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Triggering Eye Blinks in Virtual Reality

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Abstract

In Virtual Reality (VR), there is an increasing number of applications that rely on human eye blinks. Blinking induces a phenomenon called change blindness, which prevents people from perceiving changes in their environment. For example, redirection techniques leverage blink-induced change blindness to manipulate the virtual scene in an unnoticeable way. As time is mostly limited for manipulations, current approaches that wait for spontaneous eye blinks are not suitable for redirection techniques. Therefore, researchers have expressed the need for methods that trigger blinks on demand and in a controlled manner.

In the present work, various methods to trigger blinking are explored and discussed for their use in VR. Building on the results of previous research, we selected and implemented four promising methods, which are: light flashes (*Flash)*, a virtual object approaching the user (*Approaching Object*), a blurred screen (*Blur*), and an air puff near the eye (*Airpuff*). The methods are based on blink reflexes, such as the dazzle, menace, or corneal reflex, and are implemented with software and hardware.

We conducted a user study to investigate the performance of the blink triggers and evaluated them regarding their effectiveness, efficiency, reliability, noticeability, distraction, and their impact on the user's performance in a game task. In general, we found significant differences when comparing the blink trigger methods. For example, we discovered that *Approaching Object* triggered the blink most efficiently and reliably, whereas *Airpuff* was the blink trigger perceived as least distracting. We conclude this work with an overview of the advantages and disadvantages of each blink trigger method and make recommendations for suitable application scenarios.

Preface

The research presented in this thesis (i.e. ideas, theories, arguments, concepts, illustrations, tables, results, conclusions, terms) has been submitted in form of a research paper to the *ACM CHI Conference on Human Factors in Computing Systems 2023* Papers Track:

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"Induce a Blink of the Eye: Evaluating Techniques for Triggering Eye Blinks in Virtual Reality"

At the time of submission of this thesis, the research paper is under review.

Contents

Chapter 1
Introduction

1.1 Motivation

Humans experience the world through multiple senses. The sensory organs provide information to our brain that can be processed and interpreted in order to understand and make sense of the environment around us. Senses like vision, hearing, smell, taste, and touch contribute to our perception of the world. Similar to perceiving the real world, Virtual Reality (VR) allows a user to experience and interact with a computer-simulated environment. The goal is to immerse people in the virtual world, i.e., make people believe to be physically present in the virtual environment. Therefore, different senses are stimulated just like in the real world.

The strongest sense is our vision, which is typically experienced through a head-mounted display (HMD) in VR. People are believed to rely more on vision rather than on any other sense [4]. Nevertheless, our visual perception is not as good as we might think. For example, phenomena like change blindness demonstrate the limitations of our visual awareness. Change blindness can be described as the *"inability to detect changes to an object or scene"* [30]. Multiple studies [14, 27, 33] have shown that even large changes can be introduced into a scene without being noticed by the participants. Change blindness can occur due to various reasons. Common causes of change blindness include visual disruptions, such as eye blinks or saccades [30, 33]. Regarding change blindness experiments, eye blinks have some advantages over saccades: they are longer, easier to track, and more likely to be correctly classified than saccades [19, 39].

Change blindness is also leveraged in current VR research to modify a scene without users noticing. Those approaches help to overcome limitations in VR, such as the lack of haptic feedback and contribute to a higher immersion. For example, it is used for techniques like haptic remapping [20], hand redirection [39] or redirected walking (RDW) [19, 23]. RDW is a technique that utilizes scene manipulations to modify the user's walking path and thereby allows real walking in VR [19]. Past experiments on redirection showed that scene rotations during eye blinks are less detectable by participants, and therefore, algorithms like RDW can be significantly improved [19].

Another study examined the combination of blink-induced change blindness and hand redirection [39]. Instead of modifying the user's walking path, hand redirection aims to alter our virtual hand rendering in order to control our real hand movement. By offsetting the virtual hand during blink-induced change blindness, the user does not notice the manipulations, and thereby redirection can be further improved.

Currently, those approaches either instruct the user to blink consciously [19, 39] or wait for spontaneous eye blinks [23]. However, both methods are not suitable for use in redirection applications. First, instructing the participant to blink consciously contradicts the goal of performing manipulations in an unnoticeable manner, and second, spontaneous eye blinks can't be predicted and they might not occur within the short time frame of a redirection. Although blink-based redirection methods sound promising, they are limited by the drawbacks mentioned above. For this reason, we investigate methods to trigger eye blinks in VR and gain more control over the blinking behavior of participants. The goal is to elicit eye blinks on demand, in order to support techniques that take advantage of blink-induced change blindness.

1.2 Research Questions

The bachelor thesis addresses the following research questions:

- **RQ1:** Which methods to trigger eye blinks can be used in Virtual Reality?
- **RQ2:** How do different blink trigger methods compare?
- **RQ3:** What are the advantages and disadvantages of each blink trigger? Which trigger is best suited for which use case?

1.3 Research Approach

The first research question (**RQ1**) aims to explore different methods to trigger blinks in VR. As a basis, research results from previous experiments are used. Although triggering eye blinks has not been studied in VR, it has been investigated in other research fields. For example, medical studies have explored blink reflexes to draw conclusions about diseases [3, 28]. Different methods were used to trigger the blink reflex, such as shining a bright light into the eye or touching the cornea. More recent research has focused on combating symptoms of Computer Vision Syndrome (CVS). CVS causes problems like dry eyes or headaches when looking at a screen for a long time without blinking. To reduce these symptoms, researchers used different blink triggers to initiate blinking and ultimately increase the blink rate [6, 7]. For example, visual blink triggers were displayed on a screen [6], or mechanical triggers were built and integrated into eyeglasses [7]. In the conceptual part of the thesis, we evaluate if the existing methods are also suitable for VR. Some approaches can be well adopted, as they work in both the real and the virtual world. For example, visual blink triggers can be quickly integrated into VR as they can be rendered on the display of the HMD. However, VR also offers new ways to trigger blinking that were previously impossible or difficult to implement in the real world. For example, the HMD enables depth perception in VR, making effects in three-dimensional space possible. Therefore, **RQ1** is also about developing new ideas.

As mentioned before, different applications in VR depend on blinking. For example, redirection experiments leverage eye blinks to execute redirection manipulations unnoticed. Depending on the redirection technique, different requirements for blink triggers arise. In order to narrow down the topic, we have chosen a specific application field for this thesis, namely hand redirection. In hand redirection techniques, the requirements for the blink triggers are very strict. In contrast to increasing the blink rate in general, as this was the case for CVS, we focus on eliciting blinks quickly and with little distraction. Therefore, we must verify whether the methods from existing research meet the requirements for hand redirection techniques.

The second research question (**RQ2**) describes the goal of comparing different blink triggers with each other. For this purpose, we formulated six hypotheses regarding effectiveness, efficiency, reliability, noticeability, distraction, and the impact on the user's performance in a game task.

First, we implemented the blink trigger methods from the conceptual part of the paper. For each blink trigger, we tested different parameters in pilot tests, such as the intensity or duration. We then selected the most promising methods for a subsequent user study and discarded methods that were not convincing. We conducted the user study with 18 participants. The study was designed similarly to a hand redirection experiment. Participants were asked to reach for a virtual object while different blink triggers were presented. During the study, we collected data like the time of eye blinks or the noticeability of a blink trigger, which were either recorded automatically by the system or self-reported by the participants. We then analyzed the results for significant differences and compared the performance of the blink triggers with each other. We also evaluated and discussed the results in terms of our hypotheses.

The third research question (**RQ3**) aims to analyze each blink trigger individually. Based on the results of the study, the advantages and disadvantages of each blink trigger are evaluated, and consequences for the use of blink triggers are derived. Furthermore, regardless of the application field of hand redirection, we outline in which scenarios the blink triggers are most suitable based on their individual performance. For example, blink triggers that quickly trigger blinking can be used well in time-critical scenarios and vice versa. We conclude the paper with our recommendations for application scenarios, which we have summarized in a decision tree to help future researchers and practitioners choose suitable blink triggers.

1.4 Outline

Change blindness is relevant for current research on redirection techniques. The related work in this field will be introduced at the beginning of the second chapter. Subsequently, the physiological process of blinking will be discussed and research approaches that have investigated blink trigger methods in domains other than VR are presented. In the third chapter, the requirements for blink trigger methods regarding hand redirection techniques are explained and various methods to elicit eye blinks in VR are proposed. Afterward, the implementation steps of the soft- and hardware-based triggers are documented in detail. In the fifth chapter, the user study is presented including the hypotheses, the setup, the design, and the procedure of the study. Furthermore, the results of the study are discussed. As this thesis represents a first research approach to triggering blinking in VR, there are many aspects that future work can build on. In the last chapter, those ideas are explained together with the limitations of this work.

Chapter 2
Related Work

This chapter presents relevant research on triggering eye blinks in VR. First, we introduce the topic of change blindness, a phenomenon leveraged in blink-based redirection techniques. Therefore, we present existing research on change blindness in the first part of this chapter and subsequently, we show redirection experiments that use eye blinks to perform manipulations of the virtual environment. Afterward, we review literature on the anatomy and physiology of the eye and provide an overview of different types of blinks. Finally, in the last part of this chapter, we present existing approaches to trigger eye blinks.

2.1 Change Blindness in Virtual Reality

> *"Why can people look at but not always see objects that come into their field of view?"*
> – Rensink, 1997 [27]

In general, people believe to be aware of what is happening in front of them and think to notice if any major change occurs. However, past research has shown that our perception of the environment is not as good as we might think. Multiple studies successfully introduced even large and obvious changes into a scene without being noticed by the participants. The *"inability to detect changes to an object or scene"* [30] is called change blindness. Especially when changes are introduced during visual disruptions, people often fail to detect them. For example, early research found that changes are rarely noticed when they occur during a saccade [14]. Saccades are brief eye movements that occur when we shift our focus from one object to another [35, 37].

While prior experiments used simple visual scenes to apply changes, Grimes [14] investigated this phenomenon by presenting full-color pictures to the participants. Observers were instructed to view images for a later memory test and press a button if they noticed a change in the picture. Changes were only introduced during saccadic eye movement. Results revealed that people very likely failed to detect changes to the scene. Even significant differences were not perceived, although they were apparent when focusing on them.

Another approach to change detection was suggested by Rensink et al. [27] to examine whether change blindness would also occur when the viewer does not move his eyes. They introduced the *flicker paradigm*, in which an original image and a modified image are alternated with a brief blank screen in between (see Figure 2.1). In an experiment, the images were alternated repeatedly until participants noticed the change. The investigation revealed that participants took surprisingly long to detect the difference, even when the change was rather noticeable. The flicker paradigm is closely related to eye blinks, as they both produce short time frames during which the participant cannot see the image.

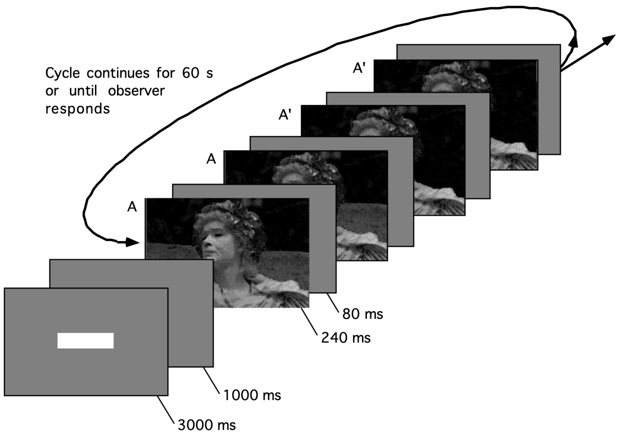


Figure 2.1: General design of the flicker paradigm (image taken from [27], © 1997 American Psychological Society)

Change blindness is also observed in VR. Since VR is experienced through an HMD, it is easy to modify the virtual world by changing the scene on the display. However, the user should not notice the scene changes to maintain a high immersion. Change blindness can be used to alter virtual environments imperceptibly. Steinicke et al. [33] were one of the first who researched the influence of stereoscopic vision on change blindness. They investigated change blindness techniques based on the flicker paradigm and found that change blindness also occurs in stereoscopic viewing conditions, like VR. The findings of Steinicke et al. encouraged more research into this topic.

Subsequent studies investigated change blindness to overcome VR limitations, for example, the lack of haptic feedback. The problem arises from how we perceive the real world. In the real world, objects provide sensory information like surface texture. However, in VR, the sense of touch is missing and consequently, the presence in a virtual environment is decreased.

One solution to this problem is the use of passive haptics, i.e. *"the use of physical props serving as proxies for virtual objects"* [20]. However, with an increasing number of virtual objects, one would need the same amount of physical props, which is no longer feasible at some point. Therefore Lohse et al. [20] introduced an approach called *Change Blindness Haptic Remapping (CBHR)* that allows the user to obtain haptic feedback from multiple virtual objects by re-purposing a single physical prop. In a user study, they leveraged change blindness to realign objects without users noticing. Particularly, the remapping occurred when the user was not looking at the object, i.e. the object was outside the user's field of view. Results revealed that only a few participants detected the remapping of the objects.

A similar approach was proposed by Suma et al. [34] to solve a different problem in VR: constrained physical space. In the real world, people can walk around to explore the environment. In VR, the virtual environment is constrained by the available physical space. Suma et al. proposed a technique that manipulates the geometry of the virtual environment by leveraging change blindness. Particularly, they applied manipulations outside the user's field of view, similar to the approach of Lohse et al. [20]. In an experiment, they investigated whether participants would notice the manipulations. Therefore, they created a virtual environment consisting of multiple rooms connected by a long hallway. The real space, however, was much smaller. Participants were instructed to enter a room and turn on a computer monitor on a desk. This task served as a distraction to unnoticeably change the orientation of the doorways and to realign the hallway behind the user's back. In the end, participants were asked to sketch a rough map of the environment. The drawn sketches were impressively similar to the static model of the virtual environment. Also, only one participant noticed the manipulation.

Overall, the approaches of Lohse et al. [20] and Suma et al. [34] show how change blindness can be successfully used in VR applications to overcome limitations of VR and enhance immersion. However, both approaches require distracting the user to perform the manipulations unnoticeably. This prevents the user from exploring the environment freely. An approach that would solve this problem was proposed by Marwecki et al. [22]. They presented a software system called Mise-Unseen, which applied unnoticeable changes to a virtual scene inside the user's field of view. Gaze data was used to create different models of user attention. They showed that when combining those models with different masking techniques, even changes in plain sight could not be detected by participants.

Another way to take advantage of change blindness without distracting the user is to leverage naturally occurring visual disruptions such as eye blinks or saccades. Sun et al. [35] proposed a technique to redirect the user based on saccades. When a saccade is detected by gaze-tracking, the virtual camera is reoriented. Thereby the user's path is manipulated, simulating larger virtual environments within a smaller physical space (see Figure 2.2). The authors induced additional saccades by subtle gaze direction to further improve this approach. They demonstrated the effectiveness of the approach in simulations and user studies and showed that their technique significantly improves redirected walking in VR.

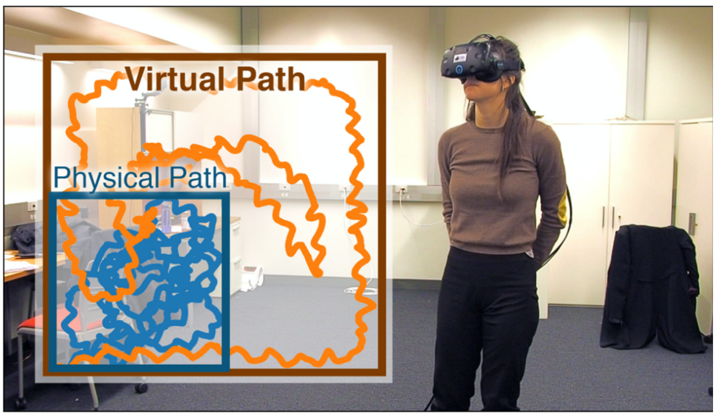


Figure 2.2: Top view of physical and virtual paths (image taken from [35], © 2018 Sun and co-authors)

Although discrete manipulations during saccades show great potential, one disadvantage is the high-performance demands on eye trackers, which require an adequately performing computer system to process, render and display images within a saccade [19]. Eye blinks are easier to track and can even be tracked with commercial eye trackers integrated into some HMDs [19, 39]. Also, they are longer than saccades and more likely to be correctly classified [19, 39]. Langbehn et al. [19] presented a new approach that leverages change blindness during eye blinks to redirect the user in VR. They performed two experiments to investigate thresholds for translational and rotational manipulations of the user's viewpoint. In both experiments, participants were instructed to blink consciously in order to apply the respective manipulation. Afterward, they asked the participants to indicate the direction of the manipulation and identified thresholds based on the findings. They found detection thresholds for rotations of 2-5 degrees and thresholds for translations of 4-9 cm. The results show a promising effect for techniques like RDW. The authors demonstrated a performance improvement of approximately 50% when applying those thresholds compared to traditional RDW.

The findings of the experiment already show great potential for redirected walking scenarios. Detection thresholds could be even higher when

- users are not instructed to blink consciously, e.g., they blink spontaneously or due to a reflex, and therefore do not expect a change to happen [19], or,
- users are walking during the manipulations instead of standing still, and therefore additional head rotations and swaying impede the change detection [23].

Nguyen and Kunz [23] introduced a technique that considered those contributing factors. They performed a user study to derive detection thresholds of blink-induced scene rotations. Since participants should not be aware of applying manipulations, they were told a cover story. Nguyen and Kunz found that detection thresholds are significantly higher when a user blinks (9.1 degrees) than when eyes are open (2.4 degrees). Also, detection thresholds are higher than those found by Langbehn et al. [19], which confirms the initial hypothesis.

Motivated by the findings of those studies, Zenner et al. [39] investigated the effects of blink-induced change blindness on another technique called hand redirection. Hand redirection is related to RDW, but instead of altering the user's walking path, it redirects the user's real hand by manipulating the mapping between the real and the virtual hand. Zenner et al. proposed a new technique called Blink-Suppressed Hand Redirection (BSHR), which is an extension of the body warping algorithm of Cheng et al. [5]. BSHR continuously shifts the hand below detection thresholds and performs an instantaneous shift when the user blinks (see Figure 2.3). They conducted a user study to obtain conservative detection thresholds and found that the thresholds of only blink-suppressed hand redirection are similar to conventional methods. Furthermore, they showed that instantaneous and continuous shifting could further increase detection thresholds.

The studies mentioned above show the relevance of leveraging change blindness in VR. Eye blinks promise to be a reliable cause of change blindness and seem more favorable than saccades. So far, studies that took advantage of blink-induced change blindness either instructed the user to blink consciously or the eye blink happened naturally, which are both not very practical. Hence, researchers mentioned the need to find ways to generate reliable blinks at any time [19, 23]. Therefore, this thesis aims to find reliable blink triggers that could be implemented in such use cases. Some of them already exist and will be discussed in the next section.

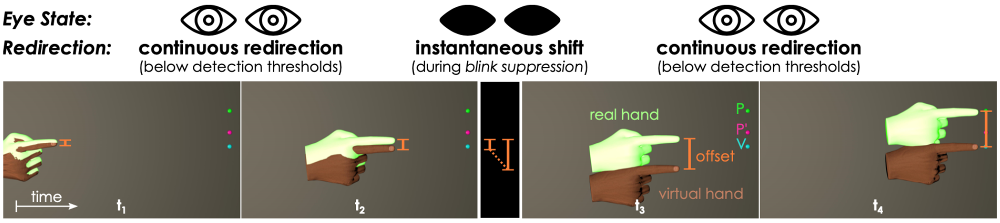


Figure 2.3: Blink-Suppressed Hand Redirection (BSHR) (image taken from [39], © 2021 IEEE)

2.2 Eye Blinks

2.2.1 Eye Anatomy and Physiology

For most people, vision is the dominant information channel. The processing of information by different systems is required to create the visual image. The anatomy of the eye is remarkably complex. The structure of the human eye can be seen in Figure 2.4. The eye consists of multiple components with different functions split into three different layers [16]:

- **External layer:** The external layer consists of the cornea and the sclera. The cornea is a transparent structure responsible for protecting the inside of the eye from foreign bodies and serves to refract the light that enters the eye. The cornea is covered by a thin layer called the tear film. It lubricates the eye and provides a moist environment that prevents it from drying out.
- **Middle layer:** The uveal tract is the middle layer of the eye. It contains the iris, ciliary body, and choroid and serves the nutrition of the eye.
- **Inner layer:** The innermost layer is the retina, which consists of photoreceptors and neural elements. The purpose of the retina is to sense light and create neural impulses sent to the brain.

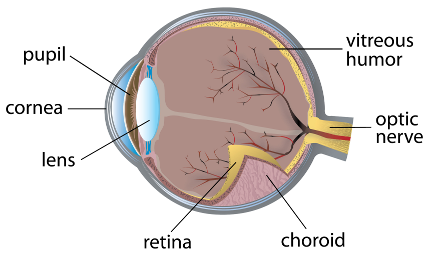


Figure 2.4: The structure of the human eye

Dowling and Dowling Jr. [10] describe how the complex process of seeing works: When we look at an object, the light rays that are reflected from the object enter our eye through the cornea, a transparent structure that serves as a window. The cornea and lens work together to bend and focus the light on the photoreceptor cells of the retina. The cornea is responsible for two-thirds of the focusing power. The goal is to produce a sharp image on the retina from light rays of different distances. The iris regulates the light entering the eye by opening or closing. In the darkness, the circular opening (pupil) of the iris widens; in brightness, the opening becomes smaller. When the light rays hit the retina, the photoreceptor cells absorb the incident light and convert it into nerve signals. There are two different types of photoreceptors: rods and cones. With the rods, we perceive the brightness, and the cones are responsible for sharp and color vision. The nerve signals are sent to the brain, where the visual image is interpreted eventually.

2.2.2 Blinking

Blinking can be described as the rapid closing and opening movements of the eyelids. The following muscles mediate eye movements like blinking: the orbicularis oculi, the levator palpebrae superiors, and the superior tarsal [11].

Eye blinks can be voluntary and involuntary (see Figure 2.5). Contrary to voluntary blinks performed intentionally, involuntary blinks happen unconsciously and mostly without being noticed at all [38]. Two types of involuntary blinks can be distinguished: spontaneous blinks and reflex blinks [1, 11].

Spontaneous blinks are the common form of blinks that account for most of the blinks we perform [1]. Primarily, they protect our eyes from drying out by lubricating the cornea [11]. Spontaneous blinking occurs naturally in frequent intervals, which can variate due to external factors and a person's mental state [2, 9]. The average person blinks approximately 15 times per minute, with each blink lasting about 0.3 to 0.4 seconds [1]. Different studies have shown how various tasks can influence the blink rate. For example, Doughty [9] showed that during a reading task, the blink rate decreased. A reduced blink rate was also reported when spending time in front of a computer screen [12]. However, Dennison et al. [8] reported that the blink rate of participants wearing an HMD increased with immersion time.

In contrast to spontaneous blinking, reflex blinking is triggered by an external stimulus and primarily serves the function of protecting our eyes [21]. A blink reflex produces a rapid and automatic closing of our eyelids without conscious control [21]. Several stimuli can cause a reflex blink, such as a strong light or a loud sound. Section 2.2.4 provides a more detailed overview of different reflexes that cause blinking and how they can be triggered.

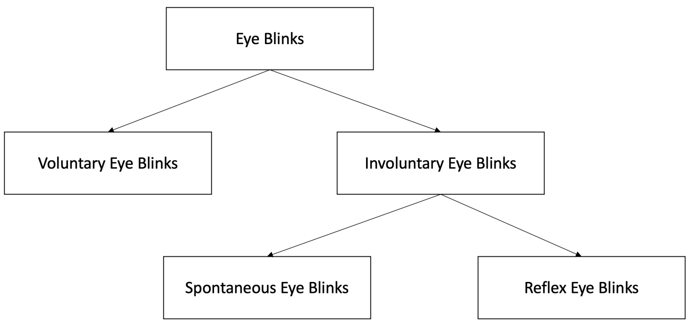


Figure 2.5: Types of eye blinks

2.2.3 Visual Suppression

During blinking, light is prevented from reaching our eyes, *"resulting in a disruption of the image on our retina"* [23]. Although blinking causes a short time frame of visual interruption, our perception of a stable and continuous world is not affected [1, 38]. Moreover, this interruption of vision is rarely noticed in contrast to a similar period of darkening the entire vision [1]. Those facts contribute to the hypothesis that visual perception is actively suppressed during blinking. Volkmann et al. [38] investigated the influence of blinking on our vision by introducing a technique of bypassing the eyelids when illuminating the retina. A study found that visual sensitivity was significantly reduced during blinks, starting shortly before the blink and lasting up until 200*ms* after the blink. Since the light was not interrupted during blinks, they concluded that an inhibitory mechanism in the brain suppressed visual perception. As visual suppression was mainly analysed in voluntary blinks, Manning et al. [21] investigated whether visual suppression also occurs in reflex blinks. They performed an experiment to measure visual sensitivity during a voluntary blink and a reflex blink induced by an air puff. Results indicate no significant difference in the amount of suppression between them.

Overall, eye blinks provide an excellent opportunity to cause change blindness as they go unnoticed due to visual suppression and occur naturally or can be triggered. In the following section, various techniques are discussed to elicit eye blinks.

2.2.4 Blink Reflexes

For decades, researchers investigated blink reflexes. Especially in clinical and physiological research, blink reflexes have seen much interest. For example, they have been triggered to test the functional integrity of afferent and efferent pathways [32]. In case of dysfunction, an abnormal blink reflex can be observed, which in turn can indicate degenerative brain disorders, like Alzheimer's or Parkinson's disease [3, 28]. We explain some of the best-known blink reflexes in more detail below.

- **Corneal Reflex**

  When a foreign object approaches the eye, it will first come in contact with the cornea, which belongs to the outer layer of the eye. By stimulating the free nerve endings in the cornea, tear production is provoked on the one hand, and on the other hand, a reflex blink is elicited [26]. The blink reflex is a natural reaction to touching the cornea to protect the eye from a foreign object. For example, a wisp of cotton can trigger the blink reflex [1]. A stimulation of only one eye will usually cause both eyelids to close [21]. In a study, Rushworth [28] found a latency between 25 and 40*msec*. As the nerve density is very high and the cornea is therefore very sensitive [26], light touches of the cornea are sufficient to trigger the reflex. Several studies successfully triggered the corneal reflex by an air puff stimulus next to the eye [7, 21, 36].

- **Glabellar Reflex**

  The glabella is a region above our nose and between our eyebrows. When the glabella is stimulated, for example, by light tapping, a blink reflex is evoked. Overend [24] first described the reflex in 1896 and called this phenomenon the glabellar tap sign. There are different ways to stimulate the glabellar reflex. In a study by Pearce [25], the examiner continuously touched the glabella with the index finger. In another study by Rushworth [28], the glabellar tap was achieved by tapping a circular metal plate placed over the glabella. In this study, the threshold to elicit the blink was found to be remarkably low, as very light taps on the glabella were sufficient. The reaction of a healthy person is that a blink follows the first few taps. After a few times, the participant gets used to the touches and the blinking stops. However, if the blinking does not stop, this may be an early sign of Parkinsonism [25].

- **Dazzle Reflex**

  The dazzle reflex can be triggered by a bright light directed into the eyes [1, 7, 11, 28]. In everyday life, this can happen, for example, when the sun blinds us. For some people, this also triggers a sneezing reflex [1]. In an experiment, an electronic flash was found to be most effective in activating the blink reflex with a flash duration of only 200 μsec [28].

- **Menace Reflex**

  The menace reflex is triggered by an unexpected or threatening object rapidly approaching the user [1, 11]. The menace reflex causes the eyelids to close to protect the eyes from the object. Other reactions, such as startling or turning the head away, may also occur. The menace reflex occurs in everyday life, for example, when a fly or a snowflake approaches our eye. But it can also be triggered intentionally by moving a hand quickly towards the eye.

- **Acoustic Reflex**

  A loud sound can elicit eye blinks [1, 28]. Säring and Cramon [29] investigated the acoustic blink reflex in a user study. They used white noise as an auditory stimulus with a duration of 50*ms*. They found that the stimulus intensity should be at least 105-110 dB SPL to elicit a blink reliably.

- **Reflex to electrical muscle stimulation**

  An electrical stimulus to the supraorbital nerve (SO) can evoke a blink reflex [28, 36]. Bembenek et al. [3] used this method to investigate whether patients with Wilson's disease have an abnormal blink reflex.

2.3 Research on Triggering Eye Blinks

Techniques to trigger blinks have also been explored for Computer Vision Syndrome, a condition caused by looking at computer displays for a very long time [6]. Blinking can help reduce CVS symptoms, like eyestrain or dry eyes. When spending too much time in front of a computer, the blink rate is reduced [12]. Nowadays, this problem is increasing since we spend more time in front of the screen.

To address the issue of CVS, Crnovrsanin et al. [6] developed a prototype system that triggers eye blinks and increases the blink rate. One of the following stimuli was triggered at a predefined interval:

- Screen flashing: A white screen appears for a short amount of time. An interval of 15*ms* was chosen to be short enough to be not intrusive. The color white was found to be the most effective, but other colors also work.

- Screen blurring: The screen gradually blurs, which should resemble the view of lost focus and thereby evoke a blink by the user to clear the view. The disadvantage is that the user has to blink to remove the blur effect and continue to work on the task.

- Border flashing: The border of the screen flashes until the user blinks.
- Pop-up notification: A pop-up window at the right corner of the screen appears to remind the user to blink.

While screen blurring and screen flashing could evoke a reflex blink, the other stimuli only reminded the user to blink. An experiment was conducted to analyze the stimuli in terms of effectiveness, intrusiveness, satisfaction, response rate, and response time. All four stimuli successfully increased the blink rate. Screen blurring was rated best in all categories except for intrusiveness and response time, where pop-up notification was better. On average, the flash stimulus was rated worst and was often found annoying by the participants. Additionally, based on the high response time of the flash stimulus, the authors conclude that it failed to trick the eye. Finally, they mention that a higher screen size might yield better results. However, the system was only tested on a monitor. Therefore, it is likely that the stimuli are even more effective in VR, where the screen almost fills the entire field of view.

A similar approach to trigger blinks was proposed by Dementyev and Holz [7] to help alleviate symptoms of CVS. Instead of presenting the stimuli on a computer screen, the authors built wearable prototype devices that track the user's blink rate and trigger blinks. The devices are integrated into glasses frames and were designed to be unobtrusive, small, and lightweight. Therefore they are very suitable to be integrated into an HMD as well. Additionally, blink detection is already included in some HMDs. The following actuation modalities were chosen to trigger blinks:

- Flashing a light: An RGB LED light was added to the glasses frame near the eye to trigger the dazzle reflex. The flash interval was the same as in [6] with an interval of 15 ms.

Figure 2.6: Glasses with an LED added to the frame (image taken from [7], © 2017 Dementyev and Holz)

- Physical tapping: Light taps around the eye were produced through a servomotor to trigger the corneal reflex.

Figure 2.7: Glasses with a servomotor added to the frame to produce taps (image taken from [7], © 2017 Dementyev and Holz)

- Air Puffs: The corneal reflex is stimulated by blowing a small air puff towards an area around the eye.

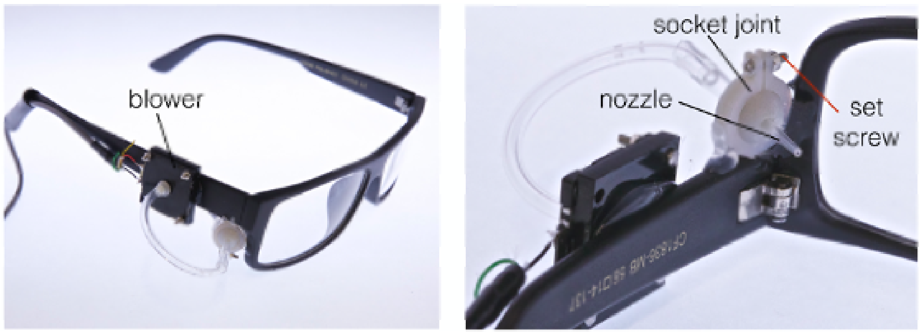


Figure 2.8: Glasses with an air puff construction added to the frame (image taken from [7], © 2017 Dementyev and Holz)

The authors also built other prototypes that were not suitable for the study, though. For example, electrical muscle stimulation was found to be uncomfortable and too invasive. Also, loud sounds could not be integrated well since the user must wear headphones constantly. However, this approach could work for VR as most VR headsets already have headphones integrated to perceive the virtual environment acoustically. The authors conducted a user study to evaluate the effectiveness of their prototypes. Results show that all three actuation methods slightly increased the blink rate, tap and air puffs even by approximately 36% compared to no actuation. Also, air puffs showed the lowest average blink delay after actuation and were most successful in producing blinks. Since the LED did not perform as well as the other modalities, the authors suggest putting the LED in front of the eye and making it brighter to be more effective. In HMDs, the LED could be replaced by screen flashing. Overall, air puffs received the best results, which is why they were further investigated in a follow-up study. This time, three different settings were investigated: location, intensity and duration. The following settings yielded the best results: *"next to the eye, high intensity (24 V), and short duration (75 ms)"* [7].

In conclusion, air puffs yielded the best results. With increasing intensity, the blink amplitude also grows. However, high-intensity air puffs might be perceived as intrusive by the participants. Hoffman and Stitt [17] found that an additional stimulus, such as a light flash or a sound at the same time as an air puff, increases the amplitude by a constant amount. Therefore, lower intensities might be sufficient when simultaneously presented with other stimuli. In general, combining different stimuli could help further increase the effectiveness of blink triggers.

The findings of the studies mentioned above provide valuable insights for the research in this thesis, as they already discussed the advantages and disadvantages of various blink triggers. In the following chapters, some of those methods will be further examined and evaluated for VR applications.

Chapter 3
Concept

In this section, we introduce the concept of blink triggers. First, we present the field of application which we have chosen for this work. The application domain results in specific requirements for blink triggers, which we will discuss in more detail afterward. We then propose various methods to trigger blinking in VR and evaluate whether they meet the requirements. We will also demonstrate the advantages and disadvantages of each method and explain how the blink triggers could be implemented in VR.

3.1 Field of Application

Blink triggers can be utilized for all applications that require blinking at specific times. In particular, there are two techniques in VR that leveraged eye blinks successfully: RDW [19, 23] and hand redirection [39]. Both methods use blinking to manipulate the virtual scene without being noticed by users. While the goal of RDW is to change the user's walking path, the purpose of hand redirection is to control the movement of the user's hand while reaching for an object. Both methods have different requirements. However, the requirements for hand redirection are stricter, especially concerning time. The blink must be elicited before the user touches the object. Since the object is usually within close distance, the time to trigger a blink is limited. Consequently, methods used for hand redirection must work very quickly. We assume that blink triggers that meet the requirements for hand redirection can also be used for other techniques or applications in VR with similar or less stringent requirements. Therefore, we decided to specifically explore blink triggers for hand redirection techniques.

3.2 Blink Trigger Requirements

The following requirements apply to the use of blink triggers in hand redirection techniques:

1. **Elicit blinks quickly**

   Methods used for hand redirection are supposed to elicit eye blinks quickly. The time between the triggering of the blink stimulus and the closing of the eyelids should be as short as possible since common reaching times are usually less than two seconds [13]. In order to perform redirection manipulations successfully, blinking must be evoked within that time.

2. **Work out of the box**

   Another requirement for blink triggers is to work out of the box, which means that users should not have to learn when to blink in advance. For example, in previous experiments, participants were asked to blink whenever a specific visual signal appeared [6]. However, such methods are not very practical for hand redirection techniques because time is limited, and participants should not focus on the occurrence of signals. Therefore, we intend to find approaches that trigger eye blinks automatically.

3. **Work reliably**

   Blink triggers are also supposed to work reliably, i.e., they should successfully elicit an eye blink after a triggered stimulus. This is important for blink-based redirection techniques, as those methods depend on the user's blink. Without blinking, the redirection can't be executed, or the participant may notice the manipulation. Therefore, the probability that the blink will occur after a blink stimulus should be as high as possible.

4. **Be barely noticeable / distracting**

   Hand redirection is usually performed without being noticed by participants. Accordingly, a blink trigger should not be noticed either. So far, this has not been taken into account in experiments. In previous experiments, participants were asked to blink consciously [39], or they were visually prompted to blink [6]. We are therefore looking for blink trigger methods that go unnoticed. For blink triggers that cannot be executed in an unnoticeable way, the goal is to execute them without distracting the user.

3.3 Blink Trigger Methods

Based on the related work and our ideas that emerged during the conceptual phase, we were able to devise different methods for triggering blinking in VR. As already explained in the previous chapter, there are different types of blinking. A distinction is made between voluntary blinking, which includes a conscious decision to close the eyes, and involuntary blinking, which is executed unconsciously (requirement 2 - work out of the box). Involuntary blinking also includes reflexive eye blinks, usually triggered by an external stimulus. Blink reflexes elicit blinking rapidly and are faster than spontaneous blinking [11] (requirement 1 - elicit blinks quickly). Therefore, reflexes are well suited for redirection experiments, especially hand redirection. In the following, we propose different blink trigger methods based on the dazzle, menace, corneal, glabellar, and acoustic reflex.

Eliciting the blink reflex also depends on the setup that is used. HMDs offer a display that covers almost the entire field of vision. Thereby visual effects that were not possible on conventional desktop screens can be applied. In addition, the stereoscopic HMD creates a perception of depth so that three-dimensional effects can be created via software. Furthermore, auditory stimuli can be realized through integrated headphones, which are built into most HMDs. Last but not least, the design of HMDs provides possibilities for attaching external technical components inside and outside the glasses. Based on these properties, we distinguish three categories of blink trigger methods: visual, mechanical, and auditory stimuli. Below, we will briefly describe each blink trigger category and present corresponding blink trigger methods.

3.3.1 Visual Stimuli

Visual blink triggers are based on an optical stimulus. Crnovrsanin et al. [6] have already investigated visual stimuli such as the flash or the blur stimulus in a study. The blink triggers were displayed on an ordinary desktop screen. They assume that the effectiveness of the blink trigger is higher the more area the screen covers in the user's field of view. Therefore, visual blink triggers rendered on the HMD are likely to work well in VR. Besides the flash and the blur stimuli we also propose a new blink trigger method based on the menace reflex.

Flash

The flash blink trigger is based on the dazzle reflex, one of the best-known reflexes that cause blinking. It is triggered by a sudden bright light directed at the eye. It occurs, for example, when we look at the sun or into a flashlight, as shown in Figure 3.1. A flash stimulus can be implemented exclusively via software by making the display light up brightly. Different parameters can be varied to optimize the trigger. According to related work, a short duration at around 15*ms* works particularly well [6]. It also reduces the probability of being noticed by the user. However, the duration is technically limited by the frame rate. Therefore, the shortest possible duration is a single frame. Other parameters that can be varied are the color and brightness of the flash. However, the brightness is also technically limited by the HMD. To compensate for the limited display brightness, we assume that a bright color like white works best to trigger the dazzle reflex. An alternative to the software-based method is using an LED, which could generate a higher brightness. The LED could be mounted next to the eyes inside the HMD so that it does not interfere with the user's view. However, Dementyev and Holz [7] found that the light source should be as central as possible, which contradicts the goal of being unobtrusive. In a first iteration, we implemented both to find the most promising approach for triggering blinks in VR.

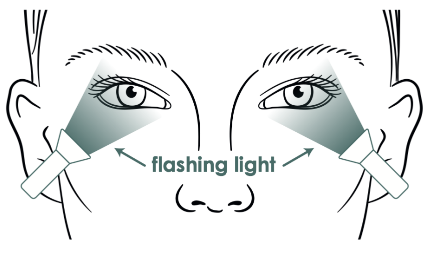


Figure 3.1: Sketch of the flash trigger concept

Blur

The blur stimulus causes our vision to become blurred for a short period of time, illustrated in Figure 3.2. A blurry vision is supposed to resemble the view of lost focus or dry eyes, as seen in patients with CVS. The user consequently blinks to eliminate the blurred view and regain clear vision. In the real world, it would be difficult to simulate this effect. In VR, however, the blur stimulus can be generated easily by software. The HMD amplifies this effect due to the large coverage of the user's field of view. There are different types of blur effects, such as gaussian blur, radial blur, or box blur. For this work, we have chosen the most common blur effect, the gaussian blur, which was also successfully used in the related work [6]. The blur stimulus can be varied in intensity and duration. It is important to ensure that the intensity is high enough to trigger blinking but not too high to be disturbing to users. It is also important to note that a high intensity should be avoided to prevent symptoms of simulator sickness. Since the blur effect takes time to be noticed by users [6], we assume that it is not as fast as other blink triggers. Therefore, similar to the experiment of Crnovrsanin et al. [6], we will not set a time limit for the blur. The blurred screen only disappears when the user blinks.

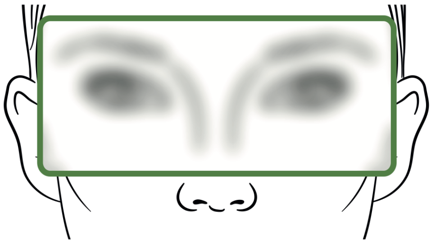


Figure 3.2: Sketch of the blur trigger concept

Approaching Object

This blink trigger is based on the menace reflex, a reflex that is triggered by an object approaching the user rapidly, as can be seen in Figure 3.3. The user gets the impression that the object is moving directly toward the eyes, causing the eyelids to close for protection. This scenario is difficult to replicate for experiments in the real world. We also did not find any related work on experiments using this method. However, VR enables us to realize this approach. The HMD offers stereoscopic vision, which leads to depth perception in virtual space. The optical illusion of a virtual object approaching the eyes can thus be realized. However, it is important to prevent the user gets startled and possibly tries to avoid the object by moving his head. Also, requirement 4 (be barely noticeable) should be considered. To optimize for the requirements, we can adjust different parameters like the object's shape, color, size, or material. In addition, we can vary parameters such as the object's speed or start position. Since we did not have any results from previous studies, we experimented with different parameter values to find suitable settings.

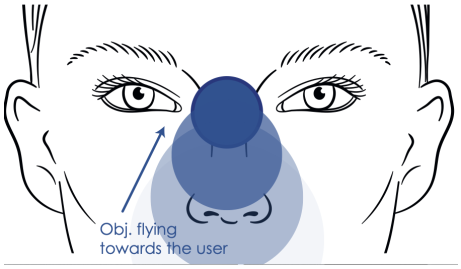


Figure 3.3: Sketch of the approaching object trigger concept

3.3.2 Mechanical Stimuli

Mechanical blink triggers are based on tactile stimuli. They are more complex to implement than software-based blink triggers because external components must be integrated that are not inherently included in the HMD. We will describe three different mechanical blink stimuli in the following.

Air Puff

The air puff blink trigger is based on the corneal reflex. The corneal reflex describes closing the eyelids by external stimulation, such as touching the cornea. It serves to protect the eye from external threats. The reflex is triggered by touching the cornea with an object or a small puff of air directed at a position near the eye. Using air puffs is preferable to an object for several reasons. On the one hand, it has already been proven to work reliably in several studies [7, 21, 36] and thus fulfills requirement 3. On the other hand, it is less intrusive (requirement 4) and runs less risk of injuring the eye. An air puff can be produced using a high-pressure micro blower, which allows a precisely controlled airflow. The micro blower could be either attached to the inside of the HMD or outside of the HMD using an extension tube that blows the air inside. Different settings of the air puff can be adjusted to achieve the best possible effect. For example, the intensity, duration, or position can be set. The air puff should not be directed at the cornea, as this can cause unpleasant irritation, and the eyes can dry out. We should instead choose a position that is close enough to the eye but does not directly hit the eye. Dementyev and Holz [7] investigated the air puff and found that a position next to the eye was most effective in triggering the blink.

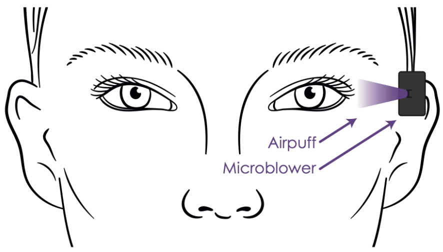


Figure 3.4: Sketch of the air puff trigger concept

Glabellar Tap

The glabellar reflex is triggered by a tap on the glabella, a region above our nose and between our eyebrows. It was found that even light touches are sufficient to trigger blinking [28]. Therefore, the glabellar tap can be used in a way that is barely noticeable to the participants (requirement 4). As the glabellar tap cannot be implemented exclusively via software, additional hardware is required that is built into the HMD. However, it is challenging to integrate the glabellar tap because of the limited space inside the HMD. Usually, the region above the eyes is covered by the HMD's face cushion and offers no space for additional electronics, like a linear motor. Thus, we propose to produce the stimulus by vibration. Vibration motors do not require much space and can be mounted into the face cushion of the HMD. As this approach has not been realized before, we experimented with different setups and parameters. For example, the duration and intensity of the vibration were varied during our tests. In the best case, blinking is also triggered with only slight intensity. Since we expected the glabellar tap to be less noticeable and distracting compared to visual blink triggers, we decided to develop a prototype.

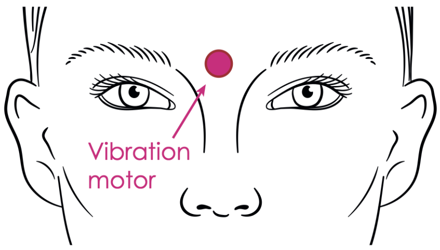


Figure 3.5: Sketch of the glabellar tap trigger concept

Electrical Muscle Stimulation

A blink reflex can be evoked by an electrical stimulus to the supraorbital nerve (SO). This method has already been successfully applied in several medical studies [3, 28, 36]. Dementyev and Holz [7] also attempted to implement this blink trigger. However, they reported that electrodes were uncomfortable to wear. In addition, this approach requires a complex setup and increases the amount of preparation needed to perform the experiment. We decided against using electrical muscle stimulation in this work, as other blink trigger methods are easier to implement and integrate into a VR setup.

3.3.3 Auditory Stimuli

The acoustic blink reflex can be triggered by an auditory stimulus, like a loud sound, which we will explain in more detail below.

Loud Sound

A sudden, loud sound can evoke a startle response including the involuntary closure of the eyelids. It is a reflexive eye blink with a short latency, which was found to be about

70*ms* [29]. The sound can be played either via headphones or external speakers. Many HMDs even have integrated headphones that could play the sound. Various parameters can be changed to optimize this blink trigger method. For example, the sound sample, the length of the sample or the volume can be varied.

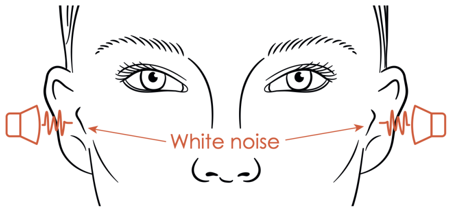


Figure 3.6: Sketch of the loud sound trigger concept

Chapter 4
Implementation

This chapter presents the implementation of the blink triggers and explains the problems encountered during implementation. Before going into the details of each blink trigger individually, we present the technical setup.

4.1 General Technical Setup

4.1.1 Hardware

A Windows 10 system equipped with an Nvidia GTX 1070 graphics card was used for implementation. Regarding the VR system, we have chosen the HTC Vive Pro Eye[1] since it has built-in eye tracking at 120*Hz* with an accuracy of 0.5°–1.1°. Eye tracking is required to detect the user's blinks in order to assess the success of the blink trigger methods. We decided on the WeMos D1 Mini to control the mechanical blink triggers, as it is easy to use, cheap, available and well-documented. The WeMos D1 Mini, depicted in Figure 4.1, is based on the ESP8266 microcontroller.

Figure 4.1: Wemos D1 Mini

[1] `https://www.vive.com/us/product/vive-pro-eye/specs` (last accessed December 1, 2022)

4.1.2 Software

The Unity Game Engine[2] at version 2020.3.6f1 was used to implement the blink triggers. Additionally, we used the following software:

- **SteamVR Unity Plugin**[3]: The plugin was used to manage the HTC Vive HMD and controllers.
- **SRanipal SDK (v1.1.0.1)**[4]: The SDK was used to receive the eye tracking data from the HTC Vive. It offers the two parameters *eye openness* and *pupil diameter*. After some exploration, we found that using the parameter *pupil diameter* (a value between 0 and 1) with a threshold of 0.5 to best detect blinks in our setup.

4.2 Implementation of the Blink Triggers

In the following sections, we present the implementation of the six blink trigger methods that we introduced in the previous chapter. The goal is to derive a set of blink triggers, which can be used for the following user study. To avoid complicating the study, we set the parameters of the blink triggers in advance. Therefore, we tested different settings during implementation in pilot tests and stored the values that worked best and most reliably for a comparative evaluation.

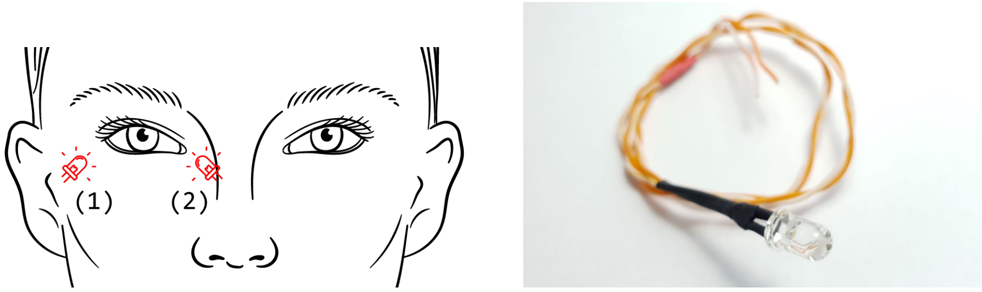
4.2.1 Flash

The flash blink trigger elicits blinking by a short, bright light. We took two approaches to generate the light: (1) incorporating an LED into the HMD and (2) creating a flashing light on the display by software.

LED Flash

A small LED (see Figure 4.2(b)) was controlled using the WeMos D1 Mini to produce a short flashing light. We attached the LED to two different positions inside the HMD (see Figure 4.2(a)) to test which position is better for triggering the blink. However, we could not determine a considerable difference. Therefore, we preferred position (1) as it is not directly in the user's field of view and is less annoying. We have also experimented with different colors. According to previous studies [6, 7], we found that white achieved the best performance in eliciting the blink. Since the LED is brighter than the HMD's display, the blink might be triggered more reliably. However, a higher intensity is also more distracting.

[2] `https://unity.com` (last accessed December 1, 2022)
[3] `https://assetstore.unity.com/packages/tools/integration/steamvr-plugin-32647` (last accessed December 1, 2022)
[4] `https://developer.vive.com/resources/vive-sense/eye-and-facial-tracking-sdk` (last accessed December 1, 2022)



(a) Position of the LED (b) LED

Figure 4.2: LED light to trigger eye blinks

Display Flash

In the second approach, the display flash, we generated a short white screen on the display, as can be seen in Figure 4.3. Technically it was implemented by a software shader in Unity. The shader affects the output of the rendered image as a camera image effect and sets the pixels to the desired color. As described in the previous section, we chose white because it is the brightest color. The advantage of this approach is that the user's entire field of vision is illuminated. According to the concept, we implemented the flash to only last a single frame, which is ca. 11*ms* at 90*fps* for the HTC Vive Pro Eye.

Figure 4.3: Implementation of the flash stimulus in Unity

In our first test runs, both approaches, i.e., the LED and the display flash, were equally able to trigger the blink. We could not detect any large differences between both methods. Since the display flash is easier to implement because it does not require additional hardware, we used a white display flash with a duration of ca. 11*ms* for the following user study.

4.2.2 Blur

This blink trigger is based on the idea of blurring the virtual scene so that users are forced to blink to regain clear vision. The blur effect is implemented only via software in Unity. A shader [5] implementing the gaussian blur is used to change the pixels in the rendered image. We have tested different intensities for the blur. At a blur size of about 0.00065, the display became blurry without being too distracting or causing simulator sickness problems. However, we found the transition between the regular scene and the blurred scene very disruptive, so we let the blur effect gradually build up until it reached maximum intensity. We found a duration of 300*ms* to be suitable for the transition. After building up, the blur remained at maximum intensity until the user blinked (see Figure 4.4).

The blur effect also imposes some requirements on the scene design. With uniformly colored surfaces, the blur is hardly visible. Therefore, it is important to include different lines, patterns, and colors in the design.

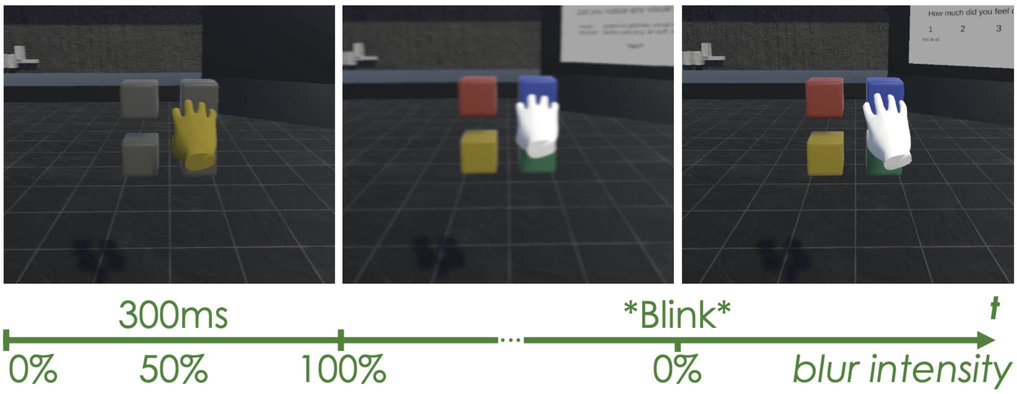


Figure 4.4: Implementation of the blur stimulus in Unity

4.2.3 Approaching Object

We implemented a virtual object that rapidly approaches the user to trigger blinking. It is realized by software in Unity and leverages depth perception in VR. After testing different shapes, colors, sizes, and materials for the object, we found that a black sphere with a diameter of *5cm* achieved the greatest effect while still being perceived as comfortable and not too disturbing. The starting position of the sphere is at a distance of 3*m* in front of the user and 50*cm* below the head. Once the trigger is started, the sphere moves toward the camera in 300*ms*, giving the user the impression that the sphere is approaching directly toward the eyes. In our initial tests, this caused a blink in almost all cases. In Unity, the sphere is instantiated as a child object of the camera, so it always moves toward the user, regardless of the viewing direction. Also, the sphere is always rendered on top of the scene, even if it is initially behind another object because the desired effect can only occur if the object is visible the whole time. Figure 4.5 shows the virtual sphere approaching the camera in Unity.

[5] blur shader based on `https://www.ronja-tutorials.com/post/023-postprocessing-blur` (last accessed December 1, 2022)

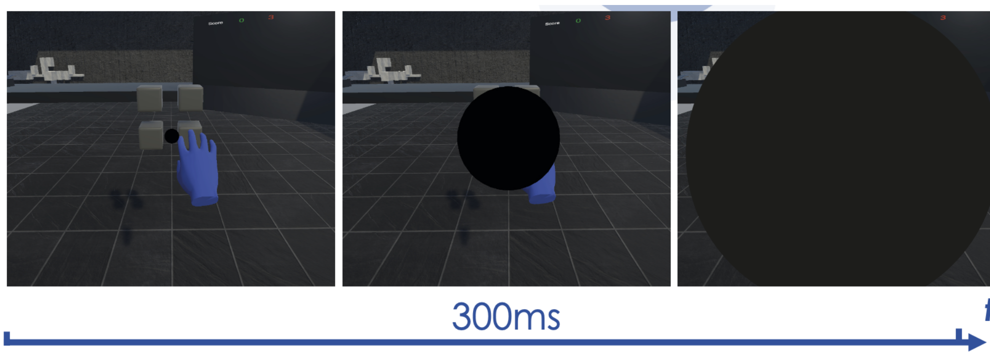


Figure 4.5: Implementation of the approaching object in Unity

4.2.4 Glabellar Tap

The glabellar tap elicits blinking by touching the region above our nose and between our eyebrows. As described in the previous chapter, we decided to implement the glabellar tap with a small vibration motor due to limited space inside the HMD. We used the *Seeed Studio Mini Vibration Motor*. As the driver for the motor, we used the Adafruit DRV2605L Haptic Motor Controller, which was controlled by the *Wemos D1 Mini*. As depicted in Figure 4.6, we integrated the vibration motor into the face cushion of the HMD by first gluing the motor to a small wooden board for stabilization and subsequently attaching it to a central position of the cushion. Afterward, we tested different parameters for the vibration. The driver's manufacturer provides a library with over 120 patterns [6], which differ in intensity, duration, and frequency of the vibration. Overall, we found that patterns with high intensity and long duration were most successful in eliciting blinks. Unfortunately, however, blinks occurred only sporadically, and none of the patterns achieved a reliable performance. Due to the poor outcome of our initial testing, we decided not to investigate this blink trigger further and not to consider it for the study.

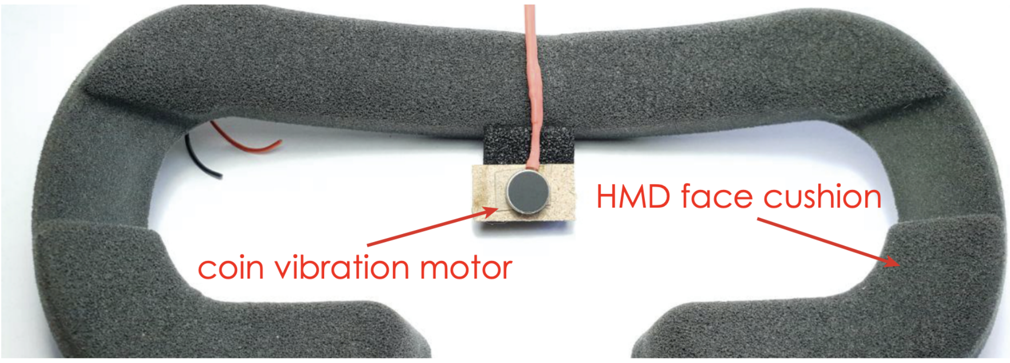


Figure 4.6: Implementation of the glabellar tap stimulus

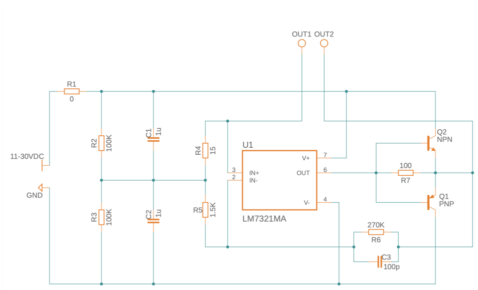
[6] `https://github.com/adafruit/Adafruit_DRV2605_Library` (last accessed December 1, 2022)

4.2.5 Air Puff

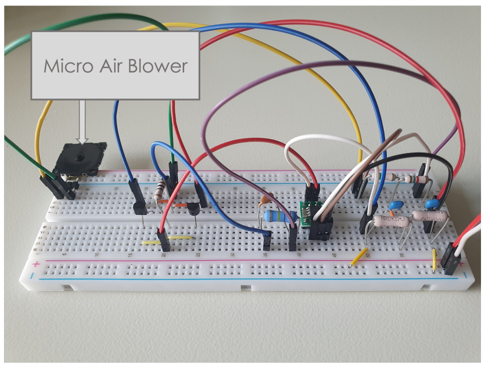
The air puff blink trigger evokes blinking by triggering the corneal reflex. It requires an external air blower device to be integrated into the HMD. Implementing this blink trigger was technically the most challenging compared to the other blink trigger methods. We have therefore built several prototypes. The individual implementation steps are explained in more detail below.

First Prototype

First, we had to decide on a suitable air blower device. Since Dementyev and Holz [7] successfully generated the blink by an air puff in a similar study, we decided to use the same device, namely the *Micro Air Blower (MZB1001T02)* from Murata. According to Dementyev and Holz [7], the device generates enough air pressure to trigger the blink. However, the micro blower cannot be powered by standard direct current but requires a special circuit, which is illustrated in Figure 4.7 (a). We first rebuilt the assembly on a breadboard, as shown in Figure 4.7 (b), to detect and fix errors quickly. We then connected the breadboard to a power source to get steady air pressure from the air blower.



(a) Driver circuit of the micro blower based on the Murata datasheet [7]



(b) First prototype of the air puff on a breadboard

Figure 4.7: Circuit and implementation of the first prototype for the air puff

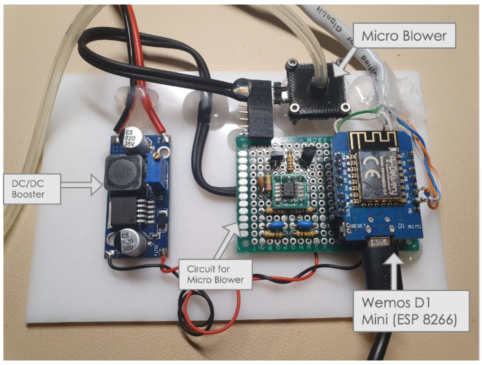
Second Prototype

Next, we further developed the prototype and integrated it into the VR setup. To generate the maximum air pressure, we took two approaches. First, we connected the air blower to a silicone tube and attached a 3D-printed nozzle (see Figure 4.8 (b)). The nozzle compresses the air at the end of the tube and thus generates a higher air pressure. Also, the air puff can thereby be positioned more accurately. Second, we connected the circuit to a DC-DC booster to generate a higher voltage out of the applied 12V/2A power supply,

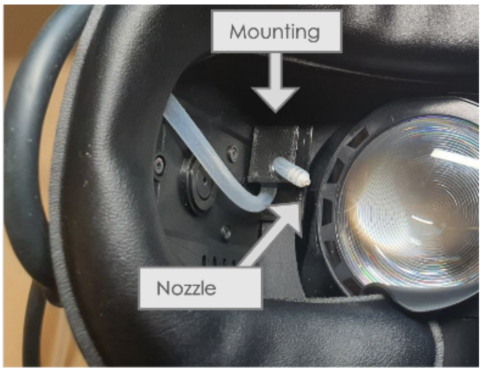
[7] `https://www.mouser.de/datasheet/2/281/murata_10072019_2019_MZB1001T02_datasheet-1660169.pdf` (last accessed December 1, 2022)

as the micro blower can operate up to 24V. However, we found that at about 20V, the highest air pressure was reached. Therefore, we used this voltage for the following tests.

For the second prototype, we used a soldering board and soldered the components onto it (see Figure 4.8 (a)). The silicone tube, attached to the air blower at one end, leads under the face cushion into the HMD with the help of a 3D printed mounting part, depicted in Figure 4.8 (b). To position the tube even more precisely, we inserted a wire into the tube so that it could be fixed in any position.



(a) Soldering board for the electronics

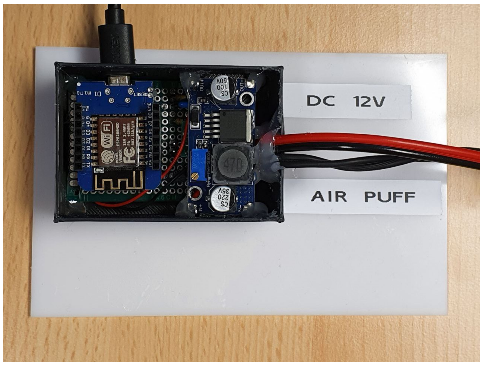


(b) Integration of the air puff into the HMD

Figure 4.8: Implementation of the second prototype of the air puff

Third Prototype

As described in the previous chapter, the positioning of the air puff is crucial. Following the results of Dementyev and Holz [7], we directed the air puff to an area lateral to the eye. We examined the performance of the air puff in a pilot test. However, the blink could not be triggered reliably. We identified insufficient air pressure as one potential reason. On the technical side, the micro blower was already set to maximum output using the DC booster. So we tried to minimize possible component interference. Therefore, we omitted the silicone tube in a third prototype and installed the air blower device directly into the HMD. We extended the cables accordingly and used plasticine to fix the micro blower inside the HMD. This enabled us to manually adjust the position in order to account for the different head shapes of participants. In the user study, we ensured that the air puff was positioned individually for each user. We tested the air puff with the same duration (300*ms*) used for the approaching object and blur and found that this duration works well in eliciting blinks. Figure 4.9 shows the final prototype of the air puff implementation, consisting of the electronic components (a) and the micro blower built into the HMD (b).



(a) Electronics for the final air puff prototype

(b) Integration of the micro blower into the HMD

Figure 4.9: Implementation of the third prototype of the air puff

4.2.6 Loud Sound

We tried to trigger the acoustic blink reflex with a loud sound. For this, we played different sound samples over the headphones of the HMD (see Figure 4.10) and tested different settings regarding the length of the sample and the volume. We found that white noise and a short sound signal were perceived most intensively. However, in line with previous research, we also found that the volume had to be very high to elicit an eye blink [7, 29]. But still with such settings, the implementation in our setup did not reliably elicit a blink. Thus, this blink trigger violated requirement 3 (work reliably) and requirement 4 (be barely noticeable and not distracting) and we decided against using it for this work.

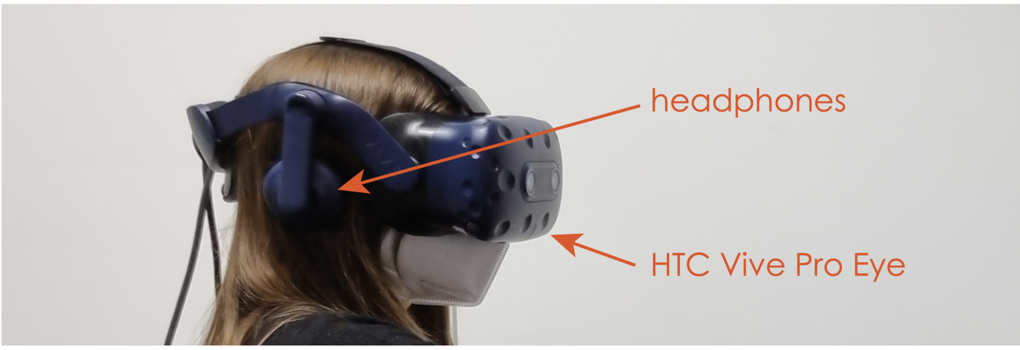


Figure 4.10: Loud sound played over the headphones of the HMD

4.3 Overview

The following table (see Figure 4.11) gives an overview of the blink trigger methods we implemented and the parameters that we found to work best. Based on the findings of previous research and our initial testing, we excluded electrical muscle stimulation, glabellar tap, and the sound trigger for the study, as they have not achieved sufficient performance. In the following, we will therefore focus on the blink triggers flash, blur, approaching object, and air puff. We have published the source code of these blink triggers in an open-source repository on GitHub [8].

Blink Trigger (Reflex)	**Category**	**Description**	**Parameter**
Flash (dazzle reflex)	visual stimuli (software)	short, bright light	• *color*: white • *duration*: 1 frame (ca. 11ms)
Blur (blur reflex)	visual stimuli (software)	blurry vision	• *intensity*: 0.0065 (blur size) • *duration*: 300ms
Approaching Object (menace reflex)	visual stimuli (software)	object rapidly approaching the eye	• *shape*: sphere • *color*: black • *size*: 5cm diameter • *distance*: 3m in front • *duration*: 300ms
Airpuff (corneal reflex)	mechanical stimuli (hardware)	air blowing next to the eye	• *intensity*: 20V • *duration*: 300ms • *location*: next to the eye

Figure 4.11: Overview of blink trigger methods and their parameters

[8] `https://github.com/AndreZenner/VR-blink-triggers` (last accessed December 1, 2022)

Chapter 5
User Study

We conducted a user study to assess the performance of the four blink trigger methods flash, blur, approaching object, and air puff in VR. The study was designed similarly to a hand redirection experiment where participants are asked to touch virtual objects. In our study, the virtual objects were four colored cubes that were part of a simple mini-game that the participants played during the study. While participants reached for the cubes, either one of the four blink trigger methods was activated or no trigger was applied, which corresponded to our baseline condition. However, in contrast to an actual redirection experiment, we did not apply redirection because we only wanted to investigate the performance of the blink triggers and eliminate other influences on the results.

In the following sections, the design and procedure of the study are explained in more detail, and the results and subsequent discussion are presented.

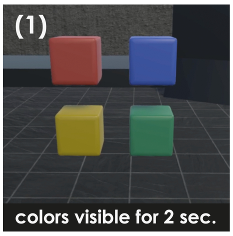
5.1 Participants

For the user study, we recruited N = 18 participants from the Saarland University and the DFKI (Deutsches Forschungszentrum für Künstliche Intelligenz). 11 were male, and 7 were female. Their average age was 26.5 (min. 18, max. 40). All participants were right-handed. 72% of the participants had a background in computer science or media informatics. The prerequisite for participation in the study was that the participants did not wear glasses or contact lenses and had no visual impairment (e.g. color blindness). Two participants stated that they wear glasses from time to time, but they reported that they could see normal without glasses and could therefore participate in the study without impairment. We also asked participants how often they use virtual reality. 4 participants stated they had not used virtual reality yet, 4 participants have used it once, 4 participants use it once in a while, 5 participants use it regularly, and 1 participant uses virtual reality daily.

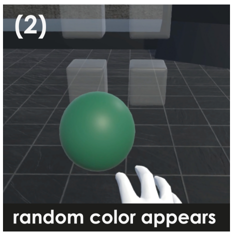
5.2 Task

Before conducting the study, we tried various approaches to investigate the blink triggers on participants. We found that participants who focused exclusively on the blink triggers showed very restricted blink behavior and might have suppressed the blink reflex, in contrast to participants who did not mentally focus on the triggers. Therefore, we decided to include a simple mini-game in the study that participants had to focus on.

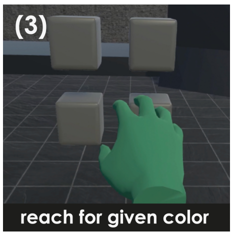
Before a trial started, participants saw four gray cubes in the middle of the virtual room and their virtual hand that they could navigate by moving the VR controller. Each of the trials ran as follows:



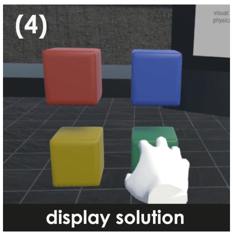
STEP 1
At the beginning of a trial, the four cubes appeared randomly in the colors red, blue, green, and yellow. After 2 seconds, they turned gray again. It was the participants' task to memorize the cubes' colors.



STEP 2
In the next step, a sphere appeared in front of the participant at a distance of 30cm, randomly displaying one of the four colors.



STEP 3
The participant then reached into the sphere with the virtual hand until the virtual hand adopted the color of the sphere. Then the participant tried to remember which of the four cubes appeared in this color and moved the hand toward this cube.



STEP 4
As soon as the participant touched the cube, the solution appeared - all four cubes reappeared in their original color. If the correct cube was touched, the participant would receive a point. The game score was displayed on a virtual canvas during the study.

5.3 Setup

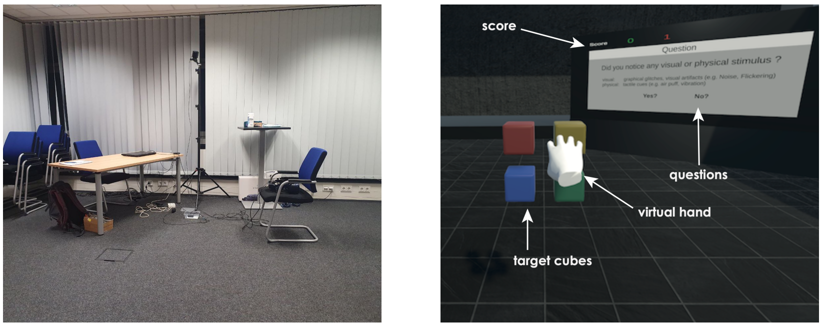
The study took place in a lab room at the DFKI. During the experiment, the participant sat on a chair in the center of the room, as shown in Figure 5.1 (a), and wore an HTC Vive

Pro Eye HMD. Participants also interacted with an HTC Vive controller to play the game and answer the questionnaires.

The study was implemented using the Unity game engine [9] (v2020.3.6f1) and ran on a laptop with Windows 10 and an Nvidia GTX 1070 graphics card. Analogous to the software of the blink triggers, the SRanipal SDK (v1.1.0.1) and the SteamVR Unity plugin were used. Additionally, we utilized the following software:

- **Unity Experiment Framework (UXF)** [10]: The framework was used to manage the user study and collect and store all data generated during the study.
- **VRQuestionnaireToolkit** [11]: The toolkit was used to conduct questionnaires in VR and store the results digitally.

In Figure 5.1 (b), the virtual room can be seen from a participant's point of view. Participants saw their virtual white hand, which they could navigate using the VR controller, four colored cubes, and a virtual canvas that displayed instructions. The room was designed in the style of a factory hall and was kept very neutral and simple overall so that the participants would not be distracted. Only minor changes were made to the room to make the blink triggers work as well as possible. For example, the floor was chosen to have a checkered pattern so that the blur effect would be more visible. Also, using gray as a color for the walls and the floor helped the flash effect to be more visible and intense.



(a) Experiment room (b) Virtual Environment

Figure 5.1: Experiment room in the real and virtual world

5.4 Procedure

The participant was welcomed to the study and asked to read and sign the *Consent Form*, which included information about the study procedure and privacy policy. It was also confirmed that the current rules regarding Covid-19 were followed.

Afterward, the study procedure was explained and the VR setup was briefly discussed. Before the start of the study, the eye tracking and the air puff had to be calibrated to

[9] `https://unity.com` (last accessed December 1, 2022)
[10] `https://github.com/immersivecognition/unity-experiment-framework` (last accessed December 1, 2022)
[11] `https://github.com/MartinFk/VRQuestionnaireToolkit` (last accessed December 1, 2022)

account for the different head shapes of the participants. First, the experimenter guided the participant through the eye tracking calibration setup of the HTC Vive Pro Eye. The setup was repeated until optimal tracking of blinking could be ensured. After that, the micro blower was tested by triggering the air puff several times. Based on the participant's feedback, the experimenter manually moved the micro blower inside the HMD until the correct position was reached. Calibration was performed first with eyes closed and then with eyes open to avoid any injury to the eye. Once everything was set up correctly, the participant was asked to put on the headphones of the HMD, which were used to play white noise during the study to prevent the user from hearing the air puff. Afterward, the participant was given time to familiarize with the game. A total of 5 practicing trials were played in which none of the blink triggers were triggered. Then the actual experiment started, and the data recording began. The participant completed 140 trials that took place one after the other, i.e. 140 rounds of the game. In each trial, the participant had to reach the target cubes at a distance of about $40cm$, as seen in Figure 5.2. During the reaching movement, a blink trigger was activated as soon as the participant had reached 30% of the distance. When the eye tracking detected a blink, the time of the blink was stored, and the response time was calculated.

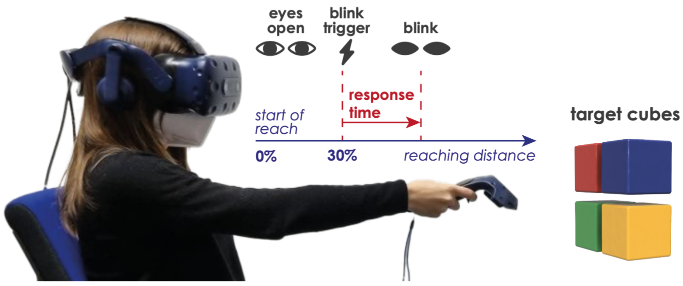


Figure 5.2: Concept of the study procedure

As soon as the participant reached the target cubes, two questions appeared on the virtual canvas:

- "Did you notice any visual or physical stimulus?" - the participant could either answer with *yes* or *no*
- "How much did you feel distracted by a stimulus?" - the participant could answer a value between 1 (not at all) and 5 (very)

Participants gave the answers verbally to the experimenter, who stored the values in the system.

After all 140 trials were completed, the participants were asked to fill out three questionnaires in VR. The first questionnaire, the SUS presence questionnaire [31], was used to measure presence in VR. The second questionnaire, the Simulator Sickness Questionnaire (SSQ) [18] helped to investigate issues regarding simulator sickness. The last questionnaire was the NASA TLX Questionnaire [15], which indicates the perceived workload.

Participants were then asked to take off the HMD and fill out a demographic questionnaire on paper. All questionnaires can be found in the Appendix.

5.5 Design

We opted for a within-subject design for the user study, i.e., each participant tests all conditions. The conditions (**independent variables**) of the study correspond to the four blink trigger methods *Flash*, *Blur*, *Approaching Object*, *Airpuff* and a *Baseline* condition. In the *Baseline* condition, time was measured analogously to the triggers, but no trigger was activated.

During our experiment, we measured the following **dependent variables** :

- *response time* - the time between triggering a stimulus and capturing an eye blink (in *ms*)
- *noticeability* - participants answered the question “Did you notice any visual or physical stimulus?” (true or false)
- *distraction* - participants answered the question “How much did you feel distracted by a stimulus?” (scale 1-5, 1: not at all, 5: very)
- *reaching time* - the time it takes participants to reach out their hand and grab a target 40*cm* away (in *ms*)
- *game result* - choice of the correct cube (true or false)

In total, participants completed 140 trials. Each of the blink trigger methods *Flash*, *Blur*, *Approaching Object*, and *Airpuff* was activated in 12 random trials, resulting in 48 trials with a blink trigger. In the remaining 92 trials, no blink trigger was activated, which was our *Baseline* condition. By having a high number of *Baseline* trials and randomizing the order of trials, we wanted to ensure that there were no learning effects and that participants did not expect the blink triggers.
Also, it was necessary for the study that participants did not know the aim of the study so that they would not consciously pay attention to blinking and thereby bias the results. Instead, participants were told that the experiment aimed to investigate how visual and physical stimuli affect people while immersed in VR.

5.6 Metrics

To evaluate the performance of the blink triggers, we used the following metrics:

- **blink response time (in seconds):** average time that elapsed between the start of the blink trigger and the eye blink
- **blink response rate (within average reaching time, 1s, 2s):** percentage of trials in which there was at least one blink within the *average reaching time*, *one second* and *two seconds* (these are typical time intervals for redirection experiments and desktop-scale reaching [13])
- **trigger distraction**: as how annoying the blink trigger was perceived on average
- **trigger noticeability**: percentage of trials the blink trigger was noticed
- **game performance**: percentage of correctly selected cubes in the game

5.7 Hypotheses

We derived the following hypotheses based on the related work and the findings we obtained from the initial testing of the blink triggers.

- **H1 - Effectiveness:** Each blink trigger is able to effectively trigger a blink, in the sense that it has a shorter *blink response time* than the *Baseline* condition.

  In a similar, non-VR setting, the effectiveness of the blink triggers blur and flash was shown by Crnovrsanin et al. [6], as they found a higher blink rate for the stimulus conditions over the non-stimulus conditions. The effectiveness of the air puff stimulus has been demonstrated by Dementyev and Holz [7] by showing a lower response time for the air puff stimulus compared to a baseline condition.

- **H2 - Efficiency:** Blink triggers differ in their efficiency, which is measured by comparing the *blink response time*. We assume the following order, from the lowest response time (fastest and most efficient blink trigger) to the highest response time (slowest and least efficient blink trigger): *Airpuff* < *Flash* < *Approaching Object* < *Blur*.

  Following the results of related work [6, 7], it can be expected that the air puff stimulus has the lowest response time and thus works the fastest, followed by the flash and blur stimuli. The high response time for the blur stimulus is partly due to the time it takes for the blur effect to build up. In addition, it does not trigger an immediate blink reflex, which is why we expected that the approaching object stimulus triggers the blink faster.

- **H3 - Reliability:** Each blink trigger reliably initiates the blink within common desktop-scale reaching times (*average reaching time*, 1s or 2s), i.e. the *blink response rate* for the blink trigger is higher than for the *Baseline* condition.

  The response rates for the blink triggers air puff, flash, and blur have been investigated in previous experiments [6, 7]. However, they used different time limits. E.g., the air puff stimulus had a significantly better response rate than the baseline condition within a time limit of two seconds [7]. Based on the reported response times [6, 7], we expect similar results for all blink triggers, even within the *average reaching time*.

- **H4 - Noticeability:** Blink triggers differ in their noticeability, measured by comparing the *trigger noticeability*. We assume that *Blur* is least noticeable.

  In previous experiments, no results have been published on the noticeability of blink triggers. We assume that participants might not notice triggers in some trials because they are short or not strong enough. After some initial tests, the blur trigger has been found to be least noticeable. Therefore, we assume that it has the lowest *trigger noticeability*.

- **H5 - Distraction:** Blink triggers differ in their degree of distraction, measured by comparing the *trigger distraction*. We expect the following order, from the lowest distraction value to the highest distraction value: *Blur* < *Airpuff* < *Flash* < *Approaching Object*.

  Crnovrsanin et al. [6] investigated obtrusiveness by asking participants to rate the blink triggers and found that the flash stimulus was more obtrusive than the blur stimulus. Also, we expected mechanical blink triggers like the air puff to be less distracting than visual blink triggers because they do not interfere with the user's view. However, as we believe blur to be the least noticeable blink trigger we also think that it is the least distracting stimulus.

- **H6 - Reduced Performance:** Blink triggers could have a negative impact on participants' game performance. We expected that the *game performance* of the conditions with blink triggers is worse than in the *Baseline* condition.

  We expected some blink triggers to distract participants (**H5**). Therefore, we concluded that participants will concentrate less on the game in these trials and thus have a worse game score than in trials in which no blink triggers are used.

5.8 Results

We measured the performance of the blink triggers using the following metrics: *blink response time*, *blink response rate (within average reaching time, 1s, 2s)*, *trigger distraction*, *trigger noticeability* and *game performance*. First, we cleaned the collected data by sorting out trials in which no blinks were detected between two consecutive trials. We then conducted an analysis of the data and evaluated the questionnaires.

5.8.1 Data Cleaning

In a few trials (70 out of 2520), no blinks were recorded before the next trial started. This may be due to a lack of blink detection by the eye tracking system. We have therefore cleaned the data and removed those trials for data analysis.

This concerns 61 out of 1656 Baseline trials (3.68%), 2 out of 216 *Approaching Object* trials (0.93%), 2 out of 216 *Airpuff* trials (0.93%), 2 out of 216 *Blur* trials (0.93%), 3 out of 216 *Flash* trials (1.39%). Therefore, we consider 2450 trials in total in the following section.

	Sum	**Mean** *(p.p.)*	**SD** *(p.p.)*	**Min** *(p.p.)*	**Max** *(p.p.)*
Baseline	61	3.39	5.64	0	18
Ap. Object	2	0.11	0.47	0	2
Airpuff	2	0.11	0.32	0	1
Blur	2	0.11	0.47	0	2
Flash	3	0.17	0.51	0	2

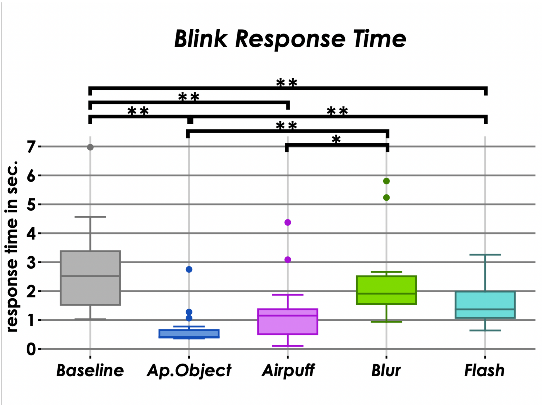
Table 5.1: Removed trials for each blink trigger *(p.p. = per participant)*

5.8.2 Data Analysis Procedure

For each of these metrics, we initially performed a Shapiro-Wilk test to test the data for normality. If the data was not normally distributed, we continued with a non-parametric test, namely the Friedman test. The Friedman test tests the null hypothesis that repeated measurements of the same individuals have the same distribution. If the test found the data to differ significantly across the conditions, we would perform pairwise Wilcoxon signed-rank post-hoc tests with Bonferroni correction. For all tests, we apply a significance level of $\alpha = 0.05$.

5.8.3 Blink Response Time

We examined the *blink response time* to investigate how much time elapsed between the triggering of the blink trigger and the participant blinking. A Shapiro-Wilk test revealed that normality cannot be assumed for *Approaching Object*, *Airpuff*, *Blur* and *Baseline* (all $p < 0.05$). Therefore, we continued with a Friedman test, which found the *blink response time* to differ significantly across the five conditions ($df = 4$, $Q = 39.96$, $p < 0.001$). Therefore, we ran pairwise Wilcoxon tests with Bonferroni-corrected p values (denoted as p'). Figure 5.3 (left) depicts the *blink response time* of the five conditions with significant differences indicated, and Figure 5.3 (right) shows the pairwise results of the Wilcoxon tests. The tests revealed that the *blink response time* of *Approaching Object*, *Airpuff* and *Flash* differs significantly from *Baseline* ($M = 2.74s$, $SD = 1.49s$) (all $p' < 0.01$). *Approaching Object* ($M = 0.67s$, $SD = 0.58s$) was the fastest trigger. It was significantly faster than *Blur* ($M = 2.25s$, $SD = 1.30s$) and *Flash* ($M = 1.56s$, $SD = 0.68s$) (both $p' < 0.01$). *Airpuff* ($M = 1.23s$, $SD = 1.08s$) was also significantly different from *Blur* ($p' = 0.02$).



	Baseline	Ap. Object	Air Puff	Blur
Ap. Object	Z = 4.23 **p' < 0.01** r = 0.71			
Air Puff	Z = 4.12 **p' < 0.01** r = 0.69	**p' = 0.34**		
Blur	**p' = 3.93**	Z = 4.12 **p' < 0.01** r = 0.69	Z = 3.04 **p' = 0.02** r = 0.51	
Flash	Z = 3.87 **p' < 0.01** r = 0.65	Z = 3.59 **p' < 0.01** r = 0.60	**p' = 0.60**	**p' = 0.12**

Figure 5.3: **Results for *blink response time*:** Box plot (left) with brackets indicating significant differences ($p' < 0.05$ (*); $p' < 0.01$ (**)) and results of the pairwise Wilcoxon tests (right) with significant differences between two conditions highlighted in green.

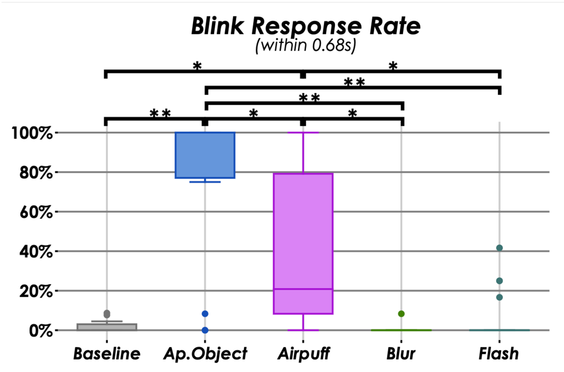
	Mean	SD	Min	Max
Baseline	2.74	1.49	1.03	6.97
Ap. Object	0.67	0.58	0.36	2.75
Airpuff	1.23	1.08	0.11	4.38
Blur	2.25	1.30	0.94	5.81
Flash	1.56	0.68	0.64	3.26

Table 5.2: Descriptive statistics on *blink response time* in seconds.

5.8.4 Blink Response Rate

Blink Response Rate within Average Reaching Time

The *blink response rate* indicates the percentage of trials in which there was at least one blink. To determine the *blink response rate* within the *average reaching time*, we first measured the reaching time for each participant. We determined the reaching time by calculating the interval between initiating the blink trigger and the participant touching the target. We found an *average reaching time* across all valid trials of 0.68s (SD = 0.49s, Min = 0.03s, Max = 9.46s). Subsequently, we ran the Shapiro-Wilk test on the *blink response rate*, which showed that normality could not be assumed for any of the five conditions (all $p <$ 0.05). Therefore, we continued with the Friedman test, which found the *blink response rate* to differ significantly across the five conditions (df = 4, Q = 45.37, $p <$ 0.001). We ran the pairwise Wilcoxon tests with Bonferroni-corrected p values (denoted as p'). Figure 5.4 (left) depicts the *blink response rate* of the five conditions with significant differences indicated, and Figure 5.4 (right) shows the pairwise results of the Wilcoxon tests. The tests revealed that only the *blink response rate* of *Approaching Object* and *Airpuff* differ significantly from *Baseline* (M = 0.02, SD = 0.03) (both $p' <=$ 0.01) within a time window of 0.68s. *Approaching Object* (M = 0.79, SD = 0.36) had the highest *blink response rate* with an average of 79%. It is significantly higher than the rate of *Airpuff* (M = 0.39, SD = 0.40), *Blur* ($M <$ 0.001, SD = 0.02) and *Flash* (M = 0.06, SD = 0.12) (all $p' <=$ 0.03). However, *Airpuff* also performed well in the short time window with a significantly higher *blink response rate* than *Blur* and *Flash* (both p' = 0.01).



	Baseline	Ap. Object	Air Puff	Blur
Ap. Object	Z = 3.50 p' < 0.01 r = 0.58			
Air Puff	Z = 3.23 p' = 0.01 r = 0.54	Z = 3.02 p' = 0.03 r = 0.50		
Blur	p' = 0.93	Z = 3.62 p' < 0.01 r = 0.60	Z = 3.30 p' = 0.01 r = 0.55	
Flash	p' = 3.74	Z = 3.56 p' < 0.01 r = 0.59	Z = 3.24 p' = 0.01 r = 0.54	p' = 0.78

Figure 5.4: **Results for *blink response rate (within average reaching time)***: Box plot (left) with brackets indicating significant differences ($p' <$ 0.05 (*); $p' <$ 0.01 (**)) and results of the pairwise Wilcoxon tests (right) with significant differences between two conditions highlighted in green.

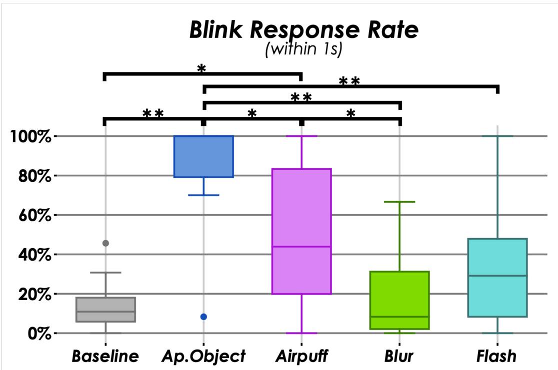
	Mean	SD	Min	Max
Baseline	0.02	0.03	0.0	0.09
Ap. Object	0.79	0.36	0.0	1.00
Airpuff	0.39	0.40	0.0	1.00
Blur	0.00	0.02	0.0	0.08
Flash	0.06	0.12	0.0	0.42

Table 5.3: Descriptive statistics on *blink response rate (within average reaching time)*.

Blink Response Rate within One Second

Next, we calculated the *blink response rate* within a time window of one second. The Shapiro-Wilk test revealed that normality could not be assumed for *Approaching Object*, *Blur*, *Flash* and *Baseline* (all $p < 0.05$). Hence, we continued with the Friedman test, which found the *blink response rate* to differ significantly across the five conditions ($df = 4$, $Q = 33.89$, $p < 0.001$) and ran the pairwise Wilcoxon tests with Bonferroni-corrected p values. Figure 5.5 (left) depicts the *blink response rate* of the five conditions with significant differences indicated, and Figure 5.5 (right) shows the pairwise results of the Wilcoxon tests.

Within a time window of one second, *Approaching Object* and *Airpuff* remain the only blink triggers that differ significantly from *Baseline* ($M = 0.13$, $SD = 0.12$) (both $p' <= 0.01$). The *blink response rate* of *Approaching Object* ($M = 0.84$, $SD = 0.29$) increased to 84%, which is significantly higher than the rate of *Airpuff* ($M = 0.52$, $SD = 0.35$), *Blur* ($M = 0.18$, $SD = 0.19$) and *Flash* ($M = 0.31$, $SD = 0.29$) (all $p' <= 0.04$). Finally, the probability of *Airpuff* to trigger blinks within one second after triggering is significantly higher than for *Blur* ($p' = 0.02$).



	Baseline	Ap. Object	Air Puff	Blur
Ap. Object	Z = 4.12 **p' < 0.01** r = 0.68			
Air Puff	Z = 3.21 **p' = 0.01** r = 0.53	Z = 2.89 **p' = 0.04** r = 0.48		
Blur	**p' = 3.63**	Z = 3.52 **p' < 0.01** r = 0.58	Z = 3.16 **p' = 0.02** r = 0.53	
Flash	**p' = 0.34**	Z = 3.42 **p' < 0.01** r = 0.57	**p' = 0.19**	**p' = 0.99**

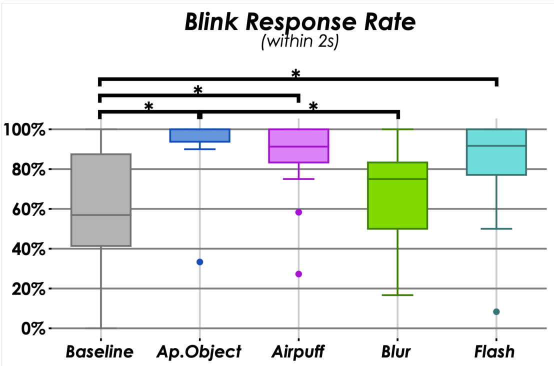
Figure 5.5: **Results for *blink response rate (within one second)***: Box plot (left) with brackets indicating significant differences ($p' < 0.05$ (*); $p' < 0.01$ (**)) and results of the pairwise Wilcoxon tests (right) with significant differences between two conditions highlighted in green.

	Mean	SD	Min	Max
Baseline	0.13	0.12	0.00	0.46
Ap. Object	0.84	0.29	0.08	1.00
Airpuff	0.52	0.35	0.00	1.00
Blur	0.18	0.19	0.00	0.67
Flash	0.31	0.29	0.00	1.00

Table 5.4: Descriptive statistics on *blink response rate (within one second)*.

Blink Response Rate within Two Seconds

Last, we considered the *blink response rate* within a time window of two seconds. The Shapiro-Wilk test revealed that normality could not be assumed for *Approaching Object*, *Airpuff*, and *Flash* (all $p < 0.05$). The Friedman test, which we subsequently performed, found the *blink response rate* to differ significantly across the five conditions ($df = 4$, $Q = 26.73$, $p < 0.001$). Therefore, we ran the pairwise Wilcoxon tests with Bonferroni-corrected p values. Figure 5.6 (left) depicts the *blink response rate* of the five conditions with significant differences indicated, and Figure 5.6 (right) shows the pairwise results of the Wilcoxon tests. A time window of two seconds shows the *blink response rate* for all blink triggers above 66%. *Approaching Object* ($M = 0.94$, $SD = 0.16$) has the highest *blink response rate* of 94%. *Approaching Object*, *Airpuff* ($M = 0.85$, $SD = 0.20$) and *Flash* ($M = 0.83$, $SD = 0.24$) differ significantly from *Baseline* ($M = 0.59$, $SD = 0.29$) (all $p' <= 0.02$). Also, for *Approaching Object*, the probability of eliciting blinks within two seconds after triggering is significantly higher than for *Blur* ($M = 0.66$, $SD = 0.26$).



	Baseline	Ap. Object	Air Puff	Blur
Ap. Object	Z = 3.24 **p' = 0.01** r = 0.54			
Air Puff	Z = 3.20 **p' = 0.01** r = 0.53	**p' = 0.55**		
Blur	**p' = 5.86**	Z = 2.95 **p' = 0.03** r = 0.49	**p' = 0.21**	
Flash	Z = 3.05 **p' = 0.02** r = 0.51	**p' = 0.58**	**p' = 9.72**	**p' = 11**

Figure 5.6: **Results for *blink response rate (within two seconds)***: Box plot (left) with brackets indicating significant differences ($p' < 0.05$ (*); $p' < 0.01$ (**)) and results of the pairwise Wilcoxon tests (right) with significant differences between two conditions highlighted in green.

	Mean	SD	Min	Max
Baseline	0.59	0.29	0.00	1.0
Ap. Object	0.94	0.16	0.33	1.0
Airpuff	0.85	0.20	0.27	1.0
Blur	0.66	0.26	0.17	1.0
Flash	0.83	0.24	0.08	1.0

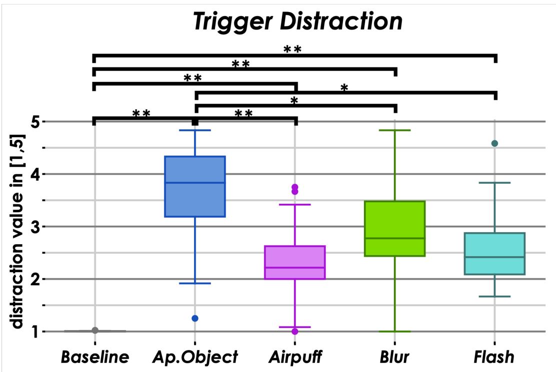
Table 5.5: Descriptive statistics on *blink response rate (within two seconds)*.

5.8.5 Trigger Distraction

We examined the *trigger distraction* to investigate how much users felt distracted by the blink triggers. A Shapiro-Wilk test revealed that normality could not be assumed for *Flash* and *Baseline* (both $p < 0.05$). Therefore, we continued with a Friedman test run on all five conditions. A Friedman test found the *trigger distraction* to differ significantly across the five conditions ($df = 4$, $Q = 50.33$, $p < 0.001$). Therefore we ran the pairwise Wilcoxon tests with Bonferroni-corrected p values.

Figure 5.7 (left) depicts the *trigger distraction* of the five conditions with significant differences indicated, and Figure 5.7 (right) shows the pairwise results of the Wilcoxon tests.

The test revealed that *Approaching Object* had the highest *trigger distraction* ($M = 3.56$, $SD = 1.08$) on average. It differs significantly from *Airpuff* ($M = 2.33$, $SD = 0.74$), *Blur* ($M = 2.83$, $SD = 1.02$) and *Flash* ($M = 2.57$, $SD = 0.74$) ($p' <= 0.02$). *Baseline* ($M = 1.00$, $SD = 0.74$) had a *trigger distraction* of M = 1.00 with significant differences to all blink triggers ($p' < 0.01$). No significant differences were observed for the remaining blink triggers.



	Baseline	Ap. Object	Air Puff	Blur
Ap. Object	Z = 4.48 **p′ < 0.01** r = 0.75			
Air Puff	Z = 3.62 **p′ < 0.01** r = 0.60	Z = 4.23 **p′ < 0.01** r = 0.71		
Blur	Z = 3.62 **p′ < 0.01** r = 0.60	Z = 3.04 **p′ = 0.02** r = 0.51	**p′ = 0.60**	
Flash	Z = 4.48 **p′ < 0.01** r = 0.75	Z = 3.29 **p′ = 0.01** r = 0.55	**p′ = 0.93**	**p′ = 1.93**

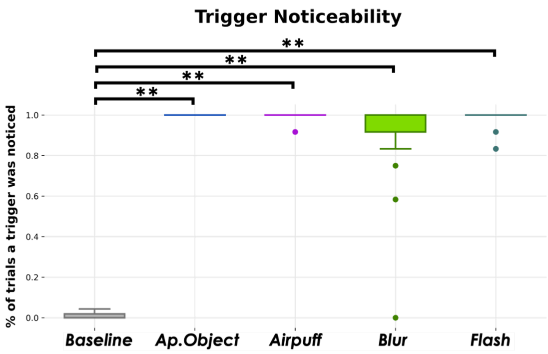
Figure 5.7: **Results for *trigger distraction***: Box plot (left) with brackets indicating significant differences ($p' < 0.05$ (*); $p' < 0.01$ (**)) and results of the pairwise Wilcoxon tests (right) with significant differences between two conditions highlighted in green.

	Mean	SD	Min	Max
Baseline	1.00	0.01	1.00	1.02
Ap. Object	3.56	1.08	1.25	4.83
Airpuff	2.33	0.74	1.00	3.75
Blur	2.83	1.02	1.00	4.83
Flash	2.57	0.74	1.67	4.58

Table 5.6: Descriptive statistics on *trigger distraction*.

5.8.6 Trigger Noticeability

The *trigger noticeability* indicates how many blink triggers were noticed by the participants on average. A Shapiro-Wilk test revealed that normality cannot be assumed for *Airpuff*, *Blur*, *Flash* and *Baseline* (all $p < 0.05$). Therefore, we continued with a Friedman test run on all five conditions. A Friedman test found the *trigger noticeability* to differ significantly across the five conditions ($df = 4$, $Q = 58.33$, $p < 0.01$). Therefore we ran the pairwise Wilcoxon tests with Bonferroni-corrected p values. The test revealed that there were no significant differences between the blink triggers. *Baseline* had a *trigger noticeability* rate of M = 0.01% ($SD = 0.01$) and was significantly different from the blink triggers (all $p' < 0.01$). In general, *Blur* was the least noticeable blink trigger with a *trigger noticeability* rate of 89% ($SD = 0.25$). The other blink trigger methods were almost always noticed with *trigger noticeability* rates of M = 99% for *Flash* ($SD = 0.09$), M = 100% for *Airpuff* ($SD = 0.02$) and M = 100% for *Approaching Object* ($SD = 0$).



	Baseline	Ap. Object	Air Puff	Blur
Ap. Object	Z = 4.48 **p‘ < 0.01** r = 0.75			
Air Puff	Z = 4.48 **p‘ < 0.01** r = 0.75	**p‘ = 3.17**		
Blur	Z = 3.68 **p‘ < 0.01** r = 0.61	**p‘ = 0.27**	**p‘ = 0.27**	
Flash	Z = 4.48 **p‘ < 0.01** r = 0.75	**p‘ = 1.80**	**p‘ = 4.14**	**p‘ = 1.05**

Figure 5.8: **Results for *trigger noticeability***: Box plot (left) with brackets indicating significant differences ($p' < 0.05$ (*); $p' < 0.01$ (**)) and results of the pairwise Wilcoxon tests (right) with significant differences between two conditions highlighted in green.

	Mean	SD	Min	Max
Baseline	0.01	0.01	0.00	0.04
Ap. Object	1.00	0.00	1.00	1.00
Airpuff	1.00	0.02	0.92	1.00
Blur	0.89	0.25	0.00	1.00
Flash	0.99	0.04	0.83	1.00

Table 5.7: Descriptive statistics on *trigger noticeability*.

5.8.7 Game Performance

We investigated the impact of blink triggers on the user's performance in a game task. We ran the Shapiro-Wilk test on the *game performance*, which showed that normality could not be assumed for any of the five conditions (all $p < 0.05$). Therefore, we continued with the Friedman test, which did not find the *game performance* to differ significantly across the five conditions ($df = 4$, $Q = 2.56$, $p = 0.69$). On average, the correct cube was selected in 94% of *Approaching Object* ($SD = 0.11$) trials, in 96% of *Airpuff* ($SD = 0.07$) trials, in 95% of *Blur* ($SD = 0.06$) trials and in 94% of *Flash* ($SD = 0.09$) trials. Therefore, *game performance* was not significantly different from *Baseline* ($SD = 0.07$), which had a rate of 95%.

	Mean	**SD**	**Min**	**Max**
Baseline	0.95	0.07	0.78	1.0
Ap. Object	0.94	0.11	0.67	1.0
Airpuff	0.96	0.07	0.75	1.0
Blur	0.95	0.06	0.83	1.0
Flash	0.94	0.09	0.67	1.0

Table 5.8: Descriptive statistics on *game performance*.

5.8.8 Questionnaires

We evaluated the SUS presence questionnaire [31], the Simulator Sickness Questionnaire (SSQ) [18], and the NASA TLX Questionnaire [15], which participants had to fill out in VR. The SUS Count ($M = 1.83$, $SD = 1.98$) and the SUS Mean ($M = 4.06$, $SD = 1.47$) indicate that the virtual environment was generally immersive. The SSQ total score of M = 34.91 ($SD = 28.74$) showed that the participants did not have sickness issues during the study. Finally, the NASA TLX resulted in a medium mental demand ($M = 55.56$, $SD = 24.67$) and medium temporal demand ($M = 37.22$, $SD = 25.97$) and a low physical demand ($M = 12.5$, $SD = 7.72$). Participants rated their performance with 82.22 ($SD = 10.88$) on average, with a medium effort of 57.22 ($SD = 23.09$). The frustration that participants perceived during the study was low ($M = 18.89$, $SD = 15.77$).

	Mean	**SD**	**Min**	**Max**
SUS count	1.83	1.98	0.00	5.00
SUS mean	4.06	1.47	1.83	6.17
SSQ total score	34.91	28.74	0.00	97.24
TLX mental demand	55.56	24.67	5	90
TLX physical demand	12.5	7.72	5	35
TLX temporal demand	37.22	25.97	5	85
TLX performance	82.22	10.88	65	100
TLX effort	57.22	23.09	15	85
TLX frustration	18.89	15.77	5	55

Table 5.9: Results of the SUS presence questionnaire, the Simulator Sickness Questionnaire (SSQ), and the NASA TLX Questionnaire.

5.9 Discussion

In a user study, we investigated the four blink trigger conditions *Flash*, *Blur*, *Approaching Object*, and *Airpuff*.

The results have shown that we can find statistically significant differences between the individual blink triggers. In the following, we will discuss the results regarding our six hypotheses formulated at the beginning. In addition, we summarize the results for each blink trigger individually and recommend suitable use cases for each blink trigger.

5.9.1 Hypotheses Evaluation

H1 - Effectiveness:

In the first hypothesis, we expected that blink triggers are effective in triggering blinks, i.e., have a shorter *blink response time* than *Baseline*. We could show **H1** for *Approaching Object*, *Airpuff*, and *Flash*, as they each had a significantly shorter *blink response time* than *Baseline*. *Blur* on the other hand did not effectively trigger eye blinks as it did not trigger eye blinks significantly faster than *Baseline*.

H2 - Efficiency:

The second hypothesis specified the order regarding the efficiency of blink triggers:
(low response time) *Airpuff* < *Flash* < *Approaching Object* < *Blur* (high response time).

However, we found *Approaching Object* performed best in triggering eye blinks fast, as it had the shortest *blink response time* of only $0.67s$. Therefore, it was significantly faster than *Blur* and *Flash*. *Airpuff* was only slightly slower than *Approaching Object* in eliciting eye blinks with a significant difference to *Blur*.

Our results for *Airpuff*, *Flash*, and *Blur* align with the results found in related work. However, we did not expect *Approaching Object* to be the fastest blink trigger in comparison. It also had the smallest deviation among participants. Therefore, it is the most effective and efficient blink trigger we tested. Our findings are consistent with our expectations, except for *Approaching Object*. **H2** is therefore only partly supported. We obtain the following order, from the lowest *blink response time* ($M = 0.67s$) to the highest response time ($M = 2.25s$): *Approaching Object* < *Airpuff* < *Flash* < *Blur*.

H3 - Reliability:

In the third hypothesis, we expected that blink triggers have a higher *blink response rate* (within *average reaching time*, $1s$ and $2s$) than *Baseline*.

Within $0.68s$, the *average reaching time* in our study, we found that *Airpuff* and *Approaching Object* reliably trigger eye blinks. However, *Approaching Object* did not work for all participants. We found that it did not reliably trigger blinking in three participants. The reason for this could not be clarified conclusively, so this should be considered when using *Approaching Object* and can be investigated in future work. *Blur* and *Flash* did not reliably trigger blinks within the *average reaching time*. Therefore, **H3** is only partly supported, and only *Approaching Object* and *Airpuff* are recommended for fast hand redirection, which requires blink triggers to work within *average reaching time*.

However, if we consider a larger time window, such as 2 seconds, *Flash* can also be recommended. Here, *Flash*, *Approaching Object*, and *Airpuff* triggered blinking in at least 83% of the trials. *Blur* was not convincing in our tests, as it was not significantly better than *Baseline*.

In conclusion, different blink triggers can be considered depending on the time window. *Approaching Object* and *Airpuff* are recommended for short time windows (up to 1 second), and *Flash* is also attractive for longer time windows (up to 2 seconds).

H4 - Noticeability:

Furthermore, we also expected that blink triggers differ in their noticeability, with *Blur* being the least noticeable blink trigger.

H4 could not be shown because no significant differences were found regarding the *trigger noticeability*. Participants almost always noticed the blink triggers. Only *Blur* was partially not noticeable for users. Surprisingly, one user did not notice the *Blur* at all. Unfortunately, we could not find the reasons for this.

In conclusion, we do not assume that blink triggers can be made completely unnoticeable for users. Therefore, it is better to focus on making them less distracting.

H5 - Distraction:

The fifth hypothesis specified the order regarding the distraction of blink triggers:
(low distraction) *Blur* < *Airpuff* < *Flash* < *Approaching Object* (high distraction)

According to our expectation, we found that *Approaching Object* was perceived as most distracting. *Airpuff*, *Flash* and *Blur* had a very similar distraction level to *Approaching Object*. However, contrary to our expectation, *Blur* was considered more distracting than the other two blink triggers. **H5** is therefore only partly supported. Overall, we found the following order, from the lowest distraction value (M = 2.33 out of 5) to the highest distraction value (M = 3.56 out of 5): *Airpuff* < *Flash* < *Blur* < *Approaching Object*.

H6 - Reduced Performance:

In the sixth hypothesis, we expected a reduced *game performance* in trials with blink triggers compared to the *Baseline* trials.

Contrary to our expectations, the blink triggers did not affect participants' *game performance*. The game results of trials with a blink trigger were almost identical to the trials of the *Baseline* condition. The percentages of correctly selected cubes were between 94% and 96%. **H6** is therefore not supported by the results. However, some participants noted that they had made the game decision (i.e., which cube to select) in advance, i.e., before the hand started to move and a blink trigger appeared. Therefore, the blink triggers did not affect their game choice anymore.

5.9.2 Application Scenarios for the Blink Triggers

In the following, we discuss the advantages and disadvantages of each blink trigger individually and recommend suitable application fields for each method. We have illustrated our results in a decision tree (see Figure 5.9), which should help researchers and practitioners to find blink triggers for their VR applications.

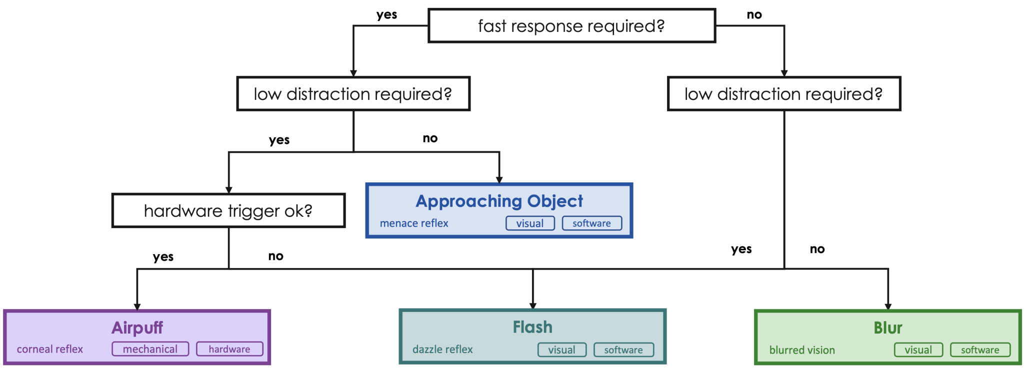


Figure 5.9: Decision tree for choosing a blink trigger

Approaching Object:

We were surprised by the results of *Approaching Object*. It triggered the blink the fastest in only 0.67 seconds. Therefore, we can recommend *Approaching Object* for scenarios where fast triggering of blinking is essential, such as in hand redirection techniques. Considering the *average reaching time* of 0.68 seconds, the blink was triggered therein in 79% of the trials. The only drawback is the high distraction of *Approaching Object*. Participants found *Approaching Object* to be the most distracting blink trigger. Overall, *Approaching Object* can be recommended for scenarios where the blink should be triggered quickly, and high distraction does not matter. Also, *Approaching Object* is easy to integrate into any application because it is a software-based blink trigger without external hardware.

In the future, it can be investigated whether *Approaching Object* can be made less distracting. For example, by increasing the transparency, the virtual sphere could look like a bubble and might be less noticeable. Also, it is likely that the object will be less distracting to users if it is integrated into the logic and design of the virtual environment. Depending on the application, different objects are conceivable. For example, in a virtual video game, a raindrop or a snowflake could fall into the eye of the user, or a fly quickly approaches the eye.

Airpuff:

The *Airpuff* scored very well overall in our study. It represents a good compromise between being fast, reliable, and not distracting for participants. In our study, it triggered eye blinks in just 1.23 seconds, which is the second-best result. At the same time, it was the least distracting blink trigger, with a *trigger distraction* value of 2.33 out of 5. Therefore, it can be used primarily in scenarios where it is important not to distract users.

Only a few participants did not react to the *Airpuff* with blinking. To make the *Airpuff* even more reliable for all users, different air blowers can be tested to produce a higher intensity. To further enhance the *Airpuff*, it can also be combined with another blink trigger, such as a sound [17]. This allows blinking to be triggered despite low intensities of the individual blink triggers.

The disadvantage of the *Airpuff* is that it requires additional hardware and therefore represents a higher effort compared to the software-based methods. Also, if users wear glasses or contact lenses, the *Airpuff* may not work reliably. Another drawback of the *Airpuff* is that the position has to be adjusted manually for each participant. By using an automated calibration in future studies, inaccuracies, that might occur when calibrating the device manually, could be avoided. The built-in eye tracking of the HTC Vive Pro Eye could be used for this.

In summary, we recommend the *Airpuff* for any use case if additional hardware is not a problem.

Blur:

The *Blur* trigger was not convincing in our study. Blinking was triggered faster by the *Blur* compared to *Baseline*, but the difference was not significant. Furthermore, the *Blur* was rated the second most distracting blink trigger by participants. However, it is interesting that the *Blur* was the only trigger a participant did not notice. We have not been able to find out the cause of this. One possible explanation is that the participant blinked too early, so the *Blur* intensity was not at 100%. However, by investigating the *blink response time* this could be ruled out. Another reason might be that the participant perceived the *Blur* as motion blur and therefore did not consider it to be a disturbing visual stimulus. Consequently, it is advisable to investigate how users experience different types of blur effects, such as motion, box, or radial blur. Furthermore, to make the *Blur* less annoying, it could be shown in a more unobtrusive way, e.g. only in certain areas of the display.

Overall, if the *Blur* could be configured to be less noticeable and more efficient, it can be recommended especially for VR scenarios, where a low noticeability of blink triggers is required.

Flash:

Flash effectively triggers the blink and is not very distracting at the same time. However, it does not achieve results as good as *Airpuff*. To make the *Flash* work more reliably, it is advisable to increase the intensity of the *Flash*. Since the brightness of the HMD is limited, using an LED could be reconsidered. Furthermore, to reduce the distraction of the *Flash*, the stimulus could also be integrated into the logic of the virtual environment. For example, in an industrial hall, there may be damaged cables hanging from the roof and causing short circuits, which can be used to simulate a flash.

The advantage of *Flash* is that it is a software-based trigger and is easy to implement. In addition, the parameters of *Flash* can be changed quickly and easily. For use cases where a fast integration of the blink trigger is important, and users should not be distracted, *Flash* is recommended.

Chapter 6
Conclusion

To conclude this thesis, we summarize the core aspects of the thesis and the findings obtained in the study. Afterward, the limitations of this work are presented, and an outlook on future work is given.

6.1 Overview

Motivated by the demand for methods to trigger blinking in VR, this work investigated different approaches and tested them in a user study. The blink triggers were specifically studied for use in redirection techniques like Blink-Suppressed Hand Redirection [39]. Therefore, the requirements were to elicit blinks quickly, work out of the box, work reliably, and be barely noticeable or distracting.

Based on the related work in the fields of medical research and the physiology of eye blinks, we developed six approaches to trigger blinking in VR, namely a flashing light, a blurred vision, an approaching object, a tap on the glabella, an air puff next to the eye, and a loud sound. The blink triggers were based on reflexes like the dazzle, menace, glabellar, corneal or acoustic reflex. We developed prototypes of each blink trigger and selected the four most promising methods. Those are (1) *Flash*, triggering a blink by a short, white screen, (2) *Blur*, triggering a blink by a blurred screen, (3) *Approaching Object*, triggering a blink by a virtual object rapidly approaching the user and (4) *Airpuff*, triggering a blink by an air puff next to the eye. The visual blink triggers *Flash*, *Blur*, and *Approaching Object* were implemented exclusively via software in Unity. For the mechanical blink trigger, the *Airpuff*, a micro blower was built into the HMD.

We examined the performance of the blink trigger methods in a user study. During the study, different metrics were measured, such as the response time, noticeability, and distraction of a blink trigger. Based on previous research results, we formulated hypotheses regarding the effectiveness, efficiency, reliability, noticeability, distraction, and the impact on game performance of the blink trigger methods. For the most part, the obtained results confirmed our hypotheses. Nevertheless, we were surprised by some of the findings. For example, *Approaching Object*, a blink trigger that has not been studied before, was able to trigger blinking the fastest in our study. However, it was also regarded as the most distracting by participants. We found *Airpuff* to be the least distracting blink trigger. In the end, we discussed each blink trigger individually and provided use case recommendations to help researchers and practitioners to select a suitable method for their application.

6.2 Limitations

Regarding the limitations of this work, it should be noted that this is the first time that blinking in VR has been explored. Although it has been studied in other research areas, such as for combating CVS, it has not been specifically researched for VR. The goal was to give a first overview of different methods and compare their performance with each other. For the user study, blink triggers were only informally tested for the best settings, and parameters were not changed during the study. Therefore, our results are related to the selected parameters.

Some blink trigger settings were also technically limited. For example, the *Flash* stimulus was limited by the display brightness of the HMD and the frame rate. Considering the results of the study, a brighter flash stimulus might work more reliably. Another example is the *Airpuff*, which is limited by the technical properties of the integrated micro blower. We chose the same device used in the study by Dementyev and Holz [7] and set the maximum intensity. However, the *Airpuff* could not always reliably trigger the blink. A higher intensity might be achieved by using another device.

Another limitation was the number of participants in the study. We conducted the study with 18 participants. When analyzing the results, we noticed large differences in the data. For example, one participant did not notice the *Blur* at all, although the other participants noticed it in most trials. The reaction to the *Airpuff* was also very different, as a few participants barely reacted, while others were obviously startled. Further studies should be conducted with more participants to find out if these reactions can be found in other participants as well and to identify correlations.

6.3 Future Work

In the future, promising blink triggers could be investigated in more detail, and different settings could be tested against each other in a study.

Due to the limitations mentioned above, the *Flash* could be tested on a brighter display, or the use of LEDs could be reconsidered. Also, the *Flash* could be shown only in a specific area of the screen, or it could be repeated instead of showing it only once. For example, two flashes could be displayed shortly in a row.

For *Blur*, it is particularly interesting to find out why one participant did not notice the *Blur* and whether this can be reproduced. A possibility is that the participant confused the blur effect with motion blur. We were unable to verify this in hindsight, but it may be considered in future studies. Furthermore, other blur effects than gaussian blur could be tested.

On a positive note, none of the participants experienced problems with simulator sickness. However, the *Blur* condition was only repeated 12 times during the study. In future studies, this should be considered, as simulator sickness could play a greater role, especially with higher intensities or longer durations of the blur effect or in scenarios where a participant is walking instead of sitting.

Approaching Object has worked surprisingly well in our study. Therefore, it is interesting to research whether there are similar techniques based on depth perception or the menace reflex. The drawback of *Approaching Object* is its high distraction. Some parameters, like the object's shape or transparency, could be changed to make it less distracting. Furthermore, it could be tried to display the object only in certain frames or render it only on one eye. This could make the object less distracting for users.

Last, the performance of *Airpuff* could be improved in future experiments. As mentioned above, this blink trigger is limited by the technical properties of the micro blower. Using a stronger micro blower could result in a more reliable blink trigger. Additionally, the calibration of the *Airpuff* could be automated as described in the previous chapter.

Overall, it is interesting to examine the relationship between reliability and distraction in more detail. So far, we have discovered that a higher reliability usually requires a higher intensity of the blink trigger, which mostly also results in a higher distraction. The goal is to find the threshold that provides the best compromise between reliability and distraction. Low intensities can work, for example, if two blink triggers are combined, as shown by Hoffmann and Stitt [17]. Triggering a flash or sound stimulus simultaneously to an air puff could increase the effectiveness even with low-intensity blink triggers. Nevertheless, if a high intensity is necessary, it could be tried to minimize the distraction by integrating the blink triggers in a way that they are perceived as part of the scene. For example, this applies to the sound trigger, which can only trigger the blink reflex at a high volume [29]. However, if the sound is coherent with the scene, users could perceive this as less annoying. For example, the sound of an explosion or a gunshot in an action game could be used.

Future research may also investigate the extent to which eye blink conditioning can be considered for VR. Conditioning means that a neutral stimulus, such as an auditory or visual stimulus that does not trigger a blink reflex, is presented together with a blink-triggering unconditional stimulus, such as the air puff. After a repeated presentation of the stimuli, blinking occurs even when the neutral stimulus is presented alone. Whether this makes sense for VR applications also depends on how often the user is shown the same stimulus. If the same stimulus is used several times, there is also a risk that the participant will become accustomed to the stimulus and, after a while, will no longer react with blinking.

Last but not least, blink triggers can be studied in more detail with respect to change blindness. Future research could investigate whether the blink triggers themselves produce change blindness. If this is the case, there would be a second possibility to perform redirection manipulations unnoticed. This is especially conceivable for methods that occlude the user's field of view, such as the *Flash* or *Approaching Object*.

Ultimately, we recommend testing the blink triggers in actual redirection experiments. Although we expect the blink triggers to work similarly to our study, this should be verified in actual use cases.

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Appendix Questionnaires

Demographics Questionnaire

Demographics User ID: ______

Q1: What is your gender?

- o Male
- o Female
- o Other
- o Prefer not say

Q2: What is your age?

____

Q3: What is your profession or field of studies?

____

Q4: Please state your visual acuity, i.e., your vision clarity.

- o Normal Vision
- o Corrected-to-Normal Vision
- o Impaired Vision

Q5: Which is your dominant hand?

- o Right
- o Left
- o Ambidextrous

Q6: Please confirm that, to the best of your knowledge, you do NOT have any disorder of your eyesight (e.g. colorblindness)

- o I confirm to have **none** of these
- o I have one of these

Q7: How often do you use Virtual Reality?

1	2	3	4	5
Never	**Used it once**	**Once in a while**	**Regularly**	**Daily**

Q8: Please state any comments you might have.

____

____

SUS Presence Questionnaire (based on [31])

Instructions: Please answer all 6 questions by clicking a point on the scale that best represents your experience with the task in the virtual environment (VE).

1. I had a sense of “being there” in the virtual environment:
   ◯ 1 = not at all ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7= very much

2. There were times during the experience when the virtual environment was the reality for me...
   ◯ 1 = at no time ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7= almost all the time

3. The virtual environment seems to me to be more like...
   ◯ 1 = images I saw ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7= somewhere I visited

4. I had a stronger sense of...
   ◯ 1 = being elsewhere ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7= being in the VE

5. I think of the virtual environment as a place in a way similar to other places that I’ve been today...
   ◯ 1 = not at all ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7= very much so

6. During the experience I often thought that I was really standing in the virtual environment...
   ◯ 1 = not very often ◯ 2 ◯ 3 ◯ 4 ◯ 5 ◯ 6 ◯ 7= very much so

Simulator Sickness Questionnaire (SSQ) (based on [18])

Instructions: Select how much each of the following symptoms is affecting you right now.

1. General discomfort
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
2. Fatique
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
3. Headache
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
4. Eye strain
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
5. Difficulty focusing
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
6. Salivation increasing
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
7. Sweating
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
8. Nausea
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
9. Difficulty concentrating
   ◯ None ◯ Slight ◯ Moderate ◯ Severe
10. Fullness of the Head
    ◯ None ◯ Slight ◯ Moderate ◯ Severe
11. Blurred vision
    ◯ None ◯ Slight ◯ Moderate ◯ Severe
12. Dizziness with eyes open
    ◯ None ◯ Slight ◯ Moderate ◯ Severe
13. Dizziness with eyes closed
    ◯ None ◯ Slight ◯ Moderate ◯ Severe
14. Vertigo (experienced as loss of orientation with respect to vertical upright)
    ◯ None ◯ Slight ◯ Moderate ◯ Severe
15. Stomach awareness (feeling of discomfort which is just short of nausea)
    ◯ None ◯ Slight ◯ Moderate ◯ Severe
16. Burping
    ◯ None ◯ Slight ◯ Moderate ◯ Severe

NASA TLX (based on [15])

Please rate all 6 measures by clicking a point on the scale that best represents your experience with the task you just completed.

Mental Demand

How mentally demanding was the task?

Low High

Physical Demand

How physically demanding was the task?

Low High

Temporal Demand

How hurried or rushed was the pace of the task?

Low High

Performance

How successful were you in accomplishing what you were asked to do?

Failure Perfect

Effort

How hard did you have to work to accomplish your level of performance?

Low High

Frustration

How insecure, discouraged, irritated, stressed, and annoyed were you?

Low High