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

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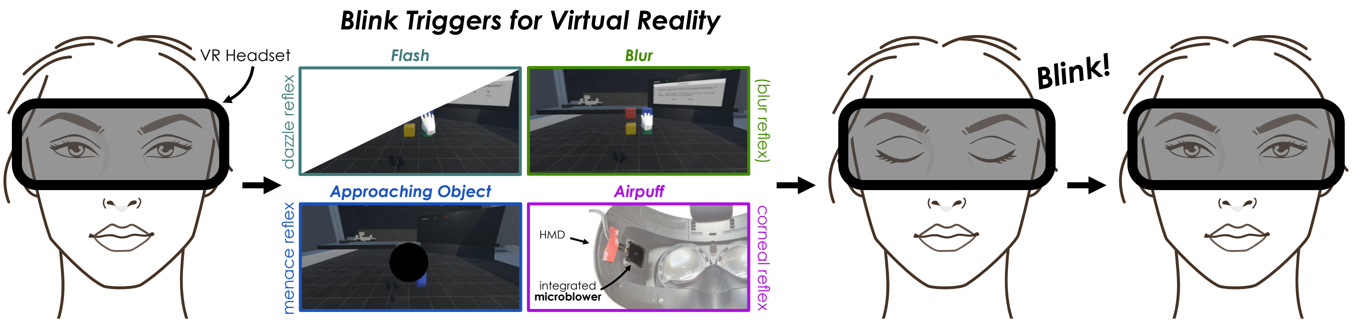

Figure 1: We explore different blink trigger methods suited specifically for virtual reality (VR). Our triggers leverage the dazzle, menace, and corneal reflexes, and simulate a blurred vision to elicit blinks on demand. By this, we improve the control over users' blinking behavior in VR to support blink-based applications and techniques. Illustration: Irina Strelnikova/stock.adobe.com

ABSTRACT

As more and more virtual reality (VR) headsets support eye tracking, recent techniques started to use eye blinks to induce unnoticeable manipulations to the virtual environment, e.g., to redirect users' actions. However, to exploit their full potential, more control over users' blinking behavior in VR is required. To this end, we propose a set of reflex-based blink triggers that are suited specifically for VR. In accordance with blink-based techniques for redirection, we formulate (i) effectiveness, (ii) efficiency, (iii) reliability, and (iv) unobtrusiveness as central requirements for successful triggers. We implement the soft- and hardware-based methods and compare the four most promising approaches in a user study. Our results highlight the pros and cons of the tested triggers, and show those based on the menace, corneal, and dazzle reflexes to perform best. From these results, we derive recommendations that help choosing suitable blink triggers for VR applications.

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CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; *User studies*; *Haptic devices*.

KEYWORDS

virtual reality, change blindness, eye blinks, blink triggers

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1 INTRODUCTION

Head-mounted displays (HMDs) can be considered the central interface for virtual reality (VR) and enable users to experience immersive virtual environments (IVEs) in ways that let them experience presence [30]. In the last decades, the quality of HMDs has advanced significantly and today, a variety of devices with consumer-friendly price tags is widely available. In parallel to the improvement of the output capabilities of HMDs (e.g., resolution, field of view, etc.), also their capability to track information about the user has improved. As a result, an ever-increasing number of HMD manufacturers started to integrate eye tracking in their devices. Taking advantage of this, techniques have been proposed that leverage human eye *blinks* and the resulting phenomenon of change blindness [25, 29, 33] to unnoticeably manipulate the virtual scene, e.g., to redirect users' actions. These techniques leverage the temporary closures of the eye lid and the accompanying visual suppression in the brain [4], for example, to improve the performance of unnoticeable redirected walking (RDW) [20, 22] and hand redirection (HR) [41].

Up to now, however, blink-based techniques share a common drawback: either (1) they require users to blink consciously when a manipulation is needed, defying the purpose of unnoticeable techniques, or (2) they depend on the occurrence of spontaneous blinks in just the right moments to induce virtual manipulations, reducing their reliability. In order to overcome these constraints and to exploit the full potential of blink-based techniques, we argue that solutions are required, which *grant the VR system more control over users' blinking behavior.*

To this end, in this paper, we explore the idea of system-controlled blink trigger methods – a concept already known outside the domain of VR [8, 9]. Such triggers would enable the VR system to trigger eye blinks on demand, for example, when a manipulation of the IVE is needed. Existing research already investigated different approaches to increase the user's average blink frequency over time, but did not yet focus on VR. Instead, proposed approaches only concentrated on desktop [8] and wearable setups [9]. Moreover, past research on blink triggers was primarily concerned with combating the *computer vision syndrome* (CVS) [8, 9] and symptoms like dry eyes. As such, previous solutions (1) did not consider the unique capabilities of VR, which might allow for novel trigger methods, and (2) were designed to meet less stringent requirements (e.g., in terms of blink response time) compared to the requirements posed by fast-paced VR techniques like haptic retargeting. Here, for example, individual blinks would need to be stimulated before the user's hand has reached a virtual object. Consequently, researchers have expressed the need for an investigation of blink triggers suited specifically for VR [20, 22] – a gap that we start to fill with the research presented in this paper. Specifically, we are, to the best of our knowledge, the first to contribute by:

- proposing and implementing perceptually-inspired soft- and hardware-based blink triggers for VR
- comparing VR blink triggers in an empirical user study analyzing their advantages and disadvantages
- deriving recommendations that help researchers and practitioners pick blink triggers for different VR use cases.

2 RELATED WORK

We briefly review techniques based on blink-induced change blindness, as they constitute the central motivation for this work. Next, we summarize physiological properties of human eye blinks and revisit previous work on triggering blinks outside VR.

2.1 Leveraging Eye Blinks in Virtual Reality

Blink-based techniques for VR are usually based on the phenomenon of *change blindness*, which is described by perceptual scientists as *"the inability to detect changes to an object or scene"* [29]. Change blindness is known since the 19th century and it has been shown that humans are susceptible to miss changes in a visual image when they are introduced, for example:

- outside the user's field of view (e.g., behind the back) [34]
- inside the user's field of view:
  - when noise (e.g., a "mudsplash" pattern) is added to the visual image [29]
  - during a blank visual stimulus [27]
  - during a saccade [15]
  - during a blink [25]

According to perceptual scientists Simons and Levin [29], changes to a visual scene are likely to be missed when they do not affect those parts that are central to our understanding of the scene. Our brain assumes that *"if the gist [of a scene] is the same, [...] the details are the same"* [29].

Today, VR techniques that deliberately exploit change blindness are on the rise. Steinicke et al. [33] could show change blindness to occur in stereoscopic viewing conditions as encountered in modern VR systems. By this, they paved the way for novel locomotion and interaction techniques in VR [23, 24]. Many approaches to *redirected walking* (RDW), for example, hide changes to the IVE by rotating or translating the virtual scene below perceptual limits to steer the user while walking [23] (applying so-called translation and rotation gains). In this context, researchers have demonstrated that saccade- [3, 35] and blink-induced change blindness [20, 22] can be taken advantage of to introduce unnoticeable gains. Langbehn et al. [20] found that the performance of RDW can be improved by approximately 50% when leveraging blinks, as each blink allows for unnoticeable translations of $4cm - 9cm$ and rotations of $2° - 5°$. Moreover, Nguyen and Kunz [22] found that the amount of undetectable scene rotation when users are walking can be increased from 2.4° when eyes are open to 9.1° when leveraging blinks to hide rotations. Their results further showed that the utilization of blinks can reduce the number of required resets while walking by 13% and the required physical space for reset-free walking by 20% [22].

Besides RDW, also techniques related to the field of VR haptics can profit from blinks and change blindness. Techniques such as *haptic retargeting* [2, 6, 39, 41] and *redirected touching* [18, 24], for example, are based on *hand redirection* (HR) and can exploit change blindness to modify the location of the virtual hand (body warping), environment (world warping), or both [2]. In this context, Zenner et al. [41] recently proposed a first algorithm for blink-suppressed hand redirection that leverages blink-induced change blindness to improve redirected reaching in VR. The authors showed that when displacing the virtual hand solely during blinks, the system can unnoticeably redirect real hand movements without the need for any hand shifting in front of the user's opened eyes. Moreover, their results suggest that techniques combining continuous hand warping [40] with blink-suppressed shifts constitute a promising avenue for future research on redirected reaching [41].

Compared to techniques that leverage saccades [3, 35], blink-based solutions come with several advantages. They do not require high-performance eye trackers as blinks can be robustly tracked with off-the-shelf hardware such as the HTC Vive Pro Eye[1] [20, 41]. Furthermore, blinks blind users for a longer time

[1]https://www.vive.com/us/product/vive-pro-eye/specs/

than saccades [20, 38, 41], and thus grant more time for blink recognition, for performing computations, and for making sure visual changes are correctly displayed. Yet, a disadvantage compared to saccades is that blink-based techniques only opportunistically exploit spontaneous blinks, which occur much less frequently than saccades. In previous investigations, this aspect has been mostly neglected and during user studies, users were asked to blink consciously and frequently [20, 41]. This, however, is no approach of practical use. Thus, to alleviate this problem, researchers formulated the need for more control over users' blinking behavior in VR [20, 22, 41] – a call motivating our work in this paper.

2.2 The Physiology of Human Eye Blinks

Blinks are characterized by a rapid closure and re-opening of the eyelid. During a blink, the pupil is occluded for approximately $100ms - 150ms$ [38] and retinal illumination is drastically decreased. Yet, although blinks effectively blind us for a brief moment, we usually do not notice these visual interruptions. A reason for that is visual suppression, a neural process linked to blinking that affects specific parietal and prefrontal brain regions [4] and lasts for approximately $100ms - 200ms$ [38]. Blinks serve multiple purposes, such as the protection and lubrication of the cornea, and different types of blinks exist:

(1) voluntary eye blinks [38]
(performed intentionally; e.g., during social interaction)
(2) involuntary eye blinks [13]
(performed unconsciously; usually unnoticed), such as:
  (a) spontaneous eye blinks [13]
  (no external stimulus; ca. $10 - 20$ times per minute)
  (b) reflex eye blinks [21]
  (external stimulus)

Spontaneous blink rate can vary with the user's activity and it was found, for example, that blink frequency decreases when reading [11] or using computer monitors [26], and to increase when wearing an HMD (compared to computer monitors) [10].

While blink-based techniques so far only exploited voluntary (type 1) and spontaneous blinks (type 2a), in this paper, we focus specifically on reflexes (type 2b) to stimulate blinks on demand. Reflex blinks are *"rapidly occurring, protective closing[s] of the eyelids"* [21] and lend themselves to system-controlled blink triggering as Manning et al. found them to be accompanied by visual suppression [21]. Reflex blinks have seen much attention in medical and physiology research as they have, for example, been used for measuring the integrity of neural pathways [32]. Yet, reflex blinks have not been systematically considered in VR research. Several well-known blink reflexes exist and are considered in this paper:

- the corneal reflex [13, 21]
(mechanical stimulation of free nerve endings in the cornea)
- the glabella reflex [28]
(mechanical stimulation of the glabella)
- the dazzle reflex [13, 28]
(bright light or flash)
- the menace reflex [13]
(object approaching fast and unexpectedly)
- the acoustic reflex [28, 36]
(loud sound)
- the electrical stimulation reflex [28] [not considered here]
(stimulation of the supraorbital nerve)

While the glabella reflex triggers a blink when the glabella, i.e., the skin between the eye brows above the nose, is tapped by an external object, the corneal reflex is provoked when a foreign object touches the cornea. It is noteworthy that the corneal reflex is sensitive even to very light stimulation, such as a puff of air [9, 21], and that it evokes a blink in both eyes even if only one eye is stimulated [21]. Moreover, very short flashes of bright light of only 200µs can suffice to trigger the dazzle reflex [28]. In contrast, the acoustic reflex usually requires very loud sounds (e.g., clicks) of $105 - 110dB$ for a reliable blink response [36].

2.3 Triggering Eye Blinks

Methods for triggering reflex blinks have been employed in the medical domain and for physiology research for decades [28]. Common approaches in these fields are tapping the glabella [28], the application of airpuff stimuli to trigger the corneal reflex [21, 37], the display of a bright flash of light [28], a loud sound [36], and the electrical stimulation of the supraorbital nerve [37]. Yet, also outside the medical domain research on triggering blinks exists. Most relevant to our work are the investigations of Crnovrsanin et al. [8] and Dementyev and Holz [9] who propose systems that increase the average blink frequency to combat the *computer vision syndrome* (CVS). Their aim is to alleviate symptoms like eyestrain or dry eyes caused by the extensive use of computer screens.

For this, Crnovrsanin et al. [8] explored four software-based methods to stimulate blinks in a desktop PC setting when the user has not blinked in a while. The authors compared a flash effect (turning the desktop screen white for $15ms$), blurring the screen (provoking a blink to clear the blur), and two methods to *remind* users to blink again, namely flashing the border of the screen and displaying a pop-up window. Their results found all four techniques to successfully increase blink frequency, but also showed that there is not a one-trigger-fits-all solution. Screen blurring was found to work most effectively and received good user satisfaction ratings while suffering from a rather long response time. In contrast, the flash stimulus performed worst and was liked the least by users.

Complementing these results, Dementyev and Holz [9] investigated hardware-based blink triggers to alleviate CVS. Here, the dazzle and corneal reflexes were stimulated through an LED (flashing white for $15ms$), light physical taps and an airpuff near the eye, respectively. Stimulation hardware was integrated into the frame of a pair of glasses. Their results suggest that all three methods can increase blink frequency with the airpuff reaching *"the best balance between success rates and distraction"* [9]. The authors further recommend to use airpuffs *"next to the eye, [of] high intensity (24 V), and short duration (75 ms)"* and highlight the need for investigating blink trigger methods for augmented and virtual reality.

While these previous works provide valuable starting points for our investigation, it remains unclear to what extent their results and methods generalize to immersive VR where the screen of an HMD can be used directly to convey stimuli inside an IVE. Moreover, a central difference to our work is that previous investigations focused on a less time-critical scenario in which the main goal was to increase the *average blink frequency over time* to combat CVS.

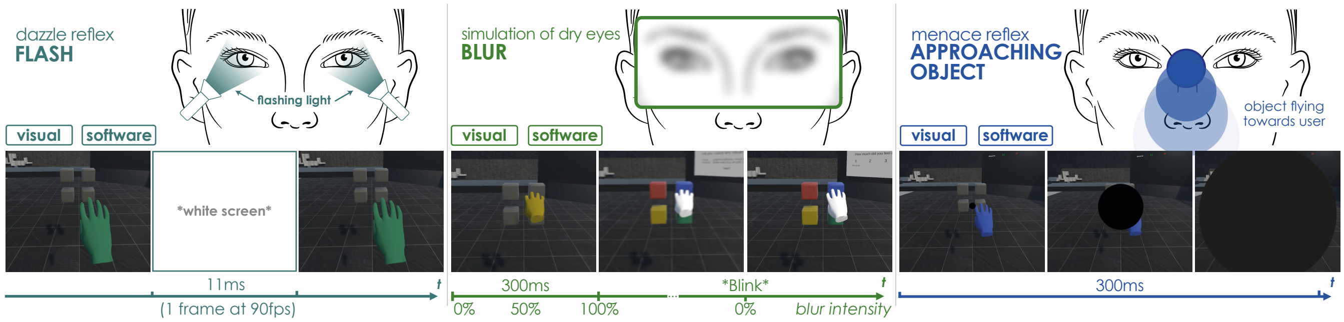

Figure 2: Implementation of the *Flash*, *Blur*, and *Approaching Object* blink triggers for VR. Illustration: komaart/stock.adobe.com

In order to support change blindness-based techniques like RDW or HR, however, methods are required that can trigger *individual blinks on demand and within short time windows.*

3 BLINK TRIGGERS FOR VIRTUAL REALITY

To find suitable blink trigger methods for VR, we start by outlining a set of requirements. Next, we introduce six trigger concepts based on different blink reflexes alongside their VR implementation. Finally, we compare the most promising methods in a user study and derive recommendations for researchers and practitioners.

3.1 Requirements

While various applications that take advantage of human eye blinks in VR can be imagined, two prominent VR techniques have been shown to successfully leverage blinks in the past: redirected walking (RDW) [20, 22] and blink-suppressed hand redirection (BSHR) [39, 41]. To derive a set of meaningful requirements for the techniques investigated in this paper, we compared these domains, which both received attention by the HCI research community recently [20, 39, 41], and decided to tailor our trigger methods and the investigated scenario to the representative use case of BSHR, specifically, haptic retargeting [2, 6, 39]. Our decision is based on the observation that BSHR implies very stringent requirements for the triggers, especially in terms of time. Thus, if a trigger works well for the scenario of reaching, we expect it to work well also in scenarios with relaxed requirements, such as for RDW or other blink-based techniques.

Based on this chosen scenario [1, 2, 6, 14, 40, 41] we argue that successful blink triggers should be able to *trigger a blink before the user's hand reaches an object in a desktop-scale distance* and formulate four corresponding requirements for VR blink triggers:

(1) *effectiveness*
In contrast to methods that only remind users to blink voluntarily (e.g., as investigated by Crnovrsanin et al. [8]), effective VR blink triggers should trigger an *automatic reflex* that elicits a blink without conscious involvement of the user.

(2) *efficiency*
As reaching for an object in a desktop-scale distance even when being redirected rarely takes more than 2*s* [14], successful VR blink triggers should be efficient when triggering blinks, i.e., elicit eye lid closing *as quickly as possible.* To measure this aspect, we require a *low response time* (i.e., time from trigger activation to blink occurrence).

(3) *reliability*
Since some blink-based techniques, e.g., for redirection, only yield correct results if the user blinks within a specific time window, e.g., during reaching [41], successful triggers should work reliably, i.e., each trigger activation should have *high chances of eliciting a blink in time.* To measure this aspect, we require a *high response rate* (i.e., percentage of trigger activations that resulted in a blink within the time window of interest – here: within the avg. reaching time during the experiment and common reaching times of 1*s* and 2*s* [14]).

(4) *unobtrusiveness*
Successful triggers should work unobtrusively, i.e., be themselves *as unnoticeable and comfortable as possible.*

3.2 Blink Trigger Methods

In the following, we present six different blink trigger methods and describe how they can be realized in VR systems. Conceptually, we found three different trigger categories to lend themselves for the use in VR, namely those based on (1) visual, (2) auditory, and (3) mechanical stimuli – all targeting different blink reflexes. The implementation of all three categories is facilitated by modern HMDs as they (1) provide screens in front of the user's eyes that fill large portions of the field of view, (2) have integrated headphones, and (3) provide a platform to mount blink trigger hardware. Additionally, more and more commercial HMDs (such as the HTC Vive Pro Eye) feature build-in eye tracking that allows for blink detection. Thus, using the HMD as the trigger platform, we iteratively developed the following trigger concepts and prototypes:

3.2.1 Visual Stimuli. Inspired by the work of Crnovrsanin et al. [8] and Dementyev and Holz [9], we transferred the established approaches of the visual *Flash* and *Blur* triggers to immersive VR. Additionally, we developed a novel visual trigger, which is, to the best of our knowledge, the first to target the menace reflex.

Flash Trigger. The *Flash* trigger is based on the dazzle reflex, which is one of the best known reflexes that cause blinking. The reflex is triggered by a sudden bright light directed at the eye and occurs, for example, when looking at the sun or a flashlight. With VR HMDs providing displays right in front of the eyes, we investigate whether the *Flash* trigger can be realized without attaching

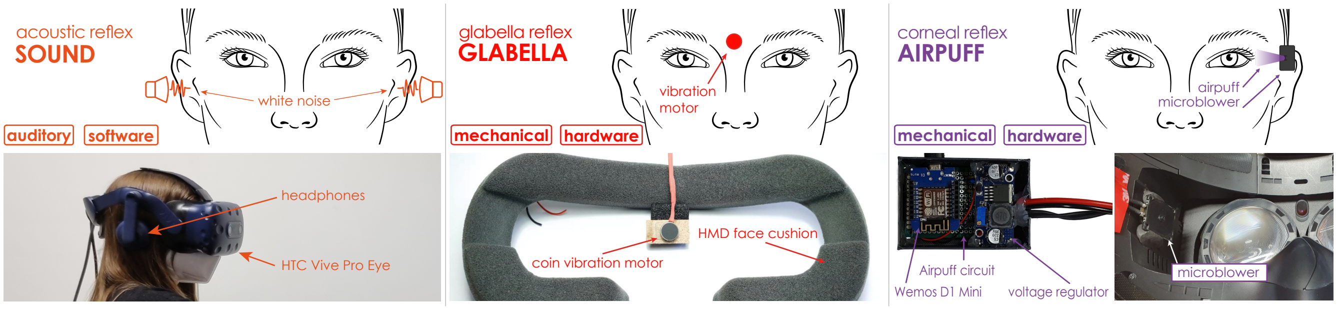

Figure 3: Implementation of the *Sound, Glabella,* and *Airpuff* blink triggers for VR. Illustration: komaart/stock.adobe.com

additional hardware to the HMD. For this, we realized a software-based *Flash* trigger by programming the display to suddenly light up and brightly illuminate the eyes.

Figure 2 illustrates the concept. After testing different colors and durations, and opting for a brief but powerful *Flash* as used in related work [8, 9, 28], we decided to use a short white stimulus. Since the max. brightness is constrained by the display inside the HMD, white was chosen to maximize retinal illumination. At the same time, the duration of the *Flash* is constrained by the refresh rate of the device and the frame rate of the VR system, which led us to display the *Flash* stimulus for one single frame (ca. 11*ms* at 90 fps, approximating the 15*ms* stimuli employed by related work [8, 9]).

Blur Trigger. The *Blur* trigger is designed to simulate a symptom of CVS in order to stimulate a blink. Specifically, this software-based trigger simulates a view through dry eyes by blurring the user's virtual camera. By this, the *Blur* trigger evokes the need to blink in order to regain clear vision. To realize the trigger, our implementation adds a Gaussian blur[2] to the rendered image before it is displayed in the HMD. To minimize obtrusion, the blur intensity builds up gradually and is removed when the user blinks.

Figure 2 shows the concept. Parameters of the trigger are the max. blur intensity and the ramp-up duration. Informal testing led us to configure our implementation as denoted in Table 1, resulting in parameters that we found to trade off blink incentive and obtrusion well while not causing motion sickness.

Approaching Object Trigger. Our third visual trigger is, to the best of our knowledge, a novel concept and the first to take advantage of the menace reflex for triggering blinks in the HCI context. The *Approaching Object* trigger works by rendering a virtual object that rapidly moves towards the user's eyes. By this, we trigger a protective closing of the eye lids, i.e., a menace reflex blink. The illusion of an object flying towards the user is facilitated by the depth perception enabled through stereoscopic HMDs. Depending on the stimulus, however, the menace reflex can cause not only a reflex blink, but also body movement or startle the user. As such side effects are not desired, we carefully considered parameters like object shape, color, size, trajectory, and speed to optimize for blink triggering while minimizing obtrusion.

After extensive informal testing, our final implementation of the *Approaching Object* trigger spawned a black virtual sphere (diameter 5*cm*) at a distance of 3*m* and 50*cm* below the HMD in front of the user. A script subsequently translated the sphere within 300*ms* in camera space towards the user, following head rotations to keep the object in sight. A shader ensured the sphere to be always rendered on top of other scene geometry. Figure 2 illustrates the trigger.

3.2.2 *Auditory Stimuli.*

Besides visual stimuli, our review of the physiology of human eye blinks has shown that also acoustic feedback can cause blinking. Thus, we also considered a *Sound* trigger.

Sound Trigger. The *Sound* trigger aims at stimulating the acoustic reflex and is implemented straightforwardly by playing a brief sound via the HMD's integrated headphones. Parameters of the *Sound* trigger are the sound itself, the volume and the duration of the playback. We observed only very high volumes to reliably elicit blinks in line with the literature [9, 36].

3.2.3 *Mechanical Stimuli.*

Apart from software-based stimuli that leverage existing hardware build into HMDs, we also considered two mechanical triggers, which both require hardware add-ons.

Glabella Trigger. The *Glabella* trigger evokes a blink by triggering the glabella reflex, i.e., by mechanically stimulating the skin above the nose between the eyebrows. With HMD face cushions covering this part of the user's face, space to integrate additional hardware for the glabella reflex is limited. Thus, due to its slim form factor, we decided to integrate a vibration motor into the cushion of the HMD (Seeed Studio Mini Vibration Motor with an Adafruit DRV2605L Haptic Motor Controller, controlled by a Wemos D1 Mini). The vibration pattern (i.e., intensity and duration) represents the central parameter of the *Glabella* trigger. To find a suitable pattern we experimented with the 123 different vibration patterns provided by the manufacturer's library (available online[3]). Moreover, in order to find a reliable yet comfortable configuration, we tested 3 different positions for the vibration motor: at, above, and below eyebrow height, centrally above the nose. We found vibrations with high intensity and long duration at or below eyebrow height to be the most reliable among the tested configurations. However, even with these configurations, we observed only an unreliable performance of the trigger. Figure 3 depicts the concept and prototype.

[2] blur shader based on https://www.ronja-tutorials.com/post/023-postprocessing-blur/

[3] https://github.com/adafruit/Adafruit_DRV2605_Library/blob/master/examples/basic/basic.ino

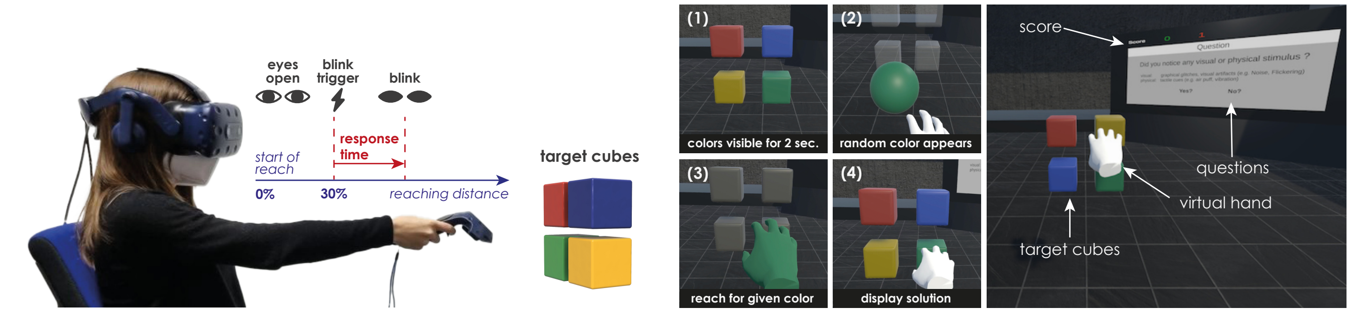

Figure 4: Left: Blink triggers are activated when the participant's hand progressed 30% towards the target cubes and the blink response time is measured. (1) to (4): The color-remembering game. Participants first remember the assignment of the four color to the four cubes, then touch the start sphere and reach for the cube that had the same color as the start sphere. While reaching for the cube, blink triggers were activated in 34% of the trials. Right: The virtual study room.

Airpuff Trigger. The *Airpuff* trigger aims to take advantage of the corneal reflex, i.e., the protective closing of the eye lids evoked when a foreign object or a blast of air is touching the cornea. The corneal reflex is an established method for triggering blinks in the medical domain [21] and showed promising results when integrated into regular glasses [9]. Thus, we transferred the concept to VR and integrated a small air blowing mechanism into the inner compartment of the HMD next to the lenses.

Figure 3 depicts the final prototype. We employed the same piezoelectric microblower as Dementyev and Holz [9] (Murata MZB1001T02). Due to the constrained space inside the HMD, we moved all remaining electronics outside the compartment. Parameters of the *Airpuff* trigger are the intensity and the duration of the airpuff, as well as its direction. In order to elicit a blink without irritating the eye too much, we mounted the blower on a plasticine socket, which allowed us to calibrate the direction of the air stream individually for each user. The blower was configured to pump a short ($300ms$) burst of air next to the left eye at high intensity ($20V$), following the recommendations of previous work [9].

4 EVALUATION

We conducted a user study to compare the proposed VR blink triggers with regard to the derived requirements. To invest the time and effort of our participants only in evaluating the most promising triggers, we sorted out methods that did not reach a satisfactory performance in informal pre-testing with our team. Here, we found the *Sound* trigger to require very loud sounds to reliably trigger blinking (in line with previous work [9, 36]). Since these loud stimuli were consistently perceived as startling and annoying, and could also be heard by bystanders, we found the *Sound* trigger to not meet the minimum requirements in terms of *unobtrusiveness* and decided to not further investigate it. In addition, the best parametrization we could find for the *Glabella* trigger only sporadically triggered a blink. Thus, the *Glabella* trigger performed too poorly with regard to the *reliability* requirement to be further investigated.

Consequently, we compared the performance of the *Flash*, *Blur*, *Approaching Object*, and *Airpuff* triggers in our user study against a *Baseline* condition in which no trigger was applied, i.e., natural blinking. The source code of these four triggers is available in an open-source repository on GitHub[4]. We designed the study task to resemble the use case of hand redirection, i.e., triggering blinks while reaching for an object. To this end, we immersed users in a representative scenario, namely, a simple color-remembering game. During this game, we applied the blink triggers when users reached for a virtual target in a desktop-scale distance. As such, our scenario implied the same strict timing constraints to the blink triggers as found, for example, in applications employing BSHR for haptic retargeting. Yet, since the proposed triggers can be applied in arbitrary use cases (i.e., not only for redirected reaching), and to contribute generalizable results, our evaluation focused on the performance of the blink triggers only and did not involve redirection. By this, our results allow us to draw conclusions about the triggers themselves and their value for VR applications independent from the combination with a specific hand redirection algorithm.

4.1 Hypotheses

Based on previous work and our observations during informal testing, we hypothesized the following:

- **H-Effectiveness**
  Each trigger is *effective* in triggering blinks, i.e., yields a shorter average blink response time than *Baseline*.
- **H-Efficiency**
  Triggers differ in their *efficiency*, i.e., their average blink response time. We expect the following order:
  (fast) *Airpuff* < *Flash* < *Approaching Object* < *Blur* (slow)

[4]https://github.com/AndreZenner/VR-blink-triggers

Table 1: Classification and parameters of the four VR blink triggers compared in the user study.

Type	Stimulus	Reflex	Trigger	Parameter	Our Settings
software	*visual*	dazzle	***Flash***	color	white
				duration	1 frame (ca. 11ms)
		(blur)	***Blur***	intensity	0.0065 (blur size)
				duration	300ms
		menace	***Approaching Object***	object	sphere (black, 5cm)
				distance	3m in front & 50cm below
				duration	300ms
hardware	*mechanical*	corneal	***Airpuff***	location	next to the eye
				intensity	high (20V)
				duration	short (300ms)

- **H-Reliability**
  Each trigger is *reliable* in triggering blinks within common desktop-scale reaching times, i.e., yields a higher average response rate than *Baseline*.
- **H-Unobtrusiveness-Unnoticeability**
  Regarding *unobtrusiveness*, triggers differ in terms of noticeability, i.e., the probability of users noticing the trigger. We expect *Blur* to be less noticeable than all other triggers.
- **H-Unobtrusiveness-Distraction**
  Regarding *unobtrusiveness*, triggers differ in distraction. We expect the following order:
  (least) *Blur* < *Airpuff* < *Flash* < *Approaching Object* (most)
- **H-Unobtrusiveness-Reduced-Performance**
  Regarding *unobtrusiveness*, triggers will negatively impact task performance, i.e., yield lower game scores than *Baseline*.

4.2 Participants

$N = 18$ ($7f$, $11m$; median age 25, min. 18, max. 40) participants recruited from the local campus volunteered to take part in the experiment. All participants were right-handed and 13 have a background in computer science and related fields. We only recruited participants that based on a self-report (1) did not have visual impairments (e.g., color blindness) to ensure that they could play the color game, and (2) could see well without glasses or contacts to ensure that the *Airpuff* stimulus could operate as planned. Our participants covered a wide range of VR experiences, with 4 participants never having experienced VR before, 4 having used VR once, 4 once in a while, 5 regularly, and 1 using VR on a daily basis.

4.3 Apparatus

The study took place in a quiet lab room at our institution. Participants remained seated throughout the experiment and wore an HTC Vive Pro Eye HMD with integrated eye trackers. In order to interact with the game, participants used the HTC Vive controllers.

The study and software-based blink triggers were implemented with the Unity game engine[5] (v2020.3.6f1), the Unity Experiment Framework (UXF)[6] [5], and the VRQuestionnaireToolkit[7] [12] on a Windows 10 system with an Nvidia GTX 1070 graphics card. The SRanipal SDK[8] (v1.1.0.1) was used for eye tracking and queried for data on eye openness. To detect blinks, the SDK's recognized pupil diameter value (in $[0, 1]$) was monitored and checked against a threshold value of 0.5 (determined during previous testing). The hardware-based *Airpuff* trigger was controlled by a Wemos D1 Mini using serial communication with the Unity application.

4.4 Procedure

The study started with the experimenter introducing the color remembering game and the participant providing informed consent to participate. To prevent bias, we did not reveal that the experiment was studying blink triggers. Instead, we told participants that the goal of the study was to investigate how different visual and physical stimuli affect users immersed in VR. The study was approved by the Ethical Review Board of the Faculty of Mathematics and Computer Science at Saarland University.

Before starting the experimental trials, the eye tracking and the *Airpuff* inside the HMD were calibrated for each participant. The headphones of the HMD played white noise during the study to make sure participants could not hear the *Airpuff* device. After calibration, participants put on the HMD. Once immersed inside the IVE (shown in Figure 4), each participant performed 5 practice trials without a trigger before starting the actual experiment.

During the experiment, each participant played the game continuously until 140 trials were completed. In each of these trials, participants had to remember the color of four cubes shown at a distance of $70cm$ in front of them. At the start of a trial, the cubes were presented with randomized colors (red, green, blue, and yellow), and the participants had $2s$ to memorize the corresponding colors. After $2s$, all four cubes turned gray and one of the four colors (random) was displayed on a start sphere that appeared $30cm$ in front of the participants. To win the game, participants had to reach forward to the start sphere, remember which of the four cubes had the same color during the $2s$-memorization phase at the beginning of the trial, and touch that cube. Once the user's hand progressed 30% along the way towards the cubes, the blink trigger associated with this trial was activated. This trigger point was chosen based on (1) informal pilot tests with all trigger types, and (2) the consideration of leaving some time for reach target prediction as often encountered in redirection scenarios [7]. Blinks were monitored using eye tracking and automatically logged. A trial was completed when the hand reached one of the cubes. After completing a trial, a prompt in VR asked participants "*Did you notice any visual or physical stimulus?*" and participants could answer either with "*yes*" or "*no*". A follow-up question asked "*How much did you feel distracted by a stimulus?*" and participants could provide their rating on a scale from 1 = *not at all* to 5 = *very*.

Once all 140 trials were completed, participants filled out the SUS presence questionnaire [31], the Simulator Sickness Questionnaire (SSQ) [17], and the NASA TLX Questionnaire [16] in VR, and completed an analogue demographic questionnaire. The session ended with a verbal debriefing during which the true cause of the study was revealed and participants could leave written comments.

4.5 Design

The study has a within-subjects design with the independent variable being the blink trigger method (*Flash*, *Blur*, *Approaching Object*, *Airpuff*, or *Baseline*). Each participant performed a total of 140 trials. Each of the four proposed triggers (*Flash*, *Blur*, *Approaching Object*, and *Airpuff*) was activated 12 times for a total of 48 randomly-chosen trials, and during the remaining 92 trials, no blink trigger was activated (*Baseline*). The randomization ensured the trigger application to be entirely unpredictable.

We measured five dependent variables to capture the performance of the triggers:

(1) *blink response time* (measured by eye tracking)
i.e., time from trigger activation to blink occurrence

[5]https://unity.com/
[6]https://github.com/immersivecognition/unity-experiment-framework
[7]https://github.com/MartinFk/VRQuestionnaireToolkit
[8]https://developer.vive.com/resources/vive-sense/eye-and-facial-tracking-sdk/

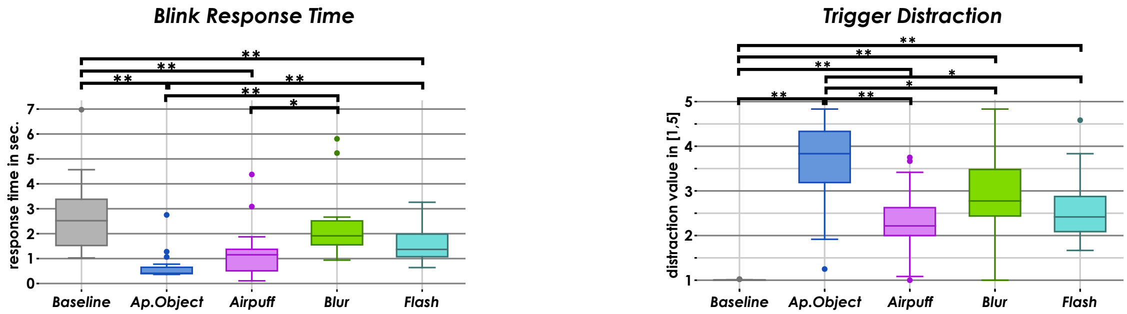

Figure 5: Box plots of blink response time (left) and trigger distraction (right). Brackets indicate statistically significant differences ($p' < .05$ (*); $p' < .01$ (**)).

(2) *blink response rate* (measured by eye tracking) i.e., percentage of trigger activations that resulted in a blink within {avg. reaching time during the experiment, 1*s*, 2*s*}
(3) *noticeability* (self-reported; binary choice)
(4) *distraction* (self-reported; 1-to-5 scale)
(5) *game performance* (measured by game logic) i.e., percentage of correctly selected cubes

4.6 Results

Before analyzing the results of the experiment, we cleaned the gathered data by scanning for cases in which no blink was logged in between two consecutive trigger activations/trials. This rare edge case could occur when a blink was not correctly detected by the eye tracking system and rendered 2.78% of the trials invalid (70 out of 2520). These trials were removed from the data set, leaving a total of 2450 valid trials for the statistical analysis. On this data, we performed Friedman tests with Bonferroni-corrected Wilcoxon signed-rank post-hoc tests to spot significant differences in the performance of the triggers for each dependent measure (applying a sig. level of $\alpha = 0.05$).

4.6.1 Blink Response Time. Figure 5 (left) shows the blink response times of the four triggers and the *Baseline*. A Friedman test revealed the response time to differ significantly across conditions ($df = 4$, $Q = 39.96$, $p < .001$). Pairwise post-hoc tests showed the response time of *Flash*, *Approaching Object*, and *Airpuff* to be significantly shorter than the *Baseline* ($M = 2.74s$, $SD = 1.49s$) (all $p' < .01$ and $r \geq .65$). *Approaching Object* resulted in fastest response times ($M = 0.67s$, $SD = 0.58s$) with the difference to *Flash* ($M = 1.56s$, $SD = 0.68s$) and *Blur* ($M = 2.25s$, $SD = 1.30s$) being found to be statistically significant (both $p' < .01$ and $r \geq .60$). Moreover, the *Airpuff* ($M = 1.23s$, $SD = 1.08s$) triggered blinks significantly faster than the *Blur* trigger.

4.6.2 Blink Response Rate. Figure 6 depicts the blink response rates of the four triggers and the *Baseline* for three representative time windows. Each window represents a common desktop-scale reaching time (left plot: avg. reaching time of 0.68*s* found in this experiment; center & right plots: common reaching times of 1*s* and 2*s* [14], respectively). Friedman tests revealed the blink response rates of the different conditions to differ significantly for all three representative time windows (all $p < .001$) and the plots indicate the results of the pairwise post-hoc tests. Within 0.68*s* after trigger activation, we found the *Approaching Object* trigger ($M = 79\%$, $SD = 36\%$) and the *Airpuff* ($M = 39\%$, $SD = 40\%$) to yield the highest probabilities for eliciting a blink, while *Flash* ($M = 6\%$, $SD = 12\%$) and *Blur* ($M = 0\%$, $SD = 2\%$) only sporadically elicited a blink in time. When considering a time window of 2*s*, these probabilities increase to $M = 94\%$ ($SD = 16\%$) for *Approaching Object*, to $M = 85\%$ ($SD = 20\%$) for *Airpuff*, to $M = 83\%$ ($SD = 24\%$) for *Flash*, and to $M = 66\%$ ($SD = 26\%$) for the *Blur* trigger.

4.6.3 Distraction. Figure 5 (right) plots how much participants were distracted by the four triggers, as well as the distraction perceived when no trigger was employed in our control condition *Baseline*. A Friedman test indicated distraction to differ significantly across the conditions ($df = 4$, $Q = 50.33$, $p < .001$). Brackets in Figure 5 show the results of the pairwise post-hoc tests. On a 1-to-5 scale, the *Approaching Object* trigger ($M = 3.57$, $SD = 1.08$) was found to be significantly more distracting than every other condition (all $p' \leq .02$ and $r \geq .51$). Differences among the remaining triggers *Flash* ($M = 2.57$, $SD = 0.74$), *Blur* ($M = 2.83$, $SD = 1.02$), and *Airpuff* ($M = 2.33$, $SD = 0.74$) were not statistically significant.

4.6.4 Noticeability. The results on noticeability show that the *Blur* trigger was least noticeable with an average probability of being noticed of $M = 89\%$ ($SD = 25\%$). All other triggers showed a noticeability of $\geq 99\%$ and the difference to the noticeability of the *Blur* trigger was not found to be significant (all $p' \geq .27$). As expected, the probability of users reporting to have noticed a stimulus in the control condition *Baseline* was negligible ($M = 1\%$, $SD = 1\%$).

4.6.5 Game Performance. The results on the number of correctly selected cubes in the color remembering game did not show an impact of the triggers on game performance. The percentage-correct was $\geq 94\%$ for all triggers, and $M = 95\%$ ($SD = 7\%$) in the control condition *Baseline*. Minor differences between the conditions were not found to be statistically significant.

4.6.6 Post-Experiment Questionnaires. The SUS Count ($M = 1.83$, $SD = 1.98$) and SUS Mean ($M = 4.06$, $SD = 1.47$) showed that the IVE was generally immersive and the SSQ total score ($M = 34.91$, $SD = 28.74$) verified that there were no sickness issues. The NASA TLX indicated the task to result in a medium workload (mental demand at $M = 55.56$ ($SD = 24.67$), temporal demand at $M = 37.22$

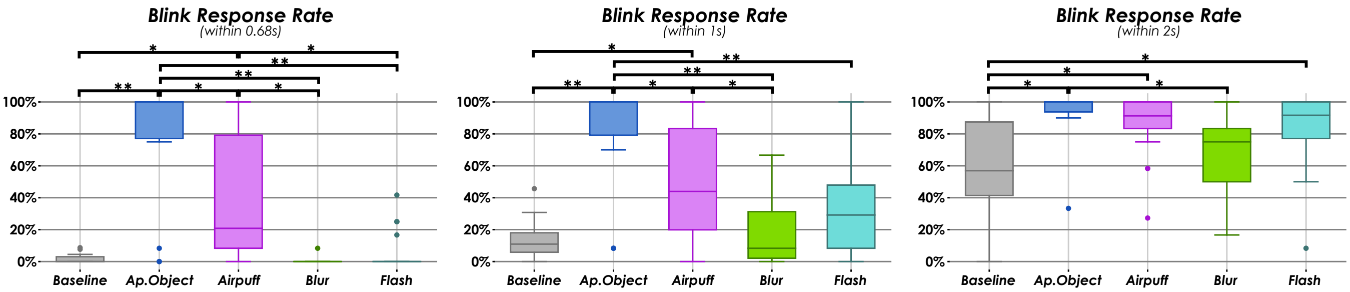

Figure 6: Box plots of the blink response rate for reaching times of $0.68s$ (avg. reaching time in our experiment), $1s$, and $2s$ (common desktop-scale reaching times [14]). Brackets indicate statistically significant differences ($p' < .05$ (*); $p' < .01$ (**)).

($SD = 25.97$), effort at $M = 57.22$ ($SD = 23.09$)) that could be handled well by the participants (overall performance subscore at $M = 82.22$ ($SD = 10.88$), all other subscores with $M \leq 18.89$).

5 DISCUSSION

To increase the control over users' blinking behavior in VR, we implemented six different blink trigger methods tailored specifically to VR. To find out which method suits best for decreasing the dependency of blink-based techniques like RDW and HR on spontaneous and voluntary blinks, we evaluated the performance of the four most promising triggers in a user study. The results reveal the pros and cons of the different methods.

5.1 Effectiveness & Efficiency

We could show **H-Effectiveness** for the *Flash*, *Approaching Object*, and *Airpuff* triggers and found all three to successfully induce blinks on demand. In contrast to that, the *Blur* trigger did not result in response times significantly different from the control condition.

Comparing the four triggers among each other, we found the *Airpuff* (corneal stimulus) to result in slightly faster blink responses than the *Flash* (dazzle stimulus), although the difference was not significant, and found the *Blur* (simulation of dry eyes) to elicit blinks the slowest as expected, with the difference to the *Approaching Object* and *Airpuff* being significant. The results of the *Approaching Object* trigger, however, were surprising to us. This method, which is unique to VR as it triggers the menace reflex leveraging the immersive capabilities of stereoscopic HMDs, resulted in the shortest response times of all triggers and showed only small variation across participants. This indicates the menace reflex to be effective and efficient, and hence highly interesting for triggering blinks in VR. Thus, overall, we found **H-Efficiency** to be generally supported by our data (but not all of the between-trigger differences were statistically significant) and found a slightly different order than expected, namely:
($M = 0.67s$) *Approaching Object* < *Airpuff* < *Flash* < *Blur* ($M = 2.25s$)

5.2 Reliability for Redirected Reaching

While all tested triggers showed blink response times compatible with RDW, only some triggers were found to be reliable for HR. Redirected reaching imposes stringent timing requirements on the blink trigger technique as a blink is required before the user's hand reaches its target, i.e., blink responses need to occur within common desktop-scale reaching times. Our experiment resulted in fast reaching motions and short average reaching times of only $M = 0.68s$ ($SD = 0.49s$), but also time windows of up to $2s$ are commonly encountered in related studies [14]. Considering these requirements, we can show **H-Reliability** and make a recommendation for reaching-related use cases only for:

- *Approaching Object* and *Airpuff* within $0.68s$ and $1s$ windows
- *Approaching Object*, *Airpuff*, and *Flash* within a $2s$ window

5.3 Noticeability, Distraction, & Game Score

Our initial aim was to develop blink triggers for VR that can go entirely unnoticed. During preparatory testing and parameter optimization, however, we found all reliable trigger configurations to result in stimuli that were noticeable by our team. Yet, it was unclear how unprimed participants naïve to the workings of the triggers would perceive the stimuli. At the time of the user study then, we only expected the triggers to differ in their noticeability (but we did not expect the triggers to go entirely unnoticed) and hypothesized the rather subtle *Blur* stimulus to be least noticeable. The results of our study finally revealed that, in line with our expectations, the *Blur* trigger was noticed the least. However, our general finding is that each tested trigger is easily noticeable and our statistical tests did not show support for **H-Unobtrusiveness-Unnoticeability**. Anecdotally, however, it remains interesting and motivating that one participant did not notice the *Blur* trigger in any trial.

Based on these results we conclude that effectively and efficiently triggering blinks in VR is possible, even during time-critical interactions like reaching. Yet, we also conclude that the presented trigger stimuli will very likely be noticed by users. Hence, it is critical to consider *how* these stimuli are perceived. To this end, our results show support for **H-Unobtrusiveness-Distraction**, i.e., triggers differ in comfort. Yet, in contrast to our expectations, we found the following relationship between triggers in terms of distraction (on a 1-to-5 scale):
($M = 2.33$) *Airpuff* < *Flash* < *Blur* < *Approaching Object* ($M = 3.57$)
Analyzing the statistical results, we conclude that the *Approaching Object* trigger was perceived as most distracting with a medium to high obtrusion. Yet, our observations during the experiment further back our parameter tuning as only 1 participant (female, age 33, using VR once in a while) showed slight signs of a startle reaction, i.e., winced slightly. This reaction, however, only occurred for the *Approaching Object* trigger and did not result in any threat

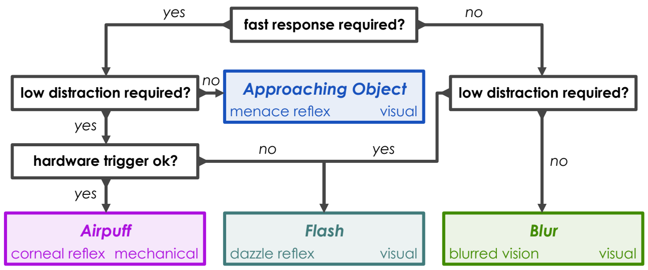

Figure 7: Decision tree for choosing a VR blink trigger.

of falling over, since participants were seated during the experiment. All other triggers were experienced without any participant showing observable signs of being startled and were perceived as significantly less obtrusive with a low to medium distraction as summarized in Figure 5 (right). When explaining the details of each trigger in the verbal debriefing after the experiment, no participant commented negatively about the triggers or expressed unwillingness to use the tested triggers – instead, many users were enthusiastic about the approaches. These results are in line with our finding that the experienced distraction from the triggers did not affect task performance, which remained high across conditions, and **H-Unobtrusiveness-Reduced-Performance** was not supported – highlighting the potential of blink triggers for productive VR systems despite their distraction. Future studies will be required to investigate how well this finding generalizes to more complex tasks and interactions.

5.4 When to Choose Which Trigger?

We condense our findings in a set of recommendations for triggering eye blinks in VR. To help researchers and practitioners in choosing suitable trigger methods, we derived a decision tree shown in Figure 7 from the results of our comparative study. According to our findings, we distinguish the following main cases:

5.4.1 Airpuff Scenarios. In use cases where fast blink responses are required and distraction is of concern, and the usage of a hardware-based solution for triggering blinks is an option, we recommend the *Airpuff* trigger. The *Airpuff* trigger was found to be the best compromise between trigger performance and comfort. It showed the second-best effectiveness and reliability, while being subtle and the least distracting trigger in our selection. Its main drawback, however, is that it requires to augment existing HMDs with additional hardware and a per-user calibration of the airpuff to account for different head sizes and geometries.

5.4.2 Flash Scenarios. In use cases where fast blink responses are required and distraction is of concern, but a hardware-based solution is *not* an option, we recommend the *Flash* trigger. The *Flash* trigger showed a triggering performance similar to the *Airpuff* and was also found to result in similar distraction. The drawback of the *Flash* trigger, however, is that with the settings tested in this study, the trigger might not always elicit blinks quickly enough for fast reaching-based scenarios like HR. A better performance might potentially be achieved by employing brighter displays inside the HMD to increase retinal illumination.

5.4.3 Approaching Object Scenarios. When fast blink responses are required but distraction is *not* of concern, we recommend the *Approaching Object* trigger. The *Approaching Object* trigger showed the best blink triggering performance in our study, proved to be very reliable even for reaching-based scenarios with strict time constraints, and is entirely software-based. Its main drawback, however, is that it startled some users and resulted in the highest distraction ratings of all tested triggers. To improve this, it seems advisable to adapt the trigger to the logic and aesthetics of the IVE. This might potentially make the stimulus appear more plausible and reduce perceived distraction. Instead of using a black sphere flying towards the user, for example, a simulation or game could show a virtual bee fly towards the user on a curvy trajectory, accompanied by buzzing sounds, or show a virtual raindrop fall into the user's face.

5.4.4 Blur Scenarios. Based on its performance in the comparative study, we would generally not recommend to use the tested configuration of the *Blur* trigger as it introduced distraction while not significantly beating the *Baseline*. Yet, one observation might justify the usage of the *Blur* trigger in scenarios where fast blink responses are not required and distraction is not of concern: The *Blur* trigger was the only trigger that was entirely unnoticeable for one of our participants. Based on this observation, further research seems worthwhile to investigate if configurations of the *Blur* trigger exist that can reliably go unnoticed for a greater population while still being capable of triggering blinking. If such configurations were found, the full potential of the *Blur* concept could be leveraged, potentially leading to a truly unobtrusive triggering technique.

5.5 Limitations & Future Work

Our results show that it is hardly possible to make blink triggers go unnoticed. Thus, when integrating them into VR applications, the goal should be to use stimuli that are perceived as comfortable. To this end, future studies should explore if tailoring the stimuli to the setting and aesthetics of the IVE can reduce distraction. In addition to that, the presented triggers can be further studied and evolved:

Our *Flash* trigger, for example, could be compared to an implementation with different flash patterns, brighter displays, or additional hardware (e.g., LEDs) build into the HMD [9]. Concerning the *Blur* trigger, we motivate future studies to explore when to best trigger the gradual blurring, how the stimulus needs to be configured to go unnoticed, and to study if such configurations can suffice to trigger blinks. Future research on menace reflex-based triggers could try to reduce distraction by rendering the *Approaching Object* only every other frame, or only on one eye [19]. In addition, to improve the *Airpuff* trigger, advanced implementations could capitalize on eye tracking cameras inside the HMD and actuate the blower nozzle to aim next to the eye for automated calibration.

Regarding the methods we sorted out for this study, we still encourage future projects to consider the acoustic reflex. *Sound* triggers might be suitable for VR applications in which loud sounds are expected (e.g., explosions in an action game). Moreover, despite the unreliable performance of the vibrotactile feedback, we recommend studying future implementations of the *Glabella* trigger that are based on tapping [28] to see if the reliability can be improved.

In addition to the triggers studied in this paper, further ideas remain to be explored, such as triggers based on EMS or temperature. Furthermore, we recommend to explore the combination of different triggers. By this, the intensity of individual stimuli could potentially be reduced while the overall effectiveness be improved.

Finally, taking into account how redirection techniques work, future research should also explore if the trigger stimuli themselves cause change blindness. If so, they would provide an additional opportunity for virtual manipulation, e.g., during the *Flash* or when the *Approaching Object* occludes the view of the virtual scene. An additional avenue for future work is to study habituation effects with regard to the blink triggers [28], and ultimately, future work should investigate systems that use redirection techniques in combination with blink triggers to shed light on how well both approaches integrate in practice.

6 CONCLUSION

Motivated by techniques that take advantage of human eye blinks to redirect users in VR [20, 41], we studied how the control over users' blinking behavior in VR can be improved. For this, we investigated six different methods to trigger eye blinks in VR, each based on a different blink reflex. After implementing the soft- and hardware-based triggers, we evaluated the four most promising approaches in an empirical user study and formulated (i) effectiveness, (ii) efficiency, (iii) reliability, and (iv) unobtrusiveness as central requirements for successful triggers. To derive recommendations, our experiment assessed the performance of a *Flash*, *Blur*, *Approaching Object*, and *Airpuff* trigger in a scenario inspired by the use case of redirected reaching [41].

Our results verified that triggering blinks in VR is possible. At the same time, we conclude that our triggers are very likely to be noticed by users and generally perceived as distracting – with different triggering techniques leading to different levels of distraction. We found the triggers based on the dazzle (*Flash*), menace (*Approaching Object*), and corneal (*Airpuff*) reflexes to perform best in terms of triggering performance and further revealed differences in the triggers' reliability in time-critical scenarios. Finally, we condensed our findings in a set of recommendations and contributed a decision tree to support researchers and practitioners in choosing suitable blink triggers for their VR applications.

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