In the Blink of an Eye – Leveraging Blink-Induced Suppression for Imperceptible Position and Orientation Redirection in Virtual Reality

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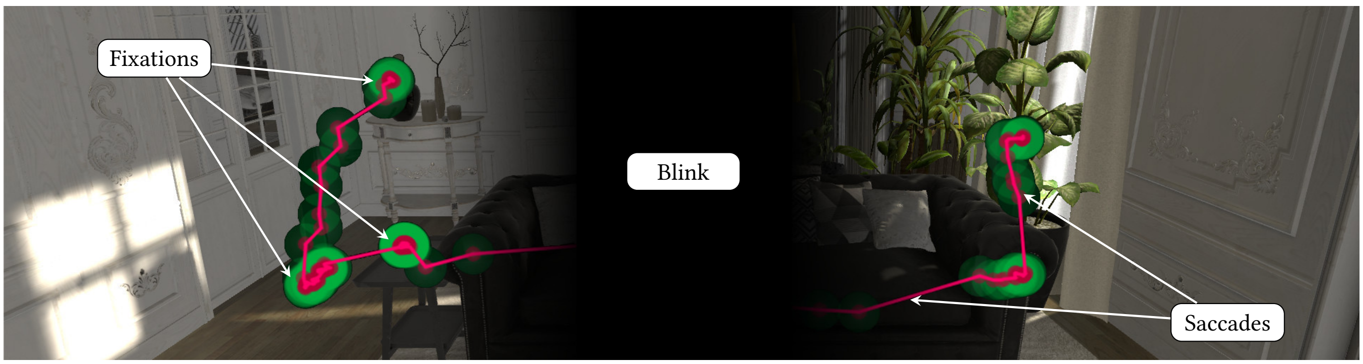

Fig. 1. Illustration of the viewing behavior of a virtual reality user including fixations (green) and saccades (red). A blink fully suppresses visual perception.

Immersive computer-generated environments (aka *virtual reality, VR*) are limited by the physical space around them, e. g., enabling natural walking in VR is only possible by perceptually-inspired locomotion techniques such as redirected walking (RDW). We introduce a completely new approach to imperceptible position and orientation redirection that takes advantage of the fact that even healthy humans are functionally blind for circa ten percent of the time under normal circumstances due to motor processes preventing light from reaching the retina (such as eye blinks) or perceptual processes suppressing degraded visual information (such as blink-induced suppression). During such periods of missing visual input, *change blindness* occurs, which denotes the inability to perceive a visual change such as the motion of an object or self-motion of the observer. We show that this phenomenon can be exploited in VR by synchronizing the computer graphics rendering system with the human visual processes for imperceptible camera movements, in particular to implement position and orientation redirection. We analyzed human sensitivity to such visual changes with detection thresholds, which revealed that commercial off-the-shelf eye trackers and head-mounted displays suffice to translate a user by circa 4 - 9 cm and rotate the user by circa 2 - 5 degrees in any direction, which could be accumulated each time the user blinks. Moreover, we show the potential for RDW, whose performance could be improved by approximately 50 % when using our technique.

CCS Concepts: • **Human-centered computing → Virtual reality**; • **Computing methodologies →** *Perception*; *Virtual reality*;

Additional Key Words and Phrases: Virtual reality, eye blinks, redirected walking, psychophysical experiments

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1 INTRODUCTION

Locomotion, the act of moving from one location to another, is the driving problem of our research as it is considered one of the most fundamental and important activities performed during interaction with our surroundings, and remains a difficult challenge to be solved in the research field of virtual reality (VR), in which users are immersed in a computer-generated virtual environment (VE). Together with continuous improvements of VR technologies over the last decades, we have seen the shift from artificial to more natural locomotion interfaces in this context [Steinicke et al. 2013]. In contrast to non-immersive VEs (such as mobile- or desktop-based computer graphics environments), immersive VR allows users to exploit *real walking* to explore a VE. When using real walking, tracked head-mounted display (HMD) movements are mapped to virtual camera motions, such that with a one-to-one mapping the virtual space that can be explored matches the available tracked physical space. While it has been shown that real walking is the most natural and intuitive form of moving through a VE [Steinicke et al. 2013], and it is more presence-enhancing than other locomotion techniques such as walking-in-place or flying [Steinicke et al. 2009; Usoh et al. 1999a], the problem arises that the space that can be explored with such one-to-one mappings is confined to the available tracking space [Steinicke et al. 2013].

Redirected walking (RDW) is a technique that induces unnoticeable rotations to the VE around a user wearing an HMD to create the illusion of walking in any direction for infinite time and distance in a VE while, in reality, the user is redirected to walk in a circle in the tracked physical space [Razzaque et al. 2001; Suma et al. 2012a]. Psychophysical experiments have shown that RDW is undetectable and thus basically equivalent to real walking in terms of vestibular, proprioceptive, and visual feedback if a tracked physical 40 m × 40 m walking area is available [Steinicke et al. 2010b]. More recent results have shown that the space can be further decreased with improved HMDs [Grechkin et al. 2016] or if the virtual paths are constrained to curved paths [Langbehn et al. 2017]. Another method is to map virtual and physical reality in such a way that only a minimal redirection is necessary [Sun et al. 2016].

While advances have been made in the research field to reduce these spatial requirements [Azmandian et al. 2016; Hodgson et al. 2014; Nescher et al. 2014; Suma et al. 2015], they are dwarfed by the demands in the gaming and entertainment fields. For instance, HTC and Valve follow the design paradigm *Room-Scale VR*, postulating that all VR experiences should be possible within the circa 4 m × 4 m walking area of a typical living room. To accommodate these spatial demands, the only possible way seems to be the use of *composites* of different techniques [Suma et al. 2012a]. Hence, there is a strong need for orthogonal concepts that can be integrated into RDW systems without tapping into the same perceptual processes.

Traditional RDW works by introducing slight continuous rotations and/or translations each rendering frame, which ideally are unnoticeable for the user. In contrast, in this article we focus on an approach that is *orthogonal* to this main line of RDW research. Instead of inducing slight manipulations in each frame, our concept is based on the approach to induce large manipulations in those frames when visual input is suppressed. Due to the orthogonal nature, both approaches could potentially be combined.

Human vision is suppressed during natural motor processes such as eye blinks and saccades, which occur infrequently, but accumulate to humans being functionally blind for about 10% of the time during waking hours [Johns et al. 2009]. These visual interruptions are responsible for a cognitive phenomenon called *change blindness*, which describes the inability to notice even large changes during brief moments of missing visual input [Simons and Levin 1997]. We believe that this constitutes potential, since the combination of an eye tracker and a graphics rendering system allow for undetectable changes, which could be used, e. g., to significantly improve RDW. While traditional RDW is only unnoticeable for rotations of 1-3 degrees per second when users are walking at their preferred speed [Razzaque 2005; Steinicke et al. 2010b], the results of our approach show that we can induce additional 5 degrees during *eye blinks* that happen every 4–19 seconds (see Figure 2).

In this article, we show that visual change during eye blinks is (i) a useful and versatile concept for perceptually-inspired locomotion in VR and (ii) easy to integrate in current-state HMDs and rendering systems, (iii) we empirically evaluate the amount of visual change, which can be induced during eye blinks, in two psychophysical experiments, and (iv) discuss the implications for practitioners in different fields.

2 RELATED WORK

In this section we first provide background information on human eye blinks, followed by an explanation of change blindness illusions and how they relate to eye blinks, and finally we discuss RDW and how our approach extends the related work.

2.1 Eye Blinks and Visual Suppression

Eye blinks are characterized by a rapid closing and opening of the eyelid with durations of 100–400 ms, depending on the situation and cause of the eye blink [Moses 1981; Ramot 2008; Relations 2006]. Apart from the motor process of eyelid movements that prevents light from reaching the retina, visual perception is additionally actively suppressed during eye blinks [Volkmann et al. 1980]. This suppression of visual input begins before the onset of the blink and lasts until after the blink [Volkmann 1986]. Visual awareness is extrapolated across such periods of suppressed visual input such that they are usually not consciously perceived [Bristow et al. 2005].

Eye blinks can be classified as *voluntary* blinks, which occur, for instance, as a means for communication and social interaction, and *involuntary* blinks, which occur in semi-regular intervals without conscious control [Fitzakerley 2015]. Causes for the latter include corneal lubrication, reflexes for the protection of the eyes, e. g., due to sudden or rapid visual motions or proximity [Collins et al. 1989], processing of certain visual stimuli, e. g., bright light [Esteban et al. 2004], vestibulo-palpebral reflexes [Fonarev 1961], blink reflexes during gaze movement [Evinger et al. 1994], and can be learned via eyeblink conditioning [Takehara et al. 2003].

Human eye blinks occur approximately 10–20 times per minute, about every 4–19 seconds [Doughty 2002; Leigh and Zee 2006]. Blink frequency can vary between gender and age and is influenced by the current activity. For instance, Sforza et al. [2008] found that women blink more often than men, and older women more often than younger women. Hall [1945] found differences in blink frequency while reading, and Patel et al. [1991] found that the frequency of blinks is greatly reduced when looking at a computer screen. In contrast, Dennison et al. [2016] observed an increased blink frequency when wearing an HMD compared to a non-immersive computer screen, and they suggested that an increased blink frequency is correlated with and potentially caused by increased visual stress and fatigue in VR.

Overall, this rich body of literature on blinks shows that there is a high number of naturally occurring blinks in VR as well as

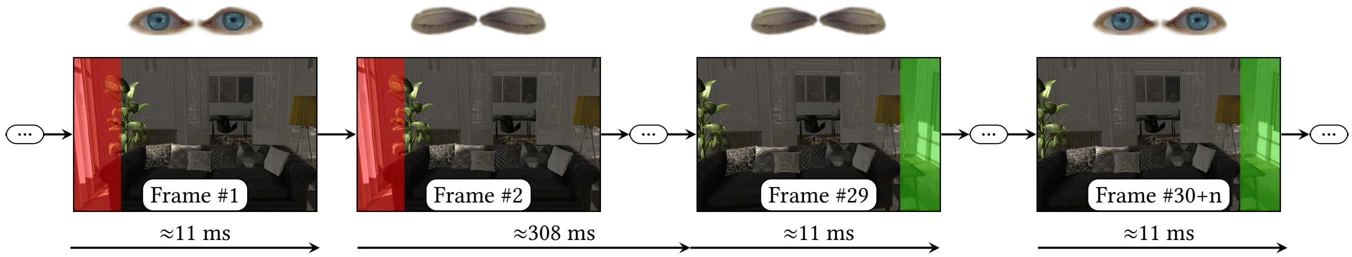


Fig. 2. Illustration of synchronizing the human visual processes with the computer graphics rendering system: On the top, a blink of the user is represented, and below, the frames that are displayed on the HMD are presented. In this illustration, we assume a framerate of 90 frames per second, i. e., one frame lasts approximately 11 ms. When the eyes are closed for at least 300 ms (28 frames ≈ 308 ms), the blink is detected and the virtual viewpoint is rotated around the up-axis. The user might keep the eyes closed a few frames longer. The green areas mark the region that is newly visible after the rotation. The red areas mark the region that is not visible anymore.

the potential to induce additional blinks due to external stimuli if needed. This illustrates the usefulness and potential impact of the techniques introduced in this article.

2.2 Change Blindness

Change blindness denotes the inability of human observers to notice significant changes to visual scenes [Kevin O'Regan et al. 2000], in particular, during brief phases of visual interruptions such as eye blinks or saccades [Rensink 2002; Rensink et al. 1997]. These visual changes can be of various types and magnitudes. Earlier work focused on artificial stimuli, showing that observers often fail to notice the displacement of a prominent line-drawn object on a computer screen if the change occurs during an eye movement [Bridgeman et al. 1994]. More recent studies showed that these effects are even stronger with naturalistic and complex stimuli usually found in the real world, such as when a conversation partner is replaced by a different person [Simons and Levin 1998] or when the walls and doors around us change position [Steinicke et al. 2011; Suma et al. 2010, 2012b]. This counter-intuitive result is of special interest; most people firmly (and erroneously) believe that they would notice such large changes of their surroundings [Levin et al. 2002, 2000].

Change blindness is made possible by a general limitation in the human ability to retain and compare visual information from moment to moment. Early experiments by Rensink et al. [2000] found a clear impact of the duration of visual interruptions (called *inter-stimulus intervals*) between scene changes on detection rates, showing that rates were significantly higher for durations of 40 ms compared to 80 ms and 160 ms. This effect could be explained by a brief lapse in human short-term high-capacity iconic memory [Coltheart 1980; Dick 1974], which includes a fleeting visual representation of the raw sensory input. When the duration of inter-stimulus intervals exceeds the duration for which the scene pertains in iconic memory, the ability to detect differences in successive scenes is reduced [Becker et al. 2000; Persuh et al. 2012].

Additionally to these theories about visual memory, change detection is influenced by oculomotor and suppression mechanisms during eye blinks and saccades. According to current theories, the human visual system uses a built-in prior assumption that the world is stable during eye movements. For instance, the perception of displacements of the scene during a saccade is suppressed or, more precisely, thresholds for the detection of a displacement of the current retinal image are elevated when this displacement occurs during an eye movement [Bridgeman et al. 1975; Niemeier et al. 2003].

In summary, eye blinks are a common and natural cause of change blindness. The limited durations of eye blinks (100–400 ms [Moses 1981; Ramot 2008; Relations 2006]) require exact timing of visual changes to have a significant effect, which can happen in the real world, e. g., causing accidents while driving [Häkkänen et al. 1999], but provide much higher potential in VR as eye blinks can be reliably tracked and registered with computer graphics changes. Moreover, the associated suppression mechanisms indicate large potential in VR as the underlying assumptions of human visual perception do not have to be true in computer graphics virtual worlds.

2.3 Redirected Walking

A large body of literature has been published on the topic of RDW since it has been introduced in 2001 [Razzaque et al. 2001]. Several authors presented review articles [Bruder et al. 2013; Langbehn and Steinicke 2018; Nilsson et al. 2018] and taxonomies [Suma et al. 2012a].

2.3.1 Continuous Manipulations. Steinicke et al. [2010b] introduced *gains* to describe differences between real and virtual motions in RDW. For instance, *rotation gains* g_R are defined as the quotient of the considered component of a virtual rotation R_{virtual} and the real-world rotation R_{real}, i.e., $g_R := \frac{R_{\text{virtual}}}{R_{\text{real}}}$. When a rotation gain g_R is applied to a real-world head rotation with angle α, the virtual camera is rotated by $\alpha \cdot g_R$ instead of α. In a similar way, *translation gains* g_T are defined as the quotient of virtual camera translations T_{virtual} and the tracked real-world head translation T_{real}, i. e., $g_T := \frac{T_{\text{virtual}}}{T_{\text{real}}}$. Moreover, *curvature gains* $g_C := \frac{1}{r}$ are defined by the radius r of the circular path in the real world onto which users are redirected while walking a straight path in the VE. Langbehn et al. [2017] extended these with *bending gains*, which incorporate the bending of a virtual curve as well. Let this curve in the VE be part of a circle with the radius r_{virtual}, bending gains are specified by $g_B := g_C \cdot r_{\text{virtual}} = \frac{r_{\text{virtual}}}{r_{\text{real}}}$.

Multiple researchers identified detection thresholds for these gains in psychophysical experiments. According to Steinicke et al. [2010b], a straight path in the VE can be turned into a circular arc

(a) (b)

Fig. 3. A participant of the experiment wearing the HTC Vive HMD and a hand-controller (inset) and the virtual environment of the experiment, which is an architectural visualization of a living room (a). Inside the HMD, the Pupil Labs eye tracking device was integrated (b). It consists of several infrared LEDs to illuminate the eyes and two cameras to enable stereoscopic tracking.

in the real world with a radius of at least 22m, for which users are not able to consciously detect manipulations. This correlates to unnoticeable rotations of circa 2.6 degrees per meter, i. e., 2.6 degrees per second when assuming a walking speed of 1 meter per second. Furthermore, rotations can be scaled with gains between 0.67 and 1.24 and translations with gains between 0.86 and 1.26, for which users are not able to consciously detect manipulations. These results have been reproduced and extended in several experiments, e. g. [Bruder et al. 2012a; Grechkin et al. 2016; Langbehn et al. 2017; Matsumoto et al. 2016; Neth et al. 2012].

2.3.2 Discrete Manipulations. Instead of inducing continuous rotations or translations as described above, an orthogonal approach is to introduce discrete manipulations by leveraging change blindness as described above. Early work by Wallis and Bulthoff [2000] has indicated that change blindness does not only pertain to changes of objects in the surroundings but can also apply to the observer's own position, orientation, and movement, which suggests applications in RDW. Steinicke et al. [2010a] introduced change blindness techniques for stereoscopic VR systems such as projection systems and HMDs [Steinicke et al. 2011] with a focus on changing the position and appearance of individual objects in the scene, whereas camera motions were not considered. Bruder et al. [2012b] have shown that change blindness can significantly change speed perception in VEs if inter-stimulus intervals are induced by blanking the view for 100 ms. Moreover, Bolte and Lappe [2015] found that saccadic eye movements can mask changes in orientation and position. They investigated the sensitivity to rotations in the transverse plane and forward/backward translations during saccades. They found detection thresholds for rotations of ±5 degrees around the up axis and translations of ±50 cm along the forward axis. Recent work by Sun et al. [2018] leveraged saccadic eye movements to improve RDW with GPU-based path planning algorithms. However, manipulations during saccades impose very high demands on eye trackers with ultra-high performance eye tracking, rendering and display: it is necessary to detect the saccade onset, predict its length, render a new image, display this image, and hope that the saccade has not ended earlier, which requires low-latency gaze data at circa 2000 Hz refresh rate or more. Bolte and Lappe [2015] had to build a research prototype of an electrooculogram to fulfill some of these requirements.

A first attempt to using eye blinks for RDW was done by Ivleva [2016]. Eye blinks are much easier to track than saccades (even with commercial off-the-shelf eye trackers integrated in HMDs), less dependent on refresh rate due to the longer blink durations, less fallible to misclassification of blinks, and useful due to both voluntary and involuntary blinks. In this article, we document that blink-induced suppression is a useful and versatile method for RDW.

3 PSYCHOPHYSICAL EXPERIMENTS

This section describes the experiments we performed to analyze human sensitivity to subtle translations and rotations induced during eye blinks. Both experiments shared a common procedure and a similar setup but they were conducted with different participants.

3.1 Experimental Setup

3.1.1 Hardware and Software. We instructed the participants to wear an HTC Vive HMD (see Figure 3), which provides a resolution of 1080×1200 pixels per eye with an approximately 110° diagonal field of view and a refresh rate of 90 Hz. Positional and rotational tracking was done by a Lighthouse tracking system that is delivered with the HTC Vive. The participants received task instructions on slides presented on the HMD. An HTC Vive controller served as an input device via which the participants provided responses during the experiment.

The VE was rendered using the Unity3D engine 5.5 and showed an architectural visualization of a living room to the participants of the experiment (see Figure 3).

We used an integration of the Pupil Labs eye-tracking device inside the HMD, which includes two 120 Hz infrared cameras and infrared illuminators (see Figure 3). The eye-tracking device was connected to the graphics rendering computer via a USB cable and configured using *Pupil Capture* v0.9.12, the software provided by Pupil Labs. During the experiment, eye and gaze data was sent from Pupil Capture to the Unity3D application permanently via UDP using the Pupil Remote plugin and the Unity3D plugin provided on Github.[1]

3.1.2 Blink Detection. The detection of blinks was implemented in the Unity3D application. In each frame, Pupil Capture provides data about eye and gaze direction, and also a confidence value between 0 and 1 that indicates how likely it is that the eyes were correctly detected. Pupil Labs recommends a confidence value of greater than 0.6.[2] We exploited this confidence interval to detect eye blinks. Based on a pre-test, we identified that if the confidence level was below 0.01 for more than 300ms (see Figure 2), chances were very high that this data was caused by an eye blink. For these values we evaluated the performance of the blink detection and measured 120 blinks from 3 different persons (ages $24 - 36$, $M = 30$, 2 male, 1 female). Participants of this test were instructed to blink consciously. When a blink was detected, a note sign appeared in the VE to inform the participants that this blink was detected. Each time a participant blinked consciously but no sign appeared, the participant reported this and it was counted as a false negative. Each time a sign appeared but the participant did not blink consciously, the participant reported this and it was counted as a false positive. The results show a success rate of 83.3% (100 out of 120) blinks that were correctly detected, which means that 16.7% (20 out of 120) blinks were false negatives. Furthermore, participants reported 8.3% (10 out of 120) false positives.

Hence, the above mentioned values appear to be a good estimate to identify eye blinks and we used those in our experiments to trigger the corresponding action, i. e., manipulation of the scene using translation and rotation. During the experiment, a false positive blink could be reported by pressing a button on the controller. Then, their current trial was repeated later and they continued with the next one. A false negative blink did not disturb the experiment since the participants were instructed to blink again until they get the detection notification.

3.2 Procedure

When participants arrived, they gave their informed consent and were provided with detailed instructions on how to perform the experimental task. The interpupillary distance (IPD) of the participants was measured and they filled out a questionnaire about vision disorders and experience with VR, games, and stereoscopic imagery, as well as the Simulator Sickness Questionnaire (SSQ) [Kennedy et al. 1993].

During the experiment, participants completed several trials one by one (see Sections 3.3.2 and 3.4.2). In each trial, they stood still in the VE and were instructed to blink consciously. When the participants were ready for the next trial (indicated by a button press), the next detected eye blink was used to induce the manipulation. After the detection of a blink the participants' viewpoint in the VE was rotated or translated on one of the three axes (or 3 anatomical planes of the human body): the forward axis (which indicates the viewing direction), the right axis (which is from the left to the right of the participant), and the up axis (which is the inverse gravitation direction).Participants were notified that the blink was detected by a note sign that appeared in the VE in front of them. After two seconds the scene went black and we asked the participants via a slide to indicate in which direction their viewpoint was rotated/translated[3] and offered two possible answers such as "left" or "right", "forward" or "backward", or "up" or "down" depending on the experiment. The two answer options could be chosen by using the touchpad of the controller. Afterwards, the next trial was started.

For each trial, participants saw the VE from a different perspective. Orientations varied between 0 and 350 degrees on the up axis and were chosen by steps of 10 degrees. The position varied between 0 and 10 cm in both directions of the forward or right axis in the transverse plane around a fixed point in the center of the virtual room.

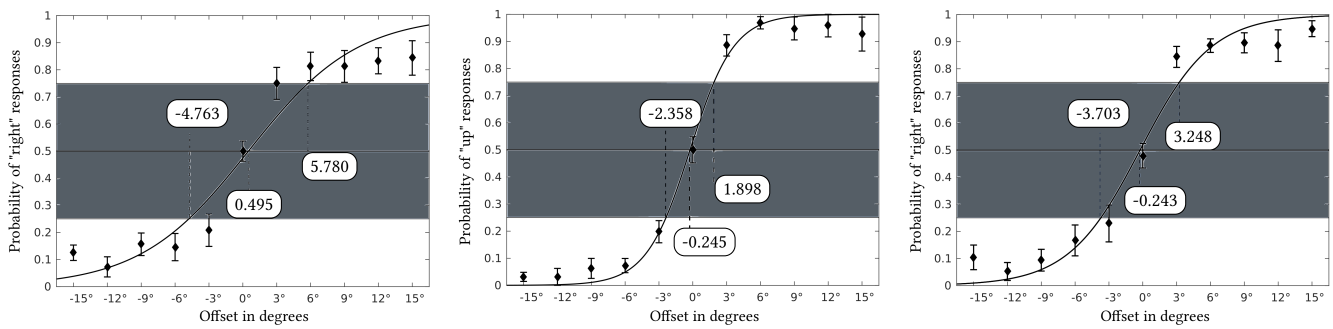
The SSQ was filled out again immediately after the experiment, further the Slater-Usoh-Steed (SUS) presence questionnaire [Usoh et al. 1999b], and a demographics questionnaire. Moreover, we asked the participants if they had used any cognitive strategy to fulfill the task. The total time per participant, including pre-questionnaires, instructions, experiment, breaks, post-questionnaires, and debriefing, was $30 - 45$ minutes. Participants wore the HMD for approximately 25 minutes.

3.2.1 Two-Alternative Forced-Choice Task. To measure the amount of deviation that is unnoticeable, we used a standard psychophysical procedure based on the 2AFC task. This experimental method is a common procedure in RDW research [Steinicke et al. 2010b].

The participants have to choose between one of two answer possibilities, in our case *"left"* and *"right"* for translations on the right axis as well as rotations around the up and forward axis, *"down"* and *"up"* for translations on the up axis as well as rotations around the right axis, and *"backward"* and *"forward"* for translations on the forward axis. Answers like "I don't know" are not allowed. Instead, the participants have to choose one option randomly and will be correct in 50% of the cases on average. The translation/rotation at which the participants respond "left" (or "down" or "backward") in 50% of the trials is taken as the point of subjective equality (PSE), at which the participants estimate the position/orientation before and after the blink as identical. As the translation/rotation decreases or increases from this value the ability of the subject to detect the difference between before and after the blinks increases, resulting in measuring points, through which a psychometric curve will be fitted

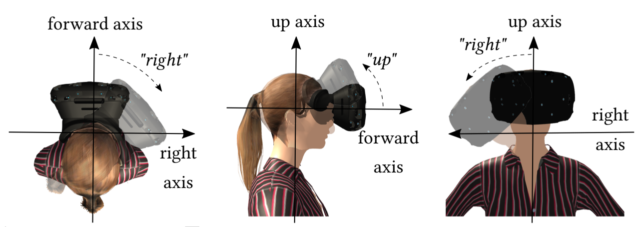
[1] https://github.com/pupil-labs/hmd-eyes
[2] https://docs.pupil-labs.com

[3] This question is equivalent to asking for the direction of the camera manipulation, but pre-tests revealed that it was easier for the participants to judge the manipulation from their egocentric perspective.



(a) (b) (c)

Fig. 4. The results of the detection thresholds experiment for reorientation during blinking. We plotted one function per block: (a) rotations around the up axis (yaw), (b) rotations around the right axis (pitch), and (c) rotations around the forward axis (roll). The PSEs as well as the lower and upper detection thresholds are highlighted in each plot.



(a) (b) (c)

Fig. 5. Rotations that were caried out during blinking: Around (a) the up axis (also known as *yaw*), (b) the right axis (also known as *pitch*), (c) and the forward axis (also known as *roll*). Only rotations with a positive gain (i. e., $\in \{3, 6, 9, 12, 15\}$ degrees) are shown here. Rotations with a negative gain (i. e., $\in \{-3, -6, -9, -12, -15\}$ degrees) are just in the opposite direction. The view direction before blinking is always straight ahead according to the forward axis. Of course, the view direction in the real world stays the same (the user is not moving physically); this figure just clarifies how the view in the virtual world changes.

for the discrimination performance. When the participant's answers converge to 100% respectively the 0% chance level, it is more likely that they can detect the translation/rotation reliably. A threshold is the point of intensity at which participants can just detect a discrepancy between before and after the blink. Since the detection rate is often a smooth and gradual increasing function, in psychophysical experiments, usually the point at which the curve reaches the middle between the chance level and 100% is taken as a threshold. Therefore, we define the detection threshold (DT) for translation/rotation smaller than the PSE to be the translation/rotation at which the participant has 75% probability of choosing the "left" response correctly and the detection threshold for translation/rotation greater than the PSE to be the translation/rotation at which the subject chooses the "left" response in only 25% of the trials (since the correct response "right" was then chosen in 75% of the trials).

3.3 Experiment 1: Reorientation during Eye Blinks

This section describes the first experiment, which we performed to analyze how much rotation of the user's view in VR can be applied during an eye blink without users noticing.

3.3.1 Participants. 16 participants (3 female and 13 male, ages 20–35, $M = 27.06$) completed the experiment. The participants were students or professionals at the local department of computer science, who obtained a monetary compensation for their participation. All of our participants had normal or corrected-to-normal vision. One participant wore glasses during the experiment and two wore contact lenses. None of our participants reported a disorder of equilibrium. No other vision disorders have been reported by our participants. 13 participants had some experience with HMDs before. The experience of the participants with 3D stereoscopic displays (cinema, games etc.) in a range of 1 (no experience) to 5 (much experience) was $M = 2.37$ ($SD = 1.63$). Most of them had some experience with 3D computer games ($M = 2.31$, $SD = 1.58$, in a range of 1 = no experience to 5 = much experience) and they usually played 3.1 hours per week on average ($SD = 3.58$). The body height of the participants varied between 1.55–1.83 m ($M = 1.74$ m, $SD = 0.08$ m). The interpupillary distance (IPD) of the participants varied between 5.9–6.9 cm ($M = 6.23$ cm, $SD = 0.25$ cm).

3.3.2 Material and Methods. We used a 3×11 full-factorial within-subjects experimental design. We had 3 different blocks where we tested rotations on all 3 axes (see Figure 5) and with 11 different offsets $\in \{0, \pm 3, \pm 6, \pm 9, \pm 12, \pm 15\}$ degrees. The order of the blocks was counter-balanced. Each condition was repeated 6 times. All trials were randomized. In total, the participants completed $3 \times 11 \times 6 = 198$ trials. Participants completed 6 training trials before each block. They were allowed to abort the experiment at any time and to take breaks at any time between blocks.

We decided on these offsets after initial tests. It turned out that 15 degrees is such a value that could be detected easily by all of the three subjects of this initial test. Hence, we chose it as the greatest offset. Furthermore, the thresholds Bolte et al. found for saccadic suppression [Bolte and Lappe 2015] are in the middle of our range which supports our choice, too.

For rendering, system control, and logging we used a computer with Intel Xeon 2.4 GHz processor and 16 cores, 32 GB of main memory and two Nvidia Geforce GTX 980 Ti graphics cards.

3.3.3 Results. Figure 4 shows the pooled results over all participants seperated by block: around the up axis (a), the right axis (b), and the forward axis (c).

In each plot, the x-axes show the applied offset in degrees. The y-axes show the probability of the participants' statement that their view was rotated right or up, respectively. For each offset, the mean and standard error bars are displayed. Each plot was fitted with a sigmoidal psychometric function, which determines the PSE and DTs.

The PSE in Figure 4(a) is 0.495, the lower detection threshold is at −4.763 and the upper detection threshold is at 5.780. The PSE in Figure 4(b) is −0.245, the lower detection threshold is at −2.358 and the upper detection threshold is at 1.898. The PSE in Figure 4(c) is −0.243, the lower detection threshold is at −3.703 and the upper detection threshold is at 3.248.

From the psychometric functions a slight bias for all PSEs was determined. In order to compare the found bias to the offset of 0.0, we performed a one sample t-test per PSE, which did not show any significant differences (Plot 4(a): $t = 1.32$, $df = 15$, $p = .21$, Plot 4(b): $t = -1.16$, $df = 15$, $p = .26$, Plot 4(c): $t = -1.28$, $df = 15$, $p = .22$).

We measured a mean SSQ-score of 11.45 ($SD = 9.41$) before the experiment, and a mean SSQ-score of 32.49 ($SD = 27.98$) after the experiment, which indicates a typical increase in VR sickness symptoms for using an HMD for this duration. The mean SUS score for the sense of feeling present in the VE was 4.66 ($SD = 0.3$) on a seven-point Likert scale, which indicates a mid-high sense of presence.

Most of the participants stated that they tried to focus on a certain point or feature in the VE to compare their position before and after blinking.

3.3.4 Discussion. For rotations, our results show detection thresholds of approximately 2–5 degrees. Furthermore, there are differences between the three axes. It appears that rotations around the right axis (pitch) are easier to detect (approximately 2.1 degrees deviation from the PSE) than rotations around the forward axis (roll) (approximately 3.5 degrees deviation from the PSE), and rotations around the up axis (yaw) (approximately 5.3 degrees deviation from the PSE). Rotations around the up axis (yaw) might be more difficult to detect because this is a more natural movement that people are used to do in the real world whereas the other two rotation axes are used less often. Rotations around the up axis are also the most relevant for RDW techniques such as curvature gains.

3.4 Experiment 2: Repositioning during Eye Blinks

This section describes the experiment we performed to determine how much unnoticeable translation of the user's view in VR is possible during an eye blink.

3.4.1 Participants. 16 participants (2 female and 14 male, ages 21–38, $M = 28.25$) completed the experiment. The participants were students, who obtained class credits, or professionals at the local

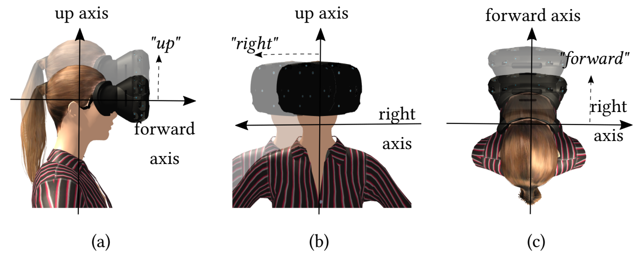


Fig. 6. Translations that were caried out during blinking: On the up axis (a), the right axis (b), and the forward axis (c). Only translations with a positive gain (i. e., $\in \{3, 6, 9, 12, 15\}$ cm) are shown here. Translations with a negative gain (i. e., $\in \{-3, -6, -9, -12, -15\}$ cm) are just to the opposite direction. The view direction before blinking is always straight ahead according to the forward axis. Of course, the view direction in the real world stays the same (the user is not moving physically); this figure just clarifies how the view in the virtual world changes.

department of computer science. All of our participants had normal or corrected-to-normal vision. None of our participants reported a disorder of equilibrium. One of our participants reported an astigmatism (corrected via glasses). No other vision disorders have been reported by our participants. All participants had experienced HMDs before. The experience of the participants with 3D stereoscopic displays (cinema, games etc.) in a range of 1 (no experience) to 5 (much experience) was $M = 3.5$ ($SD = 0.63$). Most of them had experience with 3D computer games ($M = 3.68$, $SD = 0.6$, in a range of 1 = no experience to 5 = much experience) and they usually played 8.6 hours per week on average ($SD = 8.36$). The body height of the participants varied between 1.60–1.85 m ($M = 1.77$ m, $SD = 0.07$ m). The IPD of the participants varied between 5.9–7.6 cm ($M = 6.39$ cm, $SD = 0.43$ cm).

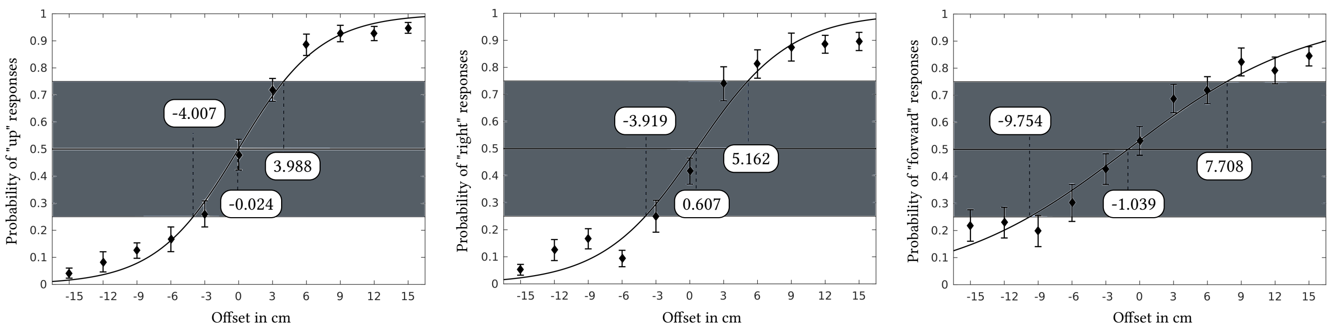
3.4.2 Material and Methods. We used a 3×11 full-factorial within-subjects experimental design. We had 3 different blocks where we tested translations on all 3 axes (see Figure 6) and with 11 different offsets $\in \{0, \pm 3, \pm 6, \pm 9, \pm 12, \pm 15\}$ cm. The order of the blocks was counter-balanced. Each condition was repeated 6 times. All trials were randomized. In total, the participants completed $3 \times 11 \times 6 = 198$ trials. Participants completed 6 training trials before each block. They were allowed to abort the experiment at any time and to take breaks at any time between blocks.

We decided on these offsets after initial tests. The lowest value that could be detected easily by all of the three subjects of this initial test was 15 cm. Hence, we chose it as the greatest offset.

For rendering, system control, and logging we used an Intel computer with 3.5 GHz Core i7 processor, 32 GB of main memory and two Nvidia Geforce GTX 980 graphics cards.

3.4.3 Results. Figure 7 shows the pooled results over all participants seperated by block: on the up axis (a), the right axis (b), and the forward axis (c).

In each plot, the x-axes show the applied offset in cm. The y-axes show the probability of the participants' statement that their view was translated right, up, or forward, respectively. For each offset,



(a) (b) (c)

Fig. 7. The results of the detection thresholds experiment for repositioning during blinking. We plotted one function per block: translations on the up axis (a), translations on the right axis (b), and translations on the forward axis (c). The PSE as well as the lower and upper detection thresholds are highlighted in each plot.

the mean and standard error bars are displayed. Each plot was fitted with a sigmoidal psychometric function.

The PSE in Figure 7(a) is −0.024 cm, the lower detection threshold is at −4.007 cm and the upper detection threshold is at 3.988 cm. The PSE in Figure 7(b) is 0.607 cm, the lower detection threshold is at −3.919 cm and the upper detection threshold is at 5.162 cm. The PSE in Figure 7(c) is −1.039 cm, the lower detection threshold is at −9.754 cm and the upper detection threshold is at 7.708 cm.

From the psychometric functions a slight bias for all PSEs was determined. In order to compare the found bias to the offset of 0.0, we performed a one sample t-test per PSE, which did not show any significant differences (Plot 7(a): $t = -0.2$, $df = 15$, $p = .84$, Plot 7(b): $t = 1.16$, $df = 15$, $p = .26$, Plot 7(c): $t = -1.63$, $df = 15$, $p = .12$).

We measured a mean SSQ-score of 7.01 ($SD = 7.34$) before the experiment, and a mean SSQ-score of 23.38 ($SD = 16.36$) after the experiment, which indicates a similar increase in VR sickness symptoms as in the first experiment. The mean SUS score for the sense of feeling present in the VE was 4.85 ($SD = 0.1$) on a seven-point Likert scale, which indicates a similar sense of presence as in the first experiment.

Again, most of the participants stated that they tried to focus on a certain point or feature in the VE to compare their position before and after blinking.

3.4.4 Discussion. For translations, the results revealed detection thresholds of approximately 4–9 cm. Furthermore, there are differences between the three axes. It appears that translations on the up axis (approximately 4 cm deviation from the PSE) and translations on the right axis (approximately 4.5 cm deviation from the PSE) are easier to detect than translations on the forward axis (approximately 8.7 cm deviation from the PSE). The reason for this might be that we are used to walking forward in viewing direction but a movement to the left or right or up or down is less often carried out. This result does not match exactly the results of Bolte et al., who found a detection threshold of 50 cm for translations on the forward axis during saccades [Bolte and Lappe 2015]. This is likely due to the difference between saccades and blinks and could also be affected by the different hardware, especially the HMD, that was used in the experiments. Furthermore, the VE might have an effect. In our experiment, the number of objects in the VE is greater and the distance from the user to some of these objects is smaller. This leads to stronger cues from the environment and more change in the retinal image. However, we also found the trend that translations on the forward axis are less obvious than on the other axes.

4 APPLICATION FOR REDIRECTED WALKING

In this section, we explain how translations and rotations induced during eye blinks can be used for perceptually-inspired locomotion techniques in VR, and describe a confirmatory study, which shows its feasibility and applicability as a supplement technique for traditional RDW.

4.1 Theoretical Supplement for Redirection Gains

Translations and rotations during unconscious eye blinks could be used to supplement translation, rotation, curvature or bending gains. The idea is that due to these gains additional unnoticeable redirection can be applied, and thus, redirection has potential to become more effective.

Translation Gain. Steinicke et al. found that a 5m virtual distance can be mapped unnoticeably to a physical distance between 3.96 and 5.81 m [Steinicke et al. 2010b]. If we assume an average walking velocity of a user with an HMD of approximately 1.2 m/s [Mohler et al. 2007], we get a total duration of the walk of 3.3 to 4.8 seconds. Again, with one blink every 4 seconds, it appears reasonable to assume that within a 5 m virtual distance, at least one eye blink will occur. This blink can trigger an additional translation of around 0.087 m, which cannot be detected reliably by the user (see Section 3). Hence, we can map a 5 m virtual distance to a physical distance between 3.873 m (i. e., 3.96 − 0.087 m) and 5.897 m (i. e., 5.81 + 0.087 m), which corresponds to an increase of the range of applicable translations by approximately 10 %.

Rotation Gain. Steinicke et al. found that users can be turned physically about 49% more or 20% less than a perceived virtual 90

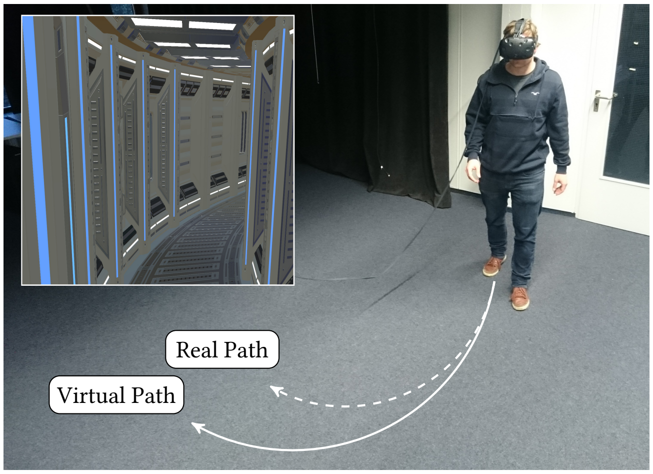


Fig. 8. A user during the confirmatory study: The bending of the virtual corridor (inset) corresponds to the path marked as *virtual path* while the user actually walks a path in the real world that is bent even more.

degrees rotation without noticing the difference. Hence, a 90 degrees virtual rotation can be mapped unnoticeably to a physical rotation between 134 and 72 degrees [Steinicke et al. 2010b]. If we assume 15 blinks per minute, we get approximately one blink every 4 seconds (see Section 1), which might be too low for a rapid head movement. However, it has been shown that saccadic eye movements and rapid head movements tend to be accompanied by blinks [Evinger et al. 1984]. Therefore, it appears reasonable to assume that if users either slowly or rapidly rotate their head by 90 degrees, chances are high that they will probably perform 1 blink [Evinger et al. 1984].

This blink can be exploited to trigger another rotation of around 5 degrees, which cannot be detected reliably by the user (see Section 3). Hence, we could map a 90 degrees virtual rotation to a physical rotation between 139 and 67 degrees, which corresponds to an increase of the range of applicable rotations by more than 16%.

Curvature Gain. Steinicke et al. found that a virtual straight path of 5 m can be mapped unnoticeably to a physical circular path of 5 m with a radius of 22 m [Steinicke et al. 2010b]. If we assume an average walking velocity of a user with an HMD of approximately 1.2 m/s [Mohler et al. 2007], a user would need about 4.16 s to walk a distance of 5 m on the curved radius. Hence, it is reasonable to assume that the user will at least blink once along the 5 m virtual path. Walking 5 m on a circle with a radius of 22 m corresponds to a rotation of 10.43 degrees. The results of our experiment described in Section 3 revealed that a blink can trigger another rotation of around 5 degrees. Such a manipulation would result in a total rotation of approximately 15 degrees after 5 m walking a circular arc, which corresponds to an increase in degrees of more than 43 %, which can be applied without users noticing.

4.2 Confirmatory Study

Section 4.1 describes how the blink-induced translational and rotational redirection can be used to increase the range of unnoticeable gains. However, so far it is still an open question whether or not those additional manipulations can be combined with the traditional RDW techniques. In a confirmatory study, we explored the question if traditional RDW techniques such as the prominent bending gains, can be improved by additional blink-induced rotations as described in Section 4.1.

4.2.1 Materials and Methods. For this confirmatory study, we implemented bending gains [Langbehn et al. 2017] and added our technique of yaw rotations during blinking. We used the setup illustrated in Figure 8. A total of 5 participants (2 female and 3 male, ages 27–38, $M = 30$, experienced VR users from our lab) with normal or corrected-to-normal vision participated in the confirmatory study. The participants were equipped with an HTC Vive HMD and an integrated Pupil Labs eye tracker. The participants were wearing Bose Quiet Comfort 25 headphones. The VE, which was rendered using Unity3D 2017.2, showed a virtual corridor as illustrated in Figure 8 (inset). The participants' task was to walk down the corridor 10 times in a clockwise direction.

We applied a bending gain of 2 to a real-world curve with a radius of 2.5 m. The walking path covered a 4 m distance in total. We used again a typical 2-AFCT method in this confirmatory study. Therefore, we asked the participants to perform a blink while walking when they heard a "beep" sound, which was displayed on their headphones. During the 4 m distance, we displayed this sound twice. When an eye blink was successfully detected afterwards, we randomly applied a yaw rotation of 5 degrees either during the first or second blink, whereas there was no manipulation during the other eye blink. The task of the participants was to identify the blink at which the scene rotation has been performed, i. e., the first or the second blink.

4.2.2 Results. The results show that participants indicated the blink correctly in half of the trials ($M = 5$, $SD = 2,34$). In total, 25 out of 50 answers indicated the blink that hid the rotation. Since we used a 2-AFCT paradigm, this means that the participants were not able to reliably detect the blink at which we added the rotation, and could only guess, resulting in a 50-50 distribution at the chance level. These results confirm that additional blink-induced rotations can be used successfully in concert with traditional RDW techniques such as bending gains, thus validating our approach.

5 GENERAL DISCUSSION

In this section, we discuss our approach, the experimental findings, and their application for RDW and other scenarios.

Our psychophysical experiments (see Section 3) revealed that imperceptible rotations of 2–5 degrees and translations of 4–9 cm of the user's viewpoint are possible during a blink without users noticing. In these experiments, the participants had to blink consciously while wearing an HMD and standing in a VE. Detection thresholds for conscious blinking might be different from natural unconscious blinking. However, during a conscious blink, the participants were more focussed on detecting the changes. Hence, our results provide conservative estimates that might even be relaxed by unconscious blinking, in which the user's attention is on different tasks such as navigation or wayfinding.

Moreover, our results show that translations and rotations during eye blinks are able to support RDW in general due to an orthogonal approach from common techniques in the literature. While the benefits for rotation and translation gains are moderate in the range of 10–20 % (see Section 4.1), major improvements can be gained for curvature gains for which rotations can be increased around 5 degrees, which corresponds to an improvement of approximately 50 % (see Section 4.1). Our confirmatory study validated that participants could not reliably detect in which of two blinks their viewpoint was manipulated while walking a curved path. This result provides again a conservative estimate since blink-induced redirection is independent from walking. Hence, it could be used at lower locomotor speeds, too, when a continuous gain is rather ineffective and a rotation of 2–5 degrees might have much more impact. However, the task during the confirmatory study, i. e., participants blink when they hear a beep, is not really a natural use case scenario. This might limit the results and a revised test in an application scenario might be appropriate.

Of course, our blink-induced masking technique might also be applied for other use cases than RDW. One promising scenario is a novel viewer guidance approach for storytelling in VR, e. g., in immersive games or interactive 360-degree movies, which is a challenging domain since users can freely decide on their own perspective in these environments in contrast to typical movies in which directors define their view [Nielsen et al. 2016; Rothe et al. 2017]. For these new paradigms of narratives, it is necessary to find novel ways of guiding the user's attention to specific regions or objects. Here, a subtle rotation of the virtual camera during a blink could attract the user's attention towards an object of interest in the story.

However, all of the examples presented so far relied on unconscious natural blinking, but redirections during blinking might also be carried out consciously. Intentionally triggering repositioning or reorientation using a hands-free method such as an eye blink can be used in a small physical space, without bulky hardware and has potential to avoid VR sickness symptoms due to blink-masked optic flow [LaViola Jr. 2000]. Since users can consciously blink numerous times per minute without effort, eye blinks provide great potential to be used as intential trigger. Because conscious blinking is required for this kind of repositioning and reorientation anyway, the detection thresholds could be neglected and even greater distances could be covered, which is refered to as *teleportation*.

6 CONCLUSION

Our novel approach of imperceptible repositioning and reorientation in immersive computer-mediated environments during blink-induced visual suppression promises to improve perceptually-inspired locomotion techniques such as RDW significantly. Our psychophysical experiments revealed that users failed to reliably detect translations of approximately 4–9 cm and rotations of approximately 2–5 degrees that are carried out during blinking, which indicates a conservative estimate that might even be relaxed by unconscious natural blinking. Differences in the amount of redirection concern the three different axes. The application of these thresholds in the context of RDW showed an improvement of around 50 %.

For the future, we want to integrate our method into existing RDW algorithms for free exploration. Furthermore, it seems to be very interesting to investigate to which extent it is possible to trigger eye blinks, e.g. by bright light or a virtual mosquito flying towards the eyes. A well established method for this is to send a subtle air surge into the eye [Weidemann et al. 2013]. This way, developers of VR applications could reliably trigger an eye blink when they want to change position or orientation of the user without notice.

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