindness* denotes the inability of the human eye to detect modifications of the scene that are rather obvious–once they have been identified [1, 4, 19]. These scene changes can be of various types and magnitudes, for example, prominent objects could appear and disappear, change color, or shift position by a few degrees [22]. Such change blindness effects occur for both static pictures as well as dynamic scenes [18, 21]. Figure 1 shows an example of such a change. In Figure 1(c) and (d) the spire within the frame has shifted position in comparison to Figure 1(a) and (b), respectively. The red frames highlight the difference between the two images, and are used for illustration purposes only.

Figure 1: Sample of cross-eye stereoscopic change blindness images: (a) and (b) show the original images, (c) and (d) show the modified images for the right and left eye, respectively. *Notice that the spire has not only shifted position, but also changed its stereoscopic depth accordingly. The red frame is added to highlight the change.*

Such change blindness effects have great potential for virtual reality (VR) environments, since they allow abrupt changes of the visual scene which are unnoticeable for users. Current research on human perception in virtual environments (VEs) focuses on identifying just-noticeable differences and detection thresholds that allow the gradual introduction of imperceptible changes to a visual scene [23]. Both of these approaches–abrupt changes and gradual changes–exploit limitations of the visual system in order to introduce significant changes to a virtual scene. Such changes are widely used for graphical trade-offs, e. g., level-of-detail representations or progressive loading of objects [4], but also in order to overcome limitations of interaction techniques [3, 9]. For example, it has been shown that rotational or translational user motions, which are mapped to smaller or larger rotations or translations in the virtual world, cannot be observed by the user [17]. Moreover, VR users compensate for these manipulations and unknowingly change their locomotion behavior in the real world [3]. However, as shown by Steinicke et al. [24, 23], the amount of such gradual changes, which cannot be perceived by a user, is limited. For this reason, additional or alternative approaches are desired that allow more abrupt, and yet significant, changes to virtual environments imperceptible for VR users.

In this paper we introduce the concept of using change blindness phenomena for VR environments, which–to our knowledge–is the first approach to study change blindness for stereoscopic display systems. We present two paradigms how change blindness

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effects can be implemented in stereoscopic VR projection systems. We evaluated both techniques under passive and active stereoscopic viewing conditions and compared the results to monoscopic change blindness phenomena. The remainder of this paper is structured as follows. Section 2 gives an overview about previous research in the field of change blindness. Section 3 introduces change blindness for stereoscopic display environments and proposes two basic stereoscopic flicker techniques which afford the use of change blindness under stereoscopic viewing conditions. Section 4 describes the experiments that we have conducted to analyze the effects of stereoscopic vision on change blindness. In Section 5 we evaluate the presented stereoscopic change blindness techniques in a practical VR-based application scenario. Section 6 concludes the paper and gives an overview about future work.

2 BACKGROUND

Abrupt changes of the visual scene can easily draw the user's attention. Researchers have found that such changes are far less noticeable when they are applied during brief visual disruptions. For example, McConkie et al. [12] examined changes made to words and text during visual disruptions introduced by saccadic eye movements. In Grimes' experiments people missed substantial scene modifications when these were performed during eye movements [6]. In these studies, changes to the scene were synchronized with measured movements of the viewer's eyes. Their results show that when changes occur only during saccadic eye movements or blinks, they are often hard to detect [7, 13]. However, change blindness is not limited to eye movements and can also occur under a variety of other visual disruptions. For instance, studies have shown that often subjects failed to notice virtually obvious changes that were introduced during a cut or pan in a motion picture. In some of these studies even the main character was altered or the heads of two persons were exchanged [10]. This observation is confirmed by the fact that people regularly fail to notice editing errors in commercial movies. Simons and Levin [21] extended this phenomenon to a real-world experience. In their experiment, subjects, who were engaged in a conversation with an experimenter, continued the conversation without hesitation after the experimenter had been replaced by a different person. The switch between the two experimenters had been performed when two persons carrying a large door walked between first experimenter and subject. In the late 1980s, further forms of visual disruptions have been shown to afford change blindness effects. In this real-world situation, subjects saw the world with both eyes, however, the impact of stereoscopic vision was not considered in these experiments. Pashler [14] showed that subjects had significant problems to detect changes in the scene when a display was flickered off and on with a brief delay of less than 100 milliseconds (cf. Figure 2). Simons et al. [20] argue that the visual transient that a saccade produces may account for a similar visual disruption that occurs during blanking out the screen of a display for a few milliseconds. In this context, Rensink et al. [19] introduced the "flicker" method in which two images of a scene, which differ in a certain portion, alternate repeatedly with a brief blank screen in-between the images [1]. With such a flickering appearance, surprisingly large differences can exist between the images without observers reliably detecting them (cf. Figure 2). Furthermore, with the flicker method the visual disruption and therefore the moment at which the change occurs can be controlled by the experimenter, in contrast to inducing the change during a saccadic eye movement [22].

Recently, Simons and Rensink [22] found evidence that attention is required to detect changes, although attention alone is not necessarily sufficient: changes to objects in the observer's focus of attention can also be missed, particularly when the changes are unexpected. These change blindness studies have led to the conclusion that the internal representation of the visual field is much more sparse than the subjective experience of "seeing" suggests and essentially contains only information about objects that are of interest to the observer [25]. This observation is confirmed by the fact that changes to semantically important objects are detected faster than changes elsewhere [22]. However, an explanation for the larger portion of the observed change blindness effects remains unknown [22].

In most experiments on change blindness two-dimensional images, pictures, animations or videos–either captured from the real world or computer generated–have been presented to the subjects [5]. During the experiments subjects had to scan two-dimensional representations for changes, while both eyes have seen essentially the same visual stimulus. However, viewing in the real world differs significantly from viewing a two-dimensional projection of a 3D scene. When viewing in the real world, binocular vision allows us to use both eyes in combination, which results in two slightly different perspectives of the same visual scene. Binocular vision has various advantages over monocular vision: Binocular summation improves the human's ability to detect faint objects. Binocular vision can provide stereopsis, describing the process in visual perception that leads to the sensation of depth from two slightly different projections. The difference between two projections of the same object on the retina is referred to as binocular disparity. Binocular fusion allows humans to perceive a single image with encoded depth information despite the fact that each eye receives its own image. Although it is known that binocularity and stereopsis are important characteristics in the human vision system, their effects on change blindness have not been examined in detail until now.

3 STEREOSCOPIC CHANGE BLINDNESS

In this section we introduce how change blindness, which has basically been considered a two-dimensional phenomenon, can be adapted to binocular vision and stereoscopic displays. Since the flicker paradigm is an established method to examine change blindness effects, it sounds reasonable to consider this method to study the influence of stereopsis on change blindness phenomena. Moreover, the alternate-frame sequencing of active shuttering systems inherently contains a flicker because of the shuttering, so that the flicker paradigm associated with change blindness can be easily adapted to active shuttering systems.

In order to extend change blindness to stereoscopy we first describe the general design of the monoscopic flicker paradigm. We consider an image A, which we refer to as the *original* image. Let A' denote the *modified* version of this image, containing a significant change from image A. Differences between original and modified image can be of any type and magnitude; for example, prominent objects could appear/disappear, switch their colors, or shift position

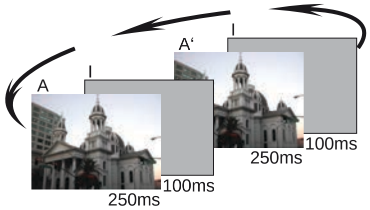

Figure 2: General design of the monosopic flicker paradigm. The "flicker" cycle consists of an example image A (building with several spires), modified image A' (right spire has shifted position), and interstimulus images which are presented after the original and after the modified image.

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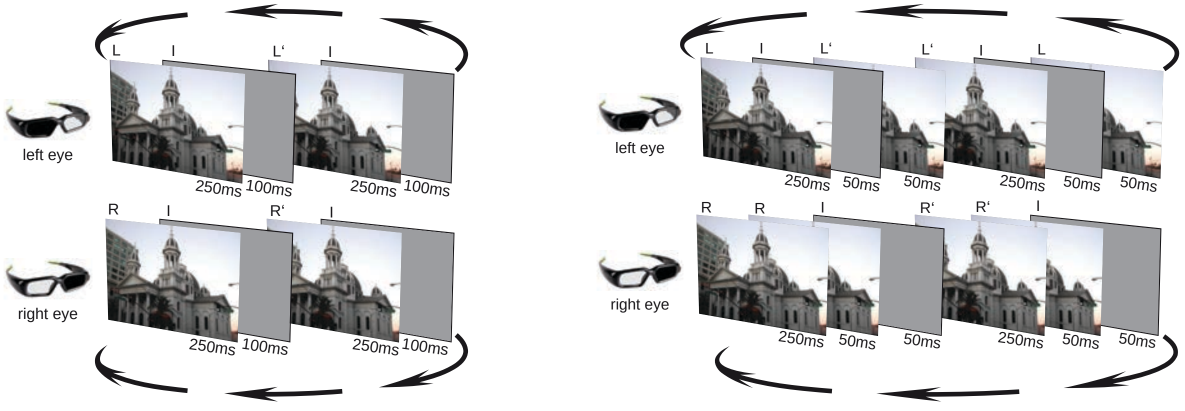
[1] Rensink et al. [19] introduced the term "change blindness" for these phenomena.



(a) Stereoscopic flicker technique

(b) Phase-shifted flicker technique

Figure 3: (a) The stereoscopic flicker sequence consists of original images L and R (left and right eye view of the same building as depicted in Figure 1), modified images L' and R', and the inter-stimulus interval consisting of two gray screens displayed to each eye simultaneously. (b) The sequence of the phase-shifted flicker technique consists of the original images L and R, the first inter-stimulus interval during which two gray screens are presented crosswise with the images L' and R, the modified images L' and R', and the second inter-stimulus interval during which two gray screens are presented crosswise with the images L and R'.

by a few degrees. In most change blindness experiments, the image A is displayed for 100ms−500ms, followed by a brief inter-stimulus image (I), before the modified image A' is shown. The image I is often chosen as a uniform gray image. Usually, observers were found to have difficulties in detecting changes between original image A and modified image A', if image A and A' were separated by an inter-stimulus image of more than 70ms duration [19, 22].

The flicker paradigm is illustrated in Figure 2. In the depicted cycle, the original image A is displayed for 250ms, followed by the brief gray screen I displayed for 100ms, followed by the modified image A' (one spire changed position), which is shown again for 250ms. Without displaying the inter-stimulus image, or once the modification has been detected, the shifted object can be observed easily, when these images are displayed alternating and superimposed.

3.1 Stereoscopic Flicker Technique

The described flicker paradigm can be adapted easily to stereoscopic displays. In contrast to previous monoscopic change blindness studies based on the flicker paradigm, in the stereoscopic viewing condition two slightly different images have to be presented to the left and the right eye, respectively. The first approach that we present here extends the monoscopic procedure in a straightforward way. Instead of presenting only one original and one modified image to both eyes, we present each eye with an individual view (with respect to the interpupillary distance) of the original and modified visual scene. Alike, the inter-stimulus image is also presented to both eyes simultaneously.

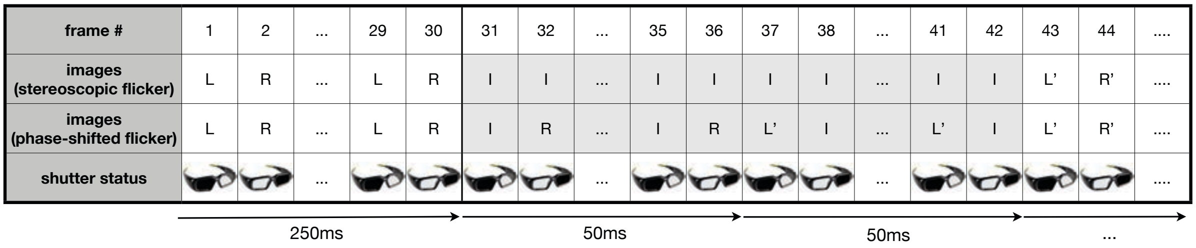
Hence, let L and R denote the original images that show the view for the left and right eye, respectively, and let L' and R' denote the corresponding modified versions of these images. Again, differences between original and modified image can be of any type and magnitude. However, in the stereoscopic case changes can also be made to the binocular disparity of certain objects or the interpupillary distance. For instance, the binocular disparity and thus the perceived depth can be changed by scaling up or scaling down the distance between the projections of an object in the images L' and R' in comparison to the disparity used in L and R. Hence, an object presented in the modified stereoscopic images could appear closer or farther away from the user than the same object in the original stereoscopic image. In accordance with the monoscopic flicker technique described above, we display the images L and R for 250ms before the brief inter-stimulus images are shown. Since we require an inter-stimulus image for each eye, we refer to the phase during which viewing of the virtual scene is disrupted as the *inter-stimulus interval*. In this straightforward approach, during the inter-stimulus interval a uniform gray image is displayed to each eye simultaneously for 100ms. After the inter-stimulus interval has elapsed, the modified images L' and R' are shown for 250ms to the left and right eye, respectively.

Figure 3(a) illustrates the stereoscopic flicker technique. The upper row shows the images for the left eye, the lower row the images for the right eye. First, both eyes see the original images for a duration of 250ms, then the inter-stimulus images are displayed for 100ms. Afterwards, the modified versions of the original images are shown for another 250ms, before the inter-stimulus images are shown again, and then the entire cycle is repeated.

3.2 Phase-Shifted Stereoscopic Flicker Technique

The aforementioned approach implements the flicker paradigm in a straightforward way. In case of a stereoscopic image that consists of a virtual scene with only zero parallax, this technique equals the monoscopic flicker technique. The described stereoscopic flicker technique introduces a first approach to study change blindness in VR systems. However, another goal of this work is to exploit change blindness phenomena to induce significant changes to the virtual world without these changes being detected by the users. The inter-stimulus interval in the stereoscopic flicker method described above lasts for 100ms and is clearly noticeable. During that interval none of the eyes perceives the virtual scene, but both eyes see the gray image. In the monoscopic case this is essential in order to be able to reduce the ability of the visual system to directly compare original and modified image. However, in a stereoscopic situation the content and the time at which each eye shall perceive corresponding information can be controlled more flexibly. For this reason the moments at which the inter-stimulus images are presented to each eye can be shifted, and it can be guaranteed that at least one eye perceives a view to the stereoscopic scene at any time.

This so-called *phase-shifted flicker technique* consists of three



frame #	1	2	...	29	30	31	32	...	35	36	37	38	...	41	42	43	44	....
images (stereoscopic flicker)	L	R	...	L	R	I	I	...	I	I	I	I	...	I	I	L'	R'	....
images (phase-shifted flicker)	L	R	...	L	R	I	R	...	I	R	L'	I	...	L'	I	L'	R'	....
shutter status			...					...					...					....

Figure 4: Display sequence for an active projection system. The images are displayed consecutively to the left and right eye. Using a refresh rate of 120Hz, every 8.33ms a new frame is presented. Row # 2 shows the procedure for the stereoscopic flicker technique, row # 3 shows the procedure for the phase-shifted stereoscopic flicker technique. The gray areas illustrate the inter-stimulus intervals.

phases starting after the original stereoscopic images are shown. First, one inter-stimulus image is presented to only one eye, whereas the other eye still perceives the corresponding view of the original scene. Then, the modified stereoscopic image is displayed to the eye to which the inter-stimulus image was displayed before, whereas the inter-stimulus image is now displayed to the other eye which saw the original image before. In the last phase the modified image for the remaining eye is displayed to that eye, while the other eye further sees the modified image, which has already been displayed in the previous phase. The phase-shifted flicker technique is illustrated in Figure 3(b). The cycle starts with the original images L and R, which are displayed for 250ms. The inter-stimulus interval is initiated by the display of a gray screen to the left eye (for 50ms), whereas the right eye continues to perceive the image R of the original scene. Then, the modified image L' is displayed to the left eye, whereas the right eye now sees the gray screen I for 50ms. Finally, the modified image R' is presented to the right eye, so that both images display the modified stereoscopic virtual scene. The phase-shifted stereoscopic flicker technique could either consider the one or the other eye first during the inter-stimulus interval.

In contrast to the stereoscopic flicker technique described in Section 3.1, at no time is the scene completely blocked out for both eyes. Furthermore, the inter-stimulus images are displayed for only 50ms to each eye. Indeed, with this technique subjects are confronted with a binocular rivalry phenomenon in which perception alternates between different images presented to each eye. During the inter-stimulus interval the images for the left and the right eye are displayed consecutively to both eyes comparable to the alternating display in active VR shuttering systems, but with a much lower frequency. This way of displaying stereoscopic images is referred to as *wiggle stereoscopy* in which the display simply alternates between left and right images. Due to persistence of vision and parallax, most people get a crude sense of dimensionality from such displays [15].

4 EXPERIMENT

In this section we describe the experiment that we have conducted in order to analyze the effects of binocular vision and stereoscopy on change blindness. We performed a within-subject design to study the subjects' ability to detect abrupt changes of essential objects in the scene after an inter-stimulus interval was induced. Subjects were instructed to view images of real-world scenes on different displays. The scenes were displayed mono- as well as stereoscopically in active and passive VR projection systems. For the stereoscopic display we used both the stereoscopic flicker technique described in Section 3.1 and the phase-shifted stereoscopic flicker technique described in Section 3.2.

4.1 Experimental Setup

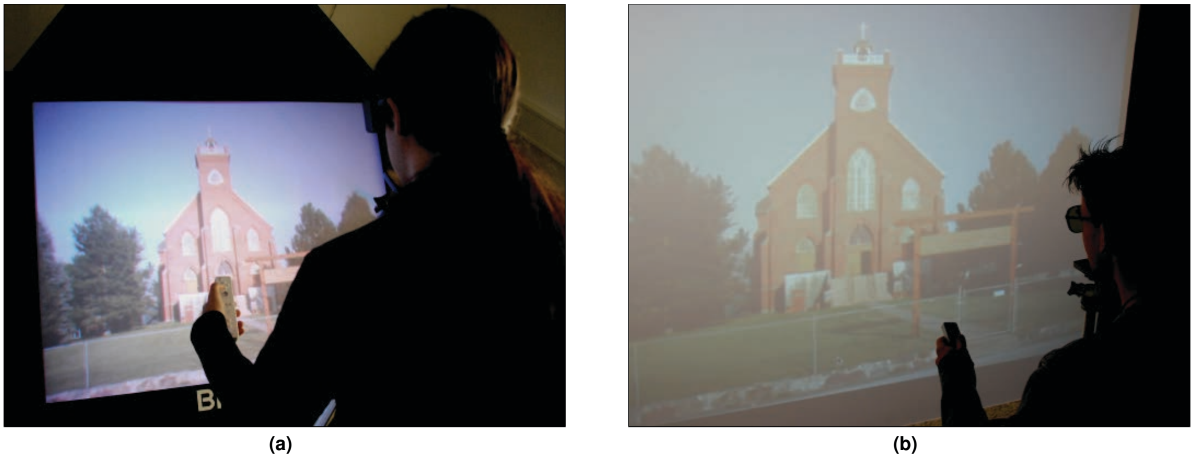
We tested the change blindness techniques in two common VR-based projection environments, i. e., an active workbench and a passive back-projection system.

4.1.1 Active Stereoscopic Workbench

We used a Baron workbench (manufactured by Barco) based on a CRT projector. The screen size of the display is 1.36m×1.02m. The screen was tilted by 45°. Subjects were seated 1m in front of the display (with eye height focussed on the center of the screen) such that a fullscreen image appeared 80° wide and 54° high. Figure 5 (a) shows a picture taken during the experiment. We displayed the images with a vertical refresh rate of 120Hz, and with the projector's native 1024×768 pixel resolution. With a refresh rate of 120Hz, the display updates approximately every 8.33ms. We displayed a simple OpenGL scene consisting of one polygon, which filled the entire viewport and onto which the stereoscopic images were mapped as textures. This procedure ensured that we were able to display each frame within the 8.33ms time limit.

Subjects wore active Crystal Eyes stereoscopic shutter glasses to separate the consecutively displayed images. Controlled via an infrared emitter the glasses alternated at 120Hz in synchronization with the refresh of the workbench. Therefore, each eye obtained a corresponding view to the scene with 60Hz, i. e., every 16.66ms the view was updated for each eye. The contrast ratio supported by the glasses was $1500:1$ with a transmittance of 32%.

Since we are interested in how long subjects require to detect a change in the scene, the duration of a cycle is a crucial issue and substantially depends on the refresh rate. For example, in order to display the original image for 250ms, the image had to be displayed 30 times (15 times for the left, and 15 times for the right eye) because of the refresh rate, which enforces a constant update every 8.33ms. With a refresh rate of 120Hz the total time in which an image was visible to the subjects was constrained to be a multiple of the minimal duration of 8.33ms. Figure 4 illustrates both proposed stereoscopic flicker techniques for an active projection system with a refresh rate of 120Hz. The left and right view of the stereoscopic images are displayed consecutively each 15 times with a refresh rate of 120Hz. The shutter mechanism of the 3D glasses ensures that, for instance, the *even* images are seen by the left eye, whereas the *odd* images are seen by the right eye only, and hence subjects perceive a stereoscopic image. The upper row shows the stereoscopic flicker technique and the lower row the phase-shifted flicker technique for an active stereoscopic projection system. As illustrated, the original images are displayed for 250ms (30 frames). Then the inter-stimulus interval is initiated. In the stereoscopic flicker tech-



(a) (b)

Figure 5: Pictures showing the experiment setup: A subject views a stereoscopic scene on (a) a Barco workbench and (b) a projection screen to which the stereoscopic flicker technique is applied. During the experiments we turned off all ambient lighting in the room.

nique (upper row) both eyes see the gray image 12 times resulting in a display duration of 100ms. This procedure results in a short, but noticeable flickering. In the phase-shifted stereoscopic flicker technique (lower row) the right eye sees the gray image 6 times resulting in a display duration of 50ms, whereas the left eye still sees the original image. Then, the left eye sees the gray image also 6 times resulting in a display duration of 50ms, whereas the right eye sees the modified image. In the final phase of the phase-shifted flicker technique, the modified image is displayed to both eyes for 250ms before the interval is initiated again, this time in the opposite order until the original image is visible to both eyes again. Note, that the entire cycle requires the same number of frames and the same time period, therefore both proposed flicker techniques, and furthermore also the inter-stimulus intervals have the same duration.

4.1.2 Passive Back-Projection Wall

In contrast to this active setup, in the passive projection environment the images are displayed simultaneously to both eyes. We used a back-projection system consisting of two DLP projectors in combination with circular polarizers. The polarization-preserving projection screen measures 2.7m×2.03m×0.005m. The projectors provided 3500 lumen with a native pixel resolution of 1024×768, the contrast ratio was 2400 : 1.

The distance between the projectors and the projection screen was about 4.5m. We seated the subjects 1.6m in front of the projection screen so that the fullscreen images appeared 80° wide and 54° high like in the active condition described above. Thus, we ensured that the image displayed by the DLP projectors had the same size, aspect ratio and number of pixels like the image displayed on the active workbench. The projectors displayed the left and right view superimposed, and the images were separated by the polarized glasses so that subjects perceived a stereoscopic image.

In both projection environments the room was entirely darkened during the experiment in order to focus the subjects' attention on the displayed images. The subjects received instructions on slides presented on the screen. A Nintendo Wii remote controller served as input device. Figure 5 (b) shows a picture taken during the experiment. A subject sits in front of the projection screen and views a stereoscopic scene to which the stereoscopic flicker method is applied. The subject had to press a button on the input device as soon as he observes the change between original and modified image. Afterwards, subjects had to tell the experimental observer where in the image the change occurred.

11 male and 3 female (ages $22 - 38$, $\varnothing : 25.43$) subjects participated in the experiment. Most subjects were students or members of the departments of computer science, mathematics, psychology, geoinformatics, and physics. All had normal or corrected to normal vision; five wore glasses or contact lenses. Seven had no experience with shutter glasses, four had some, and three had much experience with shutter glasses. All subjects were naive to the experimental conditions. Six subjects obtained class credit for their participation. The total time per subject including pre-questionnaire, instructions, training, experiment, breaks and debriefing took approximately one hour. Subjects were allowed to take breaks at any time.

4.2 Materials and Methods

At the beginning of each trial we displayed a screen to the subjects with written instruction to press a button as soon as they see a change and to verbally describe it to the experimental observer afterwards. We presented the same set of 60 colored stereoscopic images of real-world scenes to all subjects. The images were assigned randomly to each condition and projection system, and we guaranteed that each image was chosen the same number of trials for each condition and projection system, respectively. The images were carefully taken such that essential stereoscopic settings, i. e., interpupillary distance and focal length, were identical for all pictures. The interpupillary distance used for capturing the images was approximately 7cm. In the stereoscopic display all images consisted of objects with positive, zero, and negative parallax. We ensured that there were no extreme parallax effects and that the images were comfortable to view. All images were displayed fullscreen as explained above. Before each experiment, subjects were given three practice trials in which typical changes occurred as used in the experiment. The changes to the images were such that the average difference was quite large and easy to see once noticed. All images contained only a single change (object color, location, binocular disparity or presence/absence). The average change measured approximately 40 square degrees. For example, Figure 1 shows a change of $7^\circ \times 6^\circ$ degrees, which corresponds to changes of approximately 90×85 pixels (1%) from original to modified image.

We applied changes to objects of less interest, the degree of interest was determined via an independent experiment in which two naive observers provided a brief verbal description of the scene after viewing it for 5 seconds. Similar to [22] we applied changes to those objects which had not been mentioned by the observers.

In most previous experiments about monoscopic change blindness, the subjects had to detect the change in a scene that was displayed on a desktop screen. In order to be able to analyze the influence of stereoscopy to change blindness, we evaluated the subject's ability to detect changes in monoscopic images which were displayed on both screens used in the experiment, i. e., the active and passive VR projection systems (cf. Section 4.1).

We used the following three conditions in our experiment.

Condition 1: Monoscopic Flicker Technique

In order to display the image monoscopically we used always only the left images from our set of stereoscopic sample images and displayed them also for the right eye resulting in a flat 2D image with zero parallax. Half of the subjects performed the experiment first for the active system, half of the subjects first for the passive system. In order to present the images with equal brightness subjects were forced to wear the same 3D glasses as used for the stereoscopic display. However, for the experiment at the active workbench the shuttering of the 3D glasses was turned off, so that no flickering could affect the ability to detect the change. Left and right view were displayed superimposed at the passive projection system, and subjects wearing the polarization glasses saw an image with zero parallax, which corresponds to viewing a monoscopic image.

Condition 2: Stereoscopic Flicker Technique

In this condition we displayed the left and right images either simultaneously (passive projection system) or time-sequential (active workbench) as described in Section 4.1 using the stereoscopic flicker paradigm as described in Section 3.1.

Condition 3: Phase-Shifted Flicker Technique

We displayed the left and right images either simultaneously (passive projection system) or time-sequential (active workbench) as described in Section 4.1. We used the phase-shifted stereoscopic flicker paradigm described in Section 3.2.

In each condition subjects had to detect changes in 10 sample images. If a subject could not detect a change within 60s, the experimental observer told the subject about the change, and then the next trial started. All experiments have been conducted in a within-subjects design. We performed all tests in randomized order, each image was only used for one condition. Hence, all subjects saw all images, but each image was only displayed in one condition either at the active or passive VR projection system. The independent variables were the used display technology, i. e., active vs. passive stereoscopic projection, and the used change blindness technique, i. e., monoscopic vs. stereoscopic vs. phase-shifted stereoscopic flicker technique. The dependent variable was the average number of alternations (proportional to the reaction time), which was required by the subjects to see the change. Averages were taken only from correct responses, i. e., responses where the observer correctly identified both the type of change occurring and the object or area being changed. In order to focus subjects on the task, communication between experimenter and subject was limited to the absolute minimum. All instructions were displayed in the VE, and subjects responded via the Wii device.

4.3 Results

We analyzed the mean elapsed time until a change was detected with a 2×3 analysis of variance (ANOVA), testing the within-subjects effects of display technology and change blindness paradigm. The analysis revealed a significant main effect of the change blindness paradigm ($F(5,899) = 18.24, p < .001$). Post-hoc analysis with the Tukey test showed that it was significantly easier for the subjects to detect a change when the phase-shifted stereoscopic flicker technique was used compared to a change when the monoscopic or stereoscopic flicker technique was used. We found no significant difference between the conditions in which the monoscopic or stereoscopic flicker techniques were used ($p = .988$). Finally, we found no significant difference between both considered projection systems ($p = .267$).

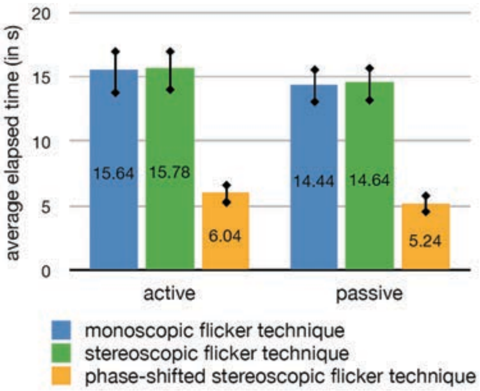


Figure 6: Pooled results of the experiment showing the mean elapsed time for the three conditions, i. e., monoscopic, stereoscopic, and phase-shifted stereoscopic flickering technique, for the active and passive VR projection system.

The error rate was 0% across all subjects, i. e., no subject reported a change that was not presented on the display. Therefore we considered the data from all trials. Figure 6 shows the mean time elapsed until a subject correctly detected a change under all conditions for the tested images. The left group of bars shows the results for the active, the right group shows the results for the passive VR projection systems. The error bars show the standard errors over all subjects.

On average subjects required 15.041s (15.643s ($SD = 18.37$) for the active VR system, 14.440s ($SD = 13.98$) for the passive VR system) to correctly detect a change in the monoscopic viewing condition. Subjects required on average more than 42 changes (44 for the active and 40 for the passive projection system) between original and modified image until they detected the difference.

Under the stereoscopic flicker technique condition, subjects required on average 15.213s (15.783s ($SD = 16.96$) for the active VR system, 14.642s ($SD = 15.38$) for the passive VR system) to correctly detect a change. The time required for subjects to detect a change was on average 2% longer in the stereoscopic viewing condition than it was in the monoscopic viewing condition. On average subjects required more than 43 changes (45 for the active and 42 for the passive projection system) between original and modified image until they detected the difference.

As expected, subjects were better in detecting the change when we used the phase-shifted stereoscopic flicker technique (Condition 3). They required on average 5.643s (6.04s ($SD = 9.61$) for the active VR system, 5.245s ($SD = 7.11$) for the passive VR system) to correctly detect a change in this condition. On average subjects required more than 16 changes (17 for the active and 14 for the passive projection system) between original and modified image until they detected the difference.

Before and after the experiment we measured simulator sickness symptoms by means of Kennedy's Simulator Sickness Questionnaire (SSQ). The Pre-SSQ score averages for all subjects to 6.41 and the Post-SSQ score to 12.29. It is known that the flicker paradigm can increase eye strain and cause headaches, especially for longer presentation times. However, in [27] Young et al. found that simulator sickness pretests may bias participants towards reporting simulator sickness symptoms higher in the post-test, which may also contribute to the increase.

4.4 Discussion

The results show that change blindness phenomena also occur in active and passive stereoscopic projection systems. Changes are even slightly harder to detect if the changes are induced when the stereoscopic flicker technique is used. As a matter of fact, stereoscopy introduces an additional dimension to the virtual scene. The internal representation of the visual field model of the scene may be more detailed when stereoscopic vision is used. However, the difference between detecting a change when using the stereoscopic flicker technique in comparison to the monoscopic flicker technique was not statistically significant. Further challenges addressing change blindness in stereoscopic viewing conditions have arisen from the results of this work, for instance, the question which type of changes can be detected more easily: changes considered in previous change blindness experiments (e. g., changes in illumination, position, etc.) or changes which relate to stereoscopic characteristics, such as interpupillary distance or binocular disparity.

As shown in the results, change blindness effects were most easily detected when the change was induced using the phase-shifted stereoscopic flicker technique. However, subjects required more than 7 changes before they were able to detect the difference between two static images. As explained in Section 3.2, the overall stereoscopic impression is rarely affected by the phase-shifted flicker sequence since at least one eye sees the scene at all times. In theory the phase-shifted sequence should be perceived as less disturbing than the inter-stimulus interval of the stereoscopic flicker sequence, which blanks out the view of both eyes for a certain time. Therefore, we believe that this technique is the most appropriate one for VR applications that require an abrupt change (cf. Section 5).

The results further show that subjects require a slightly longer period of time in order to detect a change in the active than in the passive stereoscopic projection system. This may be due to small differences in the image quality or the separation of the stereoscopic images using different setups. However, this difference was not statistically significant.

5 REAL APPLICATION TEST

We have shown that the presented techniques have potential for allowing abrupt, and yet significant, changes of a stereoscopically displayed VR environment. Since our goal is to apply change blindness in VR-based applications we conducted an informal follow-up study to evaluate the described stereoscopic techniques in a real application context. The objective of this evaluation was to reveal if inter-stimulus intervals are perceived as disturbing–or perceived at all–, and if a single, abrupt change is detectable by subjects. Therefore, we used head-tracking in combination with the visual stimuli of a virtual city model. The subjects saw the virtual model displayed on the passive projection system as used for the experiments described in Section 4.1. The subjects' task was to get an impression of the displayed VE by shifting position in the tracked 2m×2m area in front of the projection screen. 5 male subjects participated in this evaluation. All of them had participated in the experiment described in Section 4.

We displayed a virtual city model scene on the projection wall for exactly three minutes. The refresh rate of the rendering process was 60 frames per second. Hence, a subject's view was updated in real-time according to the position of the tracked head. The inter-stimulus intervals were displayed for 6 frames, i. e., 100ms. After the first 60s we displayed the inter-stimulus interval of the phase-shifted stereoscopic flicker sequence, and after further 90s we displayed the corresponding sequence of the stereoscopic flicker sequence. During the first inter-stimulus interval we removed a distant building from the virtual city model, and during the second interval we re-displayed the building. After further 30s the screen turned black and the subjects were told to take off the glasses as well as to give the experimental observer a detailed description of the virtual scene. Then, we asked them about typical VR characteristics, like latency, tracking errors, the stereoscopic effect etc. Finally, we asked the subjects if anything unexpected happened during the experiment. Two subjects reported that they had perceived a short "flash" near the end of the three minutes, which shows that they had noticed the inter-stimulus interval that corresponded to the stereoscopic flicker sequence. No subject reported that they had perceived the inter-stimulus interval that corresponded to the phase-shifted flicker sequence. Only one subject reported that he had seen the distant building vanish. Directly asked about this change, he answered that he had focused on this object by chance right when it disappeared. Even when we asked the other subjects directly whether they saw that one building had disappeared or appeared after a gray blank screen, they reported that this change had gone completely unnoticed by them.

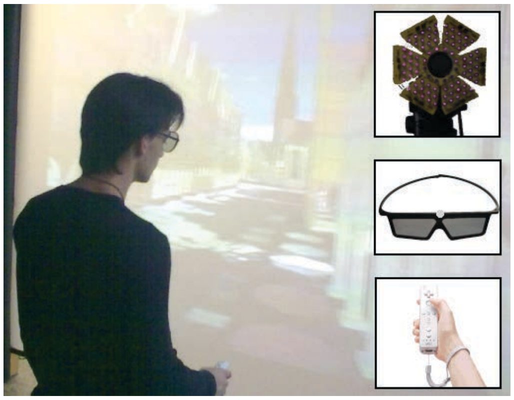


Figure 7: Picture taken during the real application test: A subject views a virtual city model on a projection screen. Parts of the optical tracking system, polarization glasses with marker and the input device are shown as insets.

6 CONCLUSION AND FUTURE WORK

In this paper we have shown that change blindness effects occur in VR systems, like they do in 2D desktop systems and computer-generated imagery. We introduced change blindness phenomena for stereoscopic VR projection systems. We proposed two different techniques, i. e., the stereoscopic flicker technique and the phase-shifted stereoscopic flicker technique, which allow researchers to substantially modify a virtual 3D scene in a manner that is difficult for observers to perceive. We found that human observers require the same time as in monoscopic scenes to detect a change when using the straightforward stereoscopic flicker technique. We have also introduced change blindness techniques and shown that the presented techniques have potential for allowing abrupt, and yet significant, changes of a stereoscopically displayed VR environment.

The approach introduced in this paper opens up new vistas for studying the change blindness phenomenon. First, basic research has to be conducted in order to examine further aspects of binocularity and stereoscopy on change blindness. Many new challenges addressing change blindness in stereoscopic viewing conditions have arisen from the results of this work, for instance, the question which type of changes can be detected more easily: changes considered in previous change blindness experiments (e. g., changes in illumination, position, etc.) or changes which relate to stereoscopic characteristics, such as interpupillary distance or binocular disparity.

In the future we plan to evaluate change blindness phenomena using eye tracking devices in projection-based setups as well as immersive head-mounted display environments. As mentioned in Section 4.3, flickering can increase eye strain and cause headaches, especially for longer presentation times. Eye trackers will allow us to apply abrupt changes during saccadic eye movements such that subjects do not perceive any visual disruption like in the currently used flicker sequences. We believe that change blindness effects have great potential to enhance perceptually-based locomotion [17, 24] and interaction techniques [3, 9] in order to manipulate the user. Objects can be added, deleted or modified via the described change blindness techniques to minimize the chance that users might notice the difference. For instance, if the user walks towards a virtual door in the VE, a positional shift of this door performed during a saccadic eye movement will allow more abrupt changes than the manipulations which are currently possible [2]. After the positional shift, the user adapts to the new position of the door in the virtual world by changing his orientation in the real world, which provides a means to influence a user's physical heading direction and walking path [2]. Despite such techniques, also more graphics-related tasks in VR may be addressed with change blindness, such as level-of-detail representations or progressive loading of objects, with the goal that users cannot perceive any changes of the scene during these processes [4]. We are confident that the proposed change blindness techniques have great potential to address open challenges of visual perception research as well as to make VR applications even more effective.

REFERENCES

[1] M. Becker and H. Pashler. Volatile visual representations: failing to detect changes in recently processed information. *Psychonomic Bulletin & Review*, 9(4):744—750, 2002.

[2] G. Bruder, F. Steinicke, and K. Hinrichs. Arch-explore: A natural user interface for immersive architectural walkthroughs. In *Proceedings of IEEE Symposium on 3D User Interfaces (3DUI)*, pages 75–82, 2009.

[3] E. Burns, S. Razzaque, A. T. Panter, M. Whitton, M. McCallus, and F. Brooks. The Hand is Slower than the Eye: A Quantitative Exploration of Visual Dominance over Proprioception. In *Proceedings of Virtual Reality*, pages 3–10. IEEE, 2005.

[4] K. Cater, A. G. Chalmers, and C. Dalton. Change blindness with varying rendering fidelity: looking but not seeing. In *SIGGRAPH Sketch*, 2001.

[5] C. Chen. *Information Visualization: Beyond the Horizon*. Springer, 2006.

[6] J. Grimes. On the failure to detect changes in scenes across saccades. *Perception (Vancouver Studies in Cognitive Science)*, 2:89–110, 1996.

[7] J. Henderson and A. Hollingworth. The role of fixation position in detecting scene changes across saccades. *Psychological Science*, 10:438—443, 1999.

[8] L. Itti. *The Handbook of Brain Theory and Neural Networks*, chapter Visual attention, pages 1196–1201. MIT Press, 2003.

[9] L. Kohli, E. Burns, D. Miller, and H. Fuchs. Combining Passive Haptics with Redirected Walking. In *Proceedings of Conference on Augmented Tele-Existence*, volume 157, pages 253 – 254. ACM, 2005.

[10] D. T. Levin and D. J. Simons. Failure to detect changes to attended objects in motion pictures. *Psychonomic Bulletin and Review*, 4(4):501–506, 1997.

[11] A. Mack. Inattentional blindness: Looking without seeing. *Current Directions in Psychological Science*, 12(5):180—184, 2003.

[12] G. McConkie and C. Currie. Visual stability across saccades while viewing complex pictures. *Journal of Experimental Psychology: Human Perception & Performance*, 22(3):563—581, 1996.

[13] J. K. O'Regan, H. Deubel, J. J. Clark, and R. A. Rensink. Picture changes during blinks: Looking without seeing and seeing without looking. *Vis. Cogn.*, 7(1/2/3):191–211, 2000.

[14] H. Pashler. Familiarity and the detection of change in visual displays. *Perception & Psychophysics*, 44(4):369—378, 1988.

[15] G. Peters. Theories of three-dimensional object perception - a survey. *Recent Research Developments in Pattern Recognition*, 2000.

[16] M. Posner and S. Petersen. The attention system of the human brain. *Annual Review of Neuroscience*, (13):25—42, 1990.

[17] S. Razzaque. *Redirected Walking*. PhD thesis, University of North Carolina, Chapel Hill, 2005.

[18] R. A. Rensink. Change detection. *Annual Review of Psychology*, (53):245–277, 2002.

[19] R. A. Rensink, J. K. O'Regan, and J. J. Clark. To see or not to see: The need for attention to perceive changes in scenes. *Psychological Science*, 8:368–373, 1997.

[20] D. Simons and M. Ambinder. Change blindness: Theory and consequences. *Current Directions in Psychological Science*, 14(1):44–48, 2005.

[21] D. Simons and D. Levin. Failure to detect changes to people during a real-world interaction. *Psychonomic Bulletin and Review*, 5:644—649, 1998.

[22] D. Simons and R. A. Rensink. Change blindness: past, present, and future. *Trends in Cognitive Sciences*, 9(1):16–20, 2005.

[23] F. Steinicke, G. Bruder, J. Jerald, H. Fenz, and M. Lappe. Estimation of detection thresholds for redirected walking techniques. In *IEEE Transaction on Visualization and Computer Graphics (TVCG)*, pages 17–27. IEEE, 2010.

[24] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe. Analyses of human sensitivity to redirected walking. In *15th ACM Symposium on Virtual Reality Software and Technology*, pages 149–156, 2008.

[25] A. Treisman and S. Gormican. Feature analysis in early vision: Evidence from search asymmetries. *Psychological Review*, 95(1):15–48, 1998.

[26] J. Wolfe. *Seeing*, chapter Visual attention, pages 335–386. Academic Press, 2000.

[27] S. D. Young, B. D. Adelstein, and S. R. Ellis. Demand characteristics in assessing motion sickness in a virtual environment: Or does taking a motion sickness questionnaire make you sick? In *IEEE Transaction on Visualization and Computer Graphics*, volume 13, pages 422–428, 2007.