Instant Hand Redirection in Virtual Reality Through Electrical Muscle Stimulation-Triggered Eye Blinks

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Figure 1: We explore the use of electrical muscle stimulation to elicit eye blinks in VR users for instantaneous hand redirection. In a first eye-tracking experiment, we verify the reliability of triggering full eye closure with our novel stimulation model (left). In a second comprehensive VR experiment, we exploit muscle stimulation in conjunction with hand tracking to achieve imperceptible redirection (middle and right). Thereby, our method does not require eye tracking.

ABSTRACT

In this paper we investigate the use of electrical muscle stimulation (EMS) to trigger eye blinks for instant hand redirection in virtual reality (VR). With the rapid development of VR technology and increasing user expectations for realistic experiences, maintaining a seamless match between real and virtual objects becomes crucial for immersive interactions. However, hand movements are fast and sometimes unpredictable, increasing the need for instantaneous redirection. We introduce EMS to the field of hand redirection in VR through precise stimulation of the eyelid muscles. By exploiting the phenomenon of change blindness through natural eye blinks, our novel stimulation model achieves instantaneous, imperceptible hand redirection without the need for eye tracking. We first empirically validate the efficiency of our EMS model in eliciting full eye closure. In a second experiment, we demonstrate the feasibility of using such a technique for seamless instantaneous displacement in VR and its particular impact for hand redirection. Among other factors, our analysis also delves into the under-explored domain of gender influence on hand redirection techniques, revealing significant gender-based performance disparities.

CCS CONCEPTS

• **Computing methodologies → Virtual reality**; **Perception**.

KEYWORDS

Hand redirection, EMS, virtual reality, redirection, VR, eye blinks

ACM Reference Format:
Colin Groth, Timon Scholz, Susana Castillo, Jan-Philipp Tauscher, and Marcus Magnor. 2023. Instant Hand Redirection in Virtual Reality Through Electrical Muscle Stimulation-Triggered Eye Blinks. In *29th ACM Symposium on Virtual Reality Software and Technology (VRST 2023), October 9–11, 2023, Christchurch, New Zealand*. ACM, New York, NY, USA, 11 pages. https://doi.org/10.1145/3611659.3615717

1 INTRODUCTION

In recent years, VR technology has evolved at a remarkable speed, with modern devices offering new features such as eye tracking (ET), facial tracking and hand tracking. As the realism of VR presentations increases, so does the user's expectations for the experience. A mismatch between the visual and tactile perception of a scene can cause irritation and break the immersion of the user.

Redirection techniques can perform unnoticeable manipulations to the real-to-virtual mapping to maintain the user's sense of presence even when the physical environment does not match the virtual one. Two representative examples are hand redirection (HaR) to adjust for an offset between real and virtual objects or redirected walking to allow exploration of larger virtual environments and avoidance of obstacles in the real room. HaR adjusts the position of

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VRST 2023, October 9–11, 2023, Christchurch, New Zealand

ACM ISBN 979-8-4007-0328-7/23/10.
https://doi.org/10.1145/3611659.3615717

the virtual hand to obtain correct haptic feedback even if the virtual and physical object positions or scene geometry do not coincide.

A practical example of the potential benefits of HaR comes from prototype production. Nowadays, when the interior of a new automobile is designed, usually virtual models are created and examined in VR. For compelling interaction and a true-to-life experience, a physical representation of the most important parts of the cabin is used as a haptic proxy. However, extensive physical models that are adjusted with each iteration of the virtual model are impractical. Here, a generic haptic proxy along with a HaR solution would save time and money while improving the overall user experience.

HaR exploits the phenomenon of virtual dominance [16]. In a conflict between visual and proprioceptive sensations, the human brain tends to trust the visual information more. Conventional HaR applies an incremental offset to the virtual hand, which is corrected by a natural compensatory movement in the opposite direction, thus reaching an offset target. Besides this continuous redirection, some works try to exploit the effect of change blindness for the purpose of redirection. Change blindness describes the phenomenon of people's inability to perceive changes in an object or scene [49]. Naturally, change blindness occurs as soon as the vision is temporarily interrupted, for example, because an eye blink is performed.

Both, research on HaR [58] and redirected walking [31, 32, 42] try to detect and utilize natural blinks for subtle redirection. Compared to other redirection methods, the exploitation of change blindness allows for instant redirection. This unnoticeable, instantaneous displacement is particularly interesting for unexpected changes in the direction of movement or to enhance continuous methods for particularly strong redirection [58]. Humans blink approximately 15-20 times per minute [39]. Relying on users to have their eyes closed at the exact moment when redirection is needed seems impractical. Accordingly, it would be highly advantageous to subtly encourage the user to blink at precise moments to exploit the associated change blindness. The literature presents methods that systematically induce eye blink. The stimulation in these cases is performed by bright light flashes [46], airpuff stimulation [35, 53], physical taps to the glabella [46] or loud sounds [48]. Unfortunately, these techniques were found to be very intrusive and do not have a good success rate in most cases.

In this paper, we investigate the actuation of eye blinks by electrical stimulation of the eyelid muscle and evaluate the applicability of this method for instant redirection. We present the first electrical muscle stimulation (EMS)-based model for symmetric blink stimulation that was developed based on extensive preliminary studies and expert knowledge. Our model achieves eye closure by low electrical currents and causes the corresponding blinking response by intrinsic body signals. The efficiency of the blink stimulation is evaluated in a first psychophysical experiment. Secondly, in an experiment on HaR in VR, we demonstrate the capability of the blink stimulation for instant redirection. Although we chose a intentionally challenging scenario for the experiment, our EMS-based instant HaR achieves detection thresholds on par with those of prior publications. In comparison to other methods, eye tracking is not required for the implementation. Moreover, we investigate the role of gender on the efficiency of HaR techniques, which is unknown to date. We found that gender indeed is important for the efficiency of the redirection, with significantly better performance in females.

2 RELATED WORK

2.1 Hand Redirection in Virtual Reality

Hand Redirection (HaR) involves deliberately manipulating the mapping between the real and virtual environment to gain control over the movement of the user's hand. In the scope of this research, HaR aims to enable the VR system to direct the user's real hand movement towards a different target than what the user perceives. This redirection can be compared to redirected walking where users are deceived into following a physical path that differs from their virtual path [19, 32, 52]. The redirection of hands is useful in various VR applications, most notably to enhance the scalability of passive haptic feedback [26].

Hartfill *et al.* explore VR avatars with fully articulated hands, fostering natural interactions in a VR environment [25]. Their study investigates non-isomorphic techniques, particularly a hand retargeting approach for slower movements, relevant in therapeutic contexts. Psychophysical experiments reveal distinct detection thresholds of mid-air motion paths, with no significant difference between dominant and non-dominant hand. In the work of Kohli *et al.* , redirected touching is introduced, a technique that combines distortions in the virtual scene with HR to convey the perception of differently shaped virtual objects using only a single haptic proxy [29]. Azmandian *et al.* later proposed using HR for haptic retargeting, allowing users to interact with spatially dislocated virtual cubes mapped onto one single physical proxy [4]. This proxy in the real environment allowed users to have proper haptic feedback during their interactions with the virtual objects. Building upon the former work, Cheng *et al.* presented research on HaR in VR for simulating touch feedback using sparse haptic proxies [9]. They demonstrated the effectiveness of continuous HaR and discovered that touch intentions could be predicted based on users' eye gaze. Their work emphasized the importance of considering both physical and cognitive factors in designing immersive and realistic VR experiences with enhanced touch sensations. Furthermore, HR has been applied to enhance the perceived resolution and speed of shape displays [1], overcome limitations in encountered-type haptic systems [2, 17], extend the range of haptic effects [56, 57], and enable more ergonomic interactions with virtual user interfaces and scenes [38]. Additionally, redirection techniques have been explored in the context of 3D interaction techniques and pseudo-haptic effects, simulating drag or weight sensations [11, 45, 47]. In most cases, hand warping techniques involve either a constant offset [5, 24] or incremental relocation of the real-to-virtual mapping [4, 7, 9, 12, 29, 51, 58].

To address the time-critical nature of hand movements, this work investigates the use of stimulated blinks as a means of achieving instantaneous redirection in hand-related tasks. Previous research by Zenner *et al.* already utilizes the change blindness effect during spontaneous blinks to offset the virtual hand [58]. In their study, blink-suppressed HaR (BSHR) was explored and found that combining BSHR with continuous redirection yielded better results than BSHR alone. The detection threshold for BSHR was around 8° (right, down) and 1.12 scale (towards). However, relying solely on spontaneous blinks occurring on average every 3 seconds may not be sufficient for fast hand movements [39]. This work focuses on exploring the use of stimulated blinks to achieve time-critical redirection in hand-related tasks, building upon previous research by Zenner *et al.* [58] and Cheng *et al.* [9].

2.2 Electric Stimulation for Eye Blinks

The beginnings of modern blink research is associated with the work of Kugelberg, who first classified the blink reflex in 1952 [30]. In this early days the reflex was triggered by physical taps. Electrical blink stimulation has been studied in recent years, mainly as a method of restoring the natural blink appearance in people with facial palsy and for facial pacing to counteract dry eye symptoms. McDonnall *et al.* were among the first to perform electrical blink stimulation [36]. In patients with facial paralysis, they detected eyelid movements on the healthy side of the face to elicit a simultaneous blink response on the paretic side. In their approach, the electrodes were implanted into the eyelid of the patient. In a more recent study, Frigerio *et al.* used transcutaneous neural stimulation by surface electrodes to elicit eye blinks in individuals with acute facial paralysis [15]. Their method had a 55% success rate, while the sensation of stimulation was rated as tolerable for daily use. In their experiments, an average current of 7.2 mA was required for full eye closure. Note, that this is well above our safety threshold of 2.5 mA. VanderWerf *et al.* investigated eyelid movements under different stimulus conditions, including electrical stimulation [53]. They inserted a direct magnetic search coil into the eye and recorded its movements with EMG of the orbicularis oculi. They found that blinks induced by electrical stimulation have the shortest duration and are the most predictable. Lylykangas and colleagues have been major contributors to the field of constant-interval electrical blink stimulation [33, 34]. While their 2018 work, investigates the overall prevention of corneal damage due to the absence of blinking [33], in a more recent publication, the authors focus on the functionality and subjective experience of timer-triggered blinks [34]. They showed that dry eye symptoms caused by chronic unilateral facial palsy could be significantly reduced by using predefined stimulation intervals. In their study of healthy participants, the stimulation was reported as not painful but mildly uncomfortable. Rantanen *et al.* investigated facial stimulation for both eye blinking and mouth movements in individuals with unilateral facial palsy [44]. Whilst no experiments were conducted, the paper provided valuable insight into the appropriate size of the electrodes for healthy stimulation ($\geq 2mA/cm^2$). Several studies show that the human blink reflex is independent from the type of stimulation. Snow and Frith investigated the relationship between the blink reflex and eyelid movement [50]. In their studies, both electrical and tapping stimulation were used with equal success. The relationship between the orbicularis oculi reflex and the type of stimulation has also been discussed by Cruccu and Deuschl [10]. They argue that blinking is generally independent on the stimulus. Other papers delved more into the investigation of the movement of the eyelid during blinking. Evinger *et al.* characterized movements of the eyelid in a study that combined a search coil and EMG of the orbicularis oculi [13]. Hammond *et al.* studied the early components of the blink, namely the cutaneous blink reflex, and how they relate to various properties of eyelid movement [23].

The former papers have demonstrated that electrical stimulation can be effectively used to restore a natural blink appearance and counteract dry eye symptoms in individuals with facial palsy. Since unilateral facial paralysis was considered the stimulation models developed so far are only suitable for unilateral blinking. Although the success rate of eliciting full eye closure varies between studies, it is clear that electrical stimulation can be an effective tool to trigger a blink response. Note that, in none of the works severe adverse effects were caused by electrical stimulation. However, it was reported to be slightly uncomfortable in some cases. Although we have focused so far on electrical stimulation, blink responses can be elicited in several other ways. In a recent work, Zenner *et al.* extensively investigated techniques for inducing the blink-reflex in immersive VR [59]. Their work compared a verity of non-electric triggers, including visual, airpuff, mechanical, and auditory stimuli. The authors compared four promising techniques in a user study to reveal insights for efficacy and design recommendations. Notably, the VR-specific trigger through approaching virtual objects achieved best reliability. Thereby, the effectiveness of most methods contrasted with their potential disturbance, which should be taken into account in design decisions. In this paper, we propose a novel stimulation model that allows for the electrical stimulation of symmetrical bilateral eye blinks. We then use our stimulation model in an experiment to evaluate its efficient use for time-critical redirection tasks.

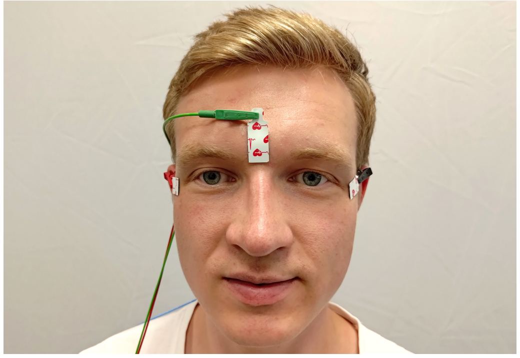

Figure 2: Placement of the adhesive electrodes.

3 STIMULATION MODEL

In this paper, we present a novel stimulation model for non-invasive and systematic actuation of eye blinks. Our model stimulates the orbicularis oculi muscles, which by contraction cause the eyelid movements. The stimulation requires only low electric currents that are safe for use in humans. The model was developed based on medical considerations and preliminary studies with multiple electrode placements tested. In order to effectively stimulate both eyes, three electrodes are attached to the wider area of the user's eye (see Fig. 2). The first electrode is placed vertically on the glabella, the area just above the nose and between the eyebrows. The other two electrodes are applied in a horizontal position on either side of the eyes next to the lateral canthal region, 0.5 cm from the orbital rim towards the ears. During stimulation, the glabella electrode serves as the anode (current = $2X$), while the other two electrodes make up the opposite pole, each with half the charge (current = $-X$

per electrode). The glabella electrode therefore operates as a current divider, distributing the stimulus equally to both eyelid muscles.

As the stimulation is applied, electric currents unfold over the orbicularis oculi, specifically the upper eyelid, causing irritation of the muscle, similar to a light physical touch. As a result, a signal is sent to the brain requesting contraction of the eyelid muscle. The blink is thus triggered by a brain signal as a natural response of the human body. Alternatively, the zygomatic branch of the facial nerve, located on the lateral part of the orbital rim, can be directly stimulated to initiate eyelid movement [15, 33, 34]. However, our pilot studies have shown that the effects of such stimulation are much smaller. In most cases, they are not sufficient to elicit a full eye closure with the required current safety threshold. Others proposed a stimulation of the supraorbital nerve with the cathode at the foramen, next to the eyebrows above the orbit, and the anode placed lateral on the forehead [53]. However, our empirical findings suggest that with a safe threshold, this stimulation is much more likely to activate the eyebrow muscles than to stimulate the nerve sufficiently for eye closure.

The effect of stimulation seems to depend only on the alteration in direct current due to abrupt stimulation changes, rather than on constant stimulation. In preliminary experiments in which we gradually ramped up the current from zero to the maximum (and vice versa), blinking could not be elicited. However, this only applies to two-sided ramping with incremental steps at the beginning and end of the stimulation. The transient state that provokes eye contraction is initiated by two events: the current alteration from full current to zero and from zero to full stimulation. However, if the stimulation does not last longer than the combined time of the reaction delay and the blink duration (around 130 + 120 ms), the body treats the two current changes as one state and only one blink is elicited.

For stimulation, we apply countercurrents to Electrical Muscle Stimulation (EMS) to achieve the same stimulating effect with half the power. Countercurrents were proposed by Aoyama *et al.* [3] for use in Galvanic Vestibular Stimulation (GVS), a special type of electrical stimulation of the vestibular system that activates the semicircular canals in the inner ear and produces a sense of motion. We have adopted the idea of countercurrent stimulation for eyelid EMS. Instead of stimulating from time 0 to N with the current X, we stimulate with half the charge but switch the polarity in between. Formally:

$$C(t) = \begin{cases} \frac{X}{2} & 0 \leq t \leq \frac{N}{2} \\ -\frac{X}{2} & \frac{N}{2} < t \leq N \\ 0 & \text{otherwise} \end{cases}$$

Hence, the amount of the electricity C used at any time t during the stimulation is halved, while the effect is sustained. In the experiments, the maximum current value X is determined per participant during the calibration phase.

The size of the electrodes has been chosen as a balance between the need for efficient stimulation and skin safety. Thereby we followed previous research on healthy stimulation to avoid skin irritation [44]. At the same time, we make sure that the electrode size is small enough to maximize efficiency. The electrodes next to the eyes have a size of 17 x 13 mm, while the electrode for the glabella position has a size of 25 x 13 mm. This larger size for the glabella electrode is appropriate as it handles twice the current of the opposite poles. We have found that the larger electrode achieves the same stimulation effect while minimizing the risk of skin irritation by covering a larger area of skin.

4 EXPERIMENTS

All experiments are approved by the university's ethics committee under the identification number FV_2023-01.

We conducted two experiments to evaluate the practical use of EMS-based blink stimulation. The first experiment validates the effectiveness of the proposed stimulation model for eye blink success rate and properties of the elicited blinks. Based on these insights, the second experiment exposes users to a realistic HaR scenario in VR where HaR is performed instantaneously during the induced eye blinks as well as with continuous redirection.

4.1 Experiment 1: Blink stimulation and ET

In a first experiment we evaluated the efficiency of our proposed eye blink stimulation model. We also aimed to gain deeper knowledge about the nature of the eye blinks that are elicited by EMS. This experiment is performed without VR glasses, but instead participants looked at images on a monitor to utilize our stationary high-performance eye tracking (ET).

Stimuli. The EMS of the eyelid muscles was performed as described in Sec. 3. As a visual stimulus, we showed multiple images from an image retargeting dataset to the participants containing artifacts from the retargeting process [8]. The images were not relevant for the evaluation of the stimulation method, but provided a visual landmark to take the participant's attention away from the electrical stimulation, as would be the case in a practical scenario with dynamic visual content. All images were displayed in random order for 18 seconds each. To provide a dummy task to participants, they were asked to explore the images and find artifacts.

Apparatus. For the EMS, we use a stimulation device from Good Vibrations Engineering [54]. The device is restricted to a maximum current of 2.5 mA per electrode. The latency between sending a signal in the application and stimulation output to the electrodes is less than 15 ms. By using battery power and information transmission via air-gapped fiber optics, the device is protected against any unanticipated power transmission. For the eye tracking we used a desktop-mounted EyeLink 1000 eye tracker by SR Research that provides a 1000 Hz sample rate and reliable blink detection.

Participants. A total of 15 participants took part in the experiment (6 females, Age range = 23-66, Avg age = 32.12, SD = 13.09). One participant terminated the experiment early by his own will. However, no participant experienced severe negative symptoms from the stimulation, e.g. severe discomfort, which would have resulted in an immediate termination of the experiment. The participation in this experiment was voluntarily and without compensation.

Procedure. Prior to the experiment, all participants were provided with a consent form and information about the experimental procedure, as well as the functionality and safety of the EMS stimulation device. We told participants that the experiment aims to

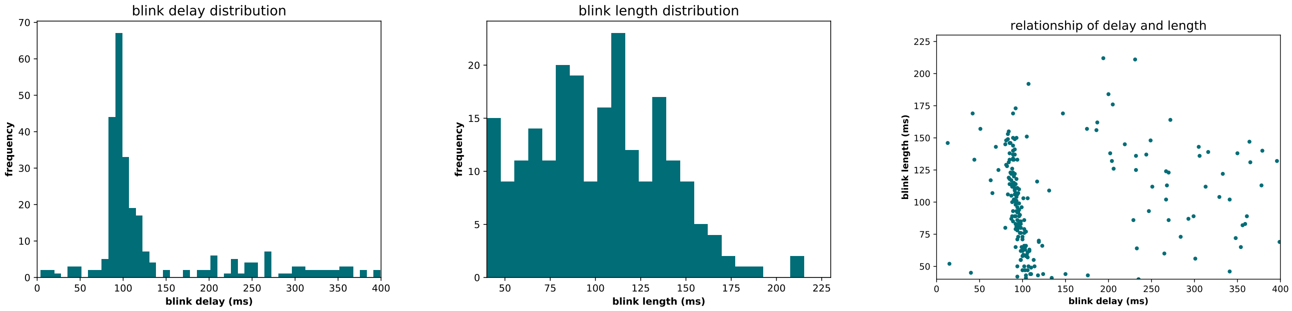

Figure 3: Distribution of the delay between start of the stimulation and start of the blink (left), blink length (middle) and relation of both former parameters (right).

investigate eye tracking in combination with EMS near the orbicularis oculi, without disclosing the true objective of blink induction to avoid any biases. The placement of the three electrodes was carried out according to the methodology described in Sec. 3, one at the glabella and two lateral to the eyes. Before attaching the electrodes, we meticulously cleaned the corresponding skin areas with an alcohol pad to enhance conductivity and electrode adhesion. Prior to the start of the experiment, the optimal stimulation current for each participant was determined. For the calibration, we gradually incremented the current until we observed induced full eye closure. This was our criterion for determining whether the blink induction was successful. Throughout the process, participants were asked to communicate any discomfort or general sensations they experience, allowing us to adjust the current intensity accordingly. The stimulation current chosen was the one that elicited the strongest blink reflex without causing unwanted negative feelings, which was double-checked by three additional stimulations to ensure consistent full eye closure. For the experimental setup, participants were positioned 95 cm in front of a screen and their heads were rested on a chin rest to maintain a consistent viewing distance (see Fig. 1). To ensure accurate eye tracking, we executed a calibration routine that personalized the eye tracker to each individual participant, followed by a validation routine to ensure accuracy. The experiment consisted of 70 stimulation trials and 30 sham trials with no stimulation, which were randomly distributed to avoid anticipation bias. Each trial lasted 3000 ms while the stimulation had a fixed duration of 40 ms, determined by previous pilot experiments. Stimulation occurred once during a random time within the stimulation trial, with a safety gap of 500 ms to the start and end of each trial to account for the eye's relaxation time after blinking. Eye blinks induce rapid changes in pupil size characterized by a decrease and subsequent increase within 500 ms after eye closure [39]. Participants did not wear glasses during the experiment to avoid interference with the eye tracking system. However, all participants reported clear visibility of the display. After the experiment, participants filled in demographic questions and rated the sensation experienced during stimulation.

Questionnaire. We ask two successive questions to evaluate participants' feeling of the electrical stimulation. First, participants classified the stimulation with one of the following categories: unnoticeable, perceptible, discomfortable, pain. For all classifications except for unnoticeable stimulations a more detailed rating of the intensity of the feeling is asked for in the next step. To rate the sensation's intensity, we use a Borg CR10 scale. This scale rates the subjective sensation of participants between 0 and 12 and represents a common approach in medicine to provide perceptual ratings. Already in early research, the perceptual intensity was found to grow with the logarithm of the physical intensity [14]. The Borg CR10 scale is based on logarithmic growth functions, determined by internal psychophysical criteria, based on former results on ratio scaling methods [6]. Multiple studies show the advantage of this measurement method over other methods like the visual analogue scale [41, 55].

4.2 Results of Experiment 1

We found that for most people the blink induction worked well while no blinks were evoked in others. Overall, 60% of the participants showed a positive blink response. For the participants where blinks could be induced properly, the average blink rate is 72%. The other participants that did not respond on the electrical stimulation, their rate of blink responses in 8% of the time is on the same level of natural eye blink behavior [39]. It is a surprising finding that for EMS-based blink stimulation two response groups seem to exist with either a consistent eye closure response or full resistance against any electrical blink stimulation. However, in our experiment the classification of the participants into one of the two response groups was found to correlate with the blink response during the calibration. When full eye closure was achieved in the calibration, the success rate for eye blinks in the experiment was also high, while the opposite is true for participants where no full eye closure could be achieved during the calibration.

Figure 3 shows the blink delay and length as well as the relation between the two parameters. For the analysis, eye blinks within 400 ms after the stimulation are considered. Later eye blinks are assumed to be spontaneous eye blinks that are not related to the electrical stimulation. The results indicate that the eye closure duration for EMS-induced eye blinks is varying significantly for most blinks lasting for 57 to 126 ms (25% and 75% percentile). The delay between start of stimulation and beginning of the eye blink, on the other hand, was found to be stable for all blinks of one individual and does also not vary considerably between participants. On average, it takes 136 ms for the blink to start after the stimulation was triggered. This duration already includes the 40 ms stimulation time. The majority of nine participants rated the feeling of the stimulation as noticeable, but did not feel uncomfortable by it. Six participants perceived the stimulation with mild to medium discomfort. One participant reported to not feel the stimulation at all in the experiment. The results showed no correlation between the feeling of the stimulation and the actual success of evoking eye closure. In the sham trials without blink stimulation, participants had their eyes closed for 10% of the time, which corresponds to normal human blink behavior [39].

4.3 Experiment 2: Hand Redirection in VR

The second experiment explores the applicability of EMS-based blink stimulation for instant HaR in VR, based on the insights of the first experiment. Besides instant HaR, we apply continuous redirection as a second condition which adjusts the offset of the virtual hand over the entire reaching distance. Previous research found continuous redirection to be an effective and subtle method [9, 58] that is used as a baseline in our experiments. The main objective is not to replace common redirection techniques but rather to provide an accompanying solution to enhance redirections with instantaneous displacements in complex situations. The implementation of the continuous redirection follows the design of Cheng *et al.* [9].

In the experiment, we use the method of constant stimuli to determine the noticeability of the redirection for a certain parameter set [19, 27, 28]. For each of the two conditions (blink, continuous), we considered a redirection along the three central axes (horizontal, vertical, gain). The redirection levels are chosen with four different offset magnitudes respectively, arranged around the detection thresholds of previous works (see Fig. 4 for explicit level values) [9, 58]. In addition, for each of these combinations, five repetitions were conducted, resulting in a total of 125 trials per participant (2 methods * 3 axes * 4 offset magnitudes * 5 repetitions + 5 control trials with no redirection). The detection probability for every redirection level is derived by the proportion of trials where the manipulation was noticed, that is the participants' amount of "No" answers over the total amount. We decided to distribute the trials equally across offset levels and presented them in random order. The frequently used 1up/1down method reported in the literature [27, 58] could have introduced an expectation bias and was therefore not chosen for the experiment. We counteract the correspondingly larger number of trials of the method of constant stimuli with a streamlined experimental design.

Virtual Environment. In the experiment, we presented a photorealistic virtual environment of a furnished room in a HMD (see Fig. 1). The virtual room contains a table and a chair that are calibrated in every experiment to match the position of their physical counterparts. The hand models are rendered with a uniform diffuse material for clear visibility. We included animations for all boxes the user had to touch to provide proper feedback. The response control for the Yes/No question is designed so that the participant loses reference to the position of their physical hand, in order not to reveal the previous manipulation in the transition between trials. We achieve this loss of reference by hiding the real hand and transferring the control to a cursor with scaled movements that only moves on the axis between the answers. In contrast to our design, previous works required participants to move their hands entirely behind their backs in each trial to reset the manipulation [58]. The described design choices allow for a fluid and fast experimental procedure, which prevents participants from becoming unmotivated or unfocused. Please refer to our supplementary video for further details. We implemented the application in *Unreal Engine 5.1*.

The EMS for eye blinks follows our method described in Sec. 3. Experiment 1 showed the duration between EMS and the muscle response for an onset of the eye blink to be mostly constant. Based on these findings, we chose a fixed delay of 150 ms between start of the stimulation and manipulation of the position of the virtual hand model. This delay already accounts for variances in blink time and the latency of the rendering and visual display.

Apparatus. We used an Oculus Quest Pro HMD with a 106° FOV and hand tracking capabilities. The resolution of that HMD is 1800 × 1920 px per eye at 90 Hz refresh rate. The processing was performed on a local workstation (RTX 3090) over a Link-Cable. For the stimulation, the same device was used in both experiments [54].

Participants. We recruited 40 participants, all of whom completed the experiment (20 females, Age range = 19-37, Avg age = 24.93, SD = 4.54). Post-hoc, the data of one person had to be excluded because he did not properly follow the experimental task. From the stimulation, most participants experienced no negative feelings. In rare cases, moderate discomfort was perceived. The majority of 36 participants were right-handed (3 left-handed, 1 two-sided). The participation was compensated with 15€. In total, 5000 trials were conducted.

Procedure. Prior to the experiment, participants were provided with a detailed explanation of the functionality of the EMS device and the task they were about to perform. They were given a consent form to fill out if they wished to participate. During the setup phase, three electrodes are placed on the participants' eye region (cf. Sec. 3), and the stimulation current was calibrated individually based on the procedure outlined in Experiment 1. Once the calibration was completed, the experiment proceeded with the calibration of the room location. Participants were instructed to place their right hand on a fixed centered position on the physical table to adjust the virtual counterpart accordingly. We also determined the maximum reach distance of the participants by asking them to extend their arm. The arm length served as a reference for the distant placement of the target boxes to account for physiological differences. In the experiment, we only let participants use the right hand to maximize the control parameters of the experiment. The initial five trials served as control trials, during which no redirection was applied. The objective of these trials was to gauge participants' understanding of the task and ensure their reliability. Note, that participants were not informed about the true objective of these validation trials.

At the beginning of each trial, participants were instructed to place their hand on a fixed virtually marked area on the table in front of them, providing a proper haptic presentation at the start. After holding the start position for a brief period of time,

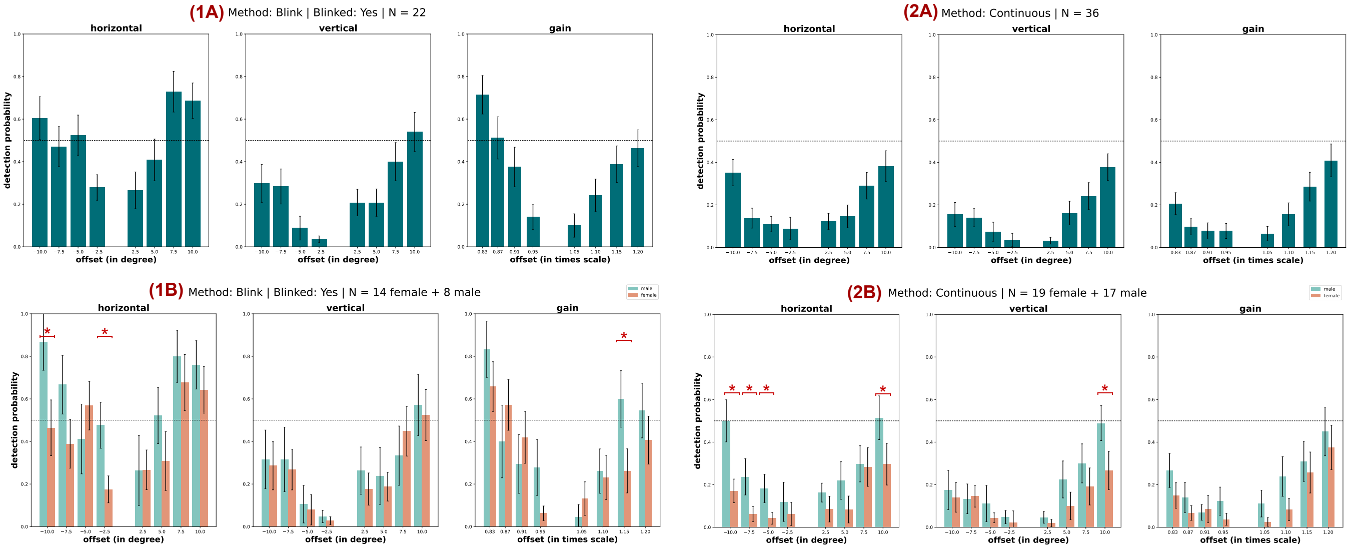

Figure 4: Detection probabilities for the offsets of the physical hand and all three axes. The results are shown for the blink condition (1) and continuous condition (2). Aside from the overall results (A) we present a direct comparison of men and women (B). Error bars represent the standard error of the mean. Statistically significant results are denoted by '*' ($p_{\text{corrected}} < 0.05$).

a box appeared at a random position but with a fixed distance from the start, which corresponded to the participant's calibrated reach distance. The random position of the target ranged from 10° to 40° vertically and -10° to 80° horizontally from the forward vector. While participants moved their hand towards the target, a certain redirection was applied. The applied HaR is relative to the gaze vector towards the target. The offsets and methods for redirection were randomized across trials. However, the eye blink stimulation was applied in all trials regardless of the redirection method to avoid bias of the participants. The blink was triggered at a randomized position between 20 and 50 percent of the reach. This safety gap ensured the blink redirection to not occur when the hand is within the visual focal area. This assumption is founded in the natural behavior of humans to fixate their reach target with the eyes and use physiotactile perception rather than to follow the path of the hand with their gaze. As soon as the manipulation enters the user's focus area during the redirection, the remapping becomes easily noticeable. In the blink trials, the hand is instantaneously moved to the offset position during the estimated eye closure. Once the participant reached the target the background was blacked out and the participant's hand disappeared. Instead, participants controlled a cursor to answer a Yes/No question *"Did the movement trajectory of the physical and virtual hand coincide?"*. After their response, the virtual room environment and hand model reappeared and the next trial commenced. Following the completion of the experiment, participants filled in demographic questions and rated their perception of the electrical stimulation, as in Experiment 1 (see Sec. 4.1).

4.4 Results of Experiment 2

For the analysis of the instant redirection during eye blinks we only considered those participants who showed a positive blink response to the stimulation during the calibration phase. These considerations are based on the results of the first experiment that has demonstrated the success of the blink stimulation to be anticipated by the level of eye closure during calibration. In our VR experiment, we achieved full eye closure by stimulation in 22 of the 36 considered participants (61.1%). The results of the continuous redirection include all participants as this method is independent of the blinking behavior. However, the subset of blink-susceptible participants showed comparable results for this condition.

The results do not include the participants who showed a poor understanding of the task or who already misperceived the trials with zero offset. For each participant, five control trials were performed without any redirection taking place. All data from participants who indicated in more than 20% of these control trials to see a manipulation that was not actually present was excluded from the analysis. In our experiment, this exclusion affects 3 out of 40 participants.

Fig. 4 illustrates the results for instant redirection during EMS-based blink stimulation (1A). The axes represent the average likelihood that a redirection was detected, separated into the three base axes, the shift in positive and negative direction, and the discrete offset levels. In the following, we assume a 50% detection probability to define the detection threshold of the redirection technique similar to previous work [9, 58]. To derive the detection threshold of the psychophysical experiments, we fit a psychometric function to the probability data. More precisely, a logistic function was applied which provides good properties for psychophysical data [27]. We base the non-linear curve-fitting on linearly interpolated thresholds as initial guesses. Tab. 1 shows the derived detection thresholds for all axes.

Furthermore, Fig. 4 shows the results for the same scene but with continuous redirection applied (2A). The overall trend of the individual axes follows the results of the blink condition, with

Table 1: Detection thresholds for the proposed blink-suppressed instant hand redirection technique.

	right / left	up / down	forward / backward
overall	5.81°/ -7.07°	9.43°/ -12.73°	1.2x / 0.88x
females	6.67°/ -10.04°	9.28°/ -12.91°	1.25x / 0.88x
males	4.89°/ -4.42°	9.61°/ -12.45°	1.16x / 0.88x

manipulations in vertical direction being the most subtle and manipulations to left/right coming more to users' attention. However, for the chosen scenario the detection probabilities of the continuous redirection condition are lower for all three axes. Even for the maximum level, which extensively exceeded the reported threshold from previous work, continuous redirection still achieved a detection rate of 31.4% on average. This surprising finding may underline that the fast scenario of our experiment was actually a good fit for this method. The time participants required to find and reach for the target from the start position does not deviate between conditions. The average time to perform the reach is 3.33 s.

VR experiences are subject to a general gender bias as noted in previous research [18, 20–22, 40]. However, it is still unclear how gender influences the success of HaR in VR. In Tab. 1 the separate detection thresholds of our results are given for men and women, respectively. To analyze differences in the results between genders, we perform pairwise two-sided independent t-tests. Prior to the pairwise tests, homogeneity of variances is tested by performing Levene's test. In case no equal population variance can be assumed, Welch's t-test is performed. To account for multiple comparisons, we adjust the resulting p-values using the procedure of Benjamini and Hochberg to decrease the false discovery rate. Fig. 4 (1B, 2B) demonstrates the results of the gender-based analysis. In line with former findings, we found major differences in the efficiency of HaR depending on the user's gender. In our experiment, given the mostly higher ratings for males, our data suggests that women are less likely to notice the redirection independent of the condition and axis. This gender difference is most pronounced for horizontal HaR. At the same time, female participants were slightly faster in performing the reach task with 3.17 s (SD = 1.97) on average compared with 3.52 s (SD = 1.74) for males. These times cover the full timespan between appearance of the target and the first hand contact with it, and therefore also include the timings participants required to locate the target.

Regardless of the efficiency of instant redirection achieved during eye blinks, practical applicability will not be obtained if the majority associates negative feelings along with the EMS-based stimulation. To evaluate participants' perception of the electrical stimulation, we perform a two step evaluation process immediately after the experiment. First, participants were asked to categorize their perception of the stimulation as either *unnoticed*, *perceptible*, *discomfortable* or *pain*. For every category (except for unnoticed stimulations) they were asked to rate the feeling of the perception on a Borg scale between 0 and 12 [6]. In our experiment, the majority of participants noticed the stimulation but did not perceive it as uncomfortable (see Fig. 5). A minority of 13% of the participants indicated to feel discomfort by the stimulation with mostly weak or moderate intensity. On the other hand, six participants did not notice the stimulation at all, including participants with good blink responses. There were no reports of more discomforting experiences. Overall, these results give a positive indication for the practical use of EMS-based stimulation in a broader audience.

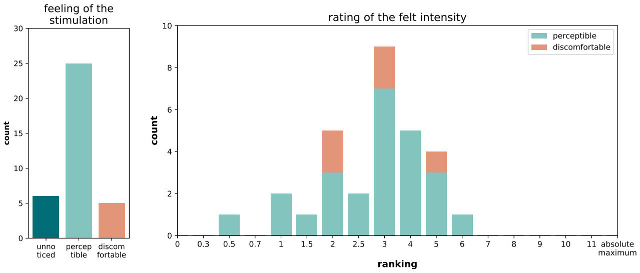

Figure 5: Rating of the feeling of the stimulation. Participants first categorized their perceived feeling (left), to then rate its intensity (right). Unnoticed sensations were not rated.

5 DISCUSSION AND LIMITATIONS

Experimental Results. Movements that are slower by nature, for example because they are performed with the whole body as in redirected walking, are known to perform much better with redirection methods, since less attention is paid to the manipulations and several displacements can be performed consecutively [58]. In our experiment we chose a challenging scenario with fast and short distance hand movements to establish a reliable baseline. Despite the challenging conditions, our EMS-based blink redirection demonstrated convincing results, with detection thresholds on par with previous work [9, 58]. With instantaneous redirection, a decisive advantage can be achieved in situations with complex conditions by repositioning the geometry of the hand unnoticed and without temporal delay. As already mentioned at the beginning, instant HaR is intended more as an extension of the well-functioning conventional redirection techniques. In continuous redirection, the intended target position has to be anticipated at the beginning of the hand movement in order to perform a suitable redirection. A version enhanced with instant HaR would be able to dynamically compensate for incorrectly anticipated directions by shifting up to 12.9° and scaling with a factor of 1.25x without the user even noticing the miscalculation. Previous work has already shown that an extension of continuous redirection with immediate displacements yields a significant improvement of the redirection threshold [58]. In their work, the authors used spontaneous eye blinks and eye tracking to exploit the effect of change blindness. For our work eye tracking is not necessary since the blink is explicitly induced at the exact moment it is needed for the unnoticed manipulation of the scene. Recently, Zenner *et al.* studied a variety of other techniques to trigger eye blinks [59]. Comparing both works, electric stimulation seems to offer higher response rates than most visual or tactile techniques. However, they showed that VR-specific visual techniques, like the simulation of approaching objects, also achieve high blink response rates. Compared with visually induced blink triggers, the electrical stimulation of change blindness comes with the advantage that the visual field is not occluded and users could be less distracted. However, more future work is needed to truly compare all relevant aspects of different eye blink stimulation models in VR scenarios.

Performance of Continuous Redirection. Besides instant HaR through exploitation of eye blinks, we also applied continuous HaR in our VR experiment. The implementation followed the work of Cheng *et al.* [9]. Unexpectedly, however, a significantly lower detection rate was obtained in our experiment than in previous work. Even the highest chosen offset value was not sufficient to determine a threshold at 50% detection likelihood. This outcome can have several reasons, which may be related to the method or virtual environment. Previous work usually performed a 1up/1down method to determine the detection threshold, which might expose issues discussed in Sec. 4.3. In contrast, we chose a method of constant stimuli. The higher efficiency of the continuous redirection may also be caused by higher immersion. In our experiment, we utilized the Meta Quest Pro VR glasses, which by design leaves a narrow reference to the real world at the lower edge of the glasses. Through this reference, which also reveals parts of the upper arm, the virtual hand may have been adopted more strongly. Furthermore, a more precise representation of the virtual hand, e.g. via better hand tracking, is known to reduce the noticeability of HaR [43].

Effect of Gender. VR was shown to be gender biased [18, 37] while its effect on HaR was not yet studied. Based on our results, we found significant disparity in the effectiveness of HaR between males and females. While HaR techniques are certainly able to unnoticeably relocate the user's hand regardless of gender, the detection probabilities of women are significantly lower. This divergence appears more pronounced, with larger redirection offsets. Although both redirection methods showed different detectability in the experiment, the relative difference in results between men and women was comparable. Besides the stronger impact of the method on women, however, a difference in the feeling of stimulation is also discernible. While the classification of the stimulation as noticeable but not unpleasant were evenly distributed between the genders, categorizations as uncomfortable were solely made by women. Thereby, the average selected current intensity is comparable. An equal number of men and women classified the stimulation as imperceptible. In summary, especially for women, the VR experience can be greatly improved with redirection strategies, even when strong redirection is required. Future studies on redirection should account for gender effects, since a difference in the efficiency of the techniques is evident.

Positive vs. Negative Offsets. Most previous redirection studies assume redirection offsets of the hand to be equal in positive and negative direction of an axis and, thus, only consider displacements in right, up and forward direction. However, some former works already gave an indication for disparities in detection threshold by the shift direction along an axis [5, 12, 25]. Our results demonstrate a redirection along an axis to have a significantly different detectability depending on the direction of the shift. These differences in notability were most profound on the vertical axis and non-significant for the horizontal axis, which is true for both conditions. Please refer to Tab. 1 and Fig. 4 for detailed results. All our findings of varying effectiveness of the redirection methods based on the axis offset direction were independent of gender.

General Observations and Safety for EMS. According to current state of the science, EMS of the eye muscle is considered safe given moderate currents (≤ 3 mA), and is used in a variety of research works and medical applications [15, 33, 34, 36, 44, 50, 53]. The eye closure serve as a protective mechanism of the body against the EMS, similar to a fly hitting the eyelid. While our experiments involved multiple stimulations on the same individual with consistent current and setup, stimulations were perceived with varying intensity, and the resulting blinks differed in strength. Therefore, a correlation between the perceived intensity of stimulation and the intensity of the blink is likely to be apparent. We also found the conductivity of participants' skin to be important. During initial experiments, conductivity decreased when the skin was not cleaned with an alcohol pad, necessitating higher currents to achieve the same blink effect. This higher resistance even pushed the bar of needed currents above the maximum 2.5 mA in some cases. Furthermore, we noticed that low currents (< 0.2 mA) induced rapid light flashes in front of the participants' eyes. Most likely these flashes are the result of excitation of the retina through electrical flow. There appears to be an optimal stimulation current around 0.6 mA at which the stimulation works most effectively. Current values that surpass this threshold, no longer trigger eye blinks and become less noticeable. While no adverse effects were observed in this work, intense EMS should always be used with caution. All of our experiments involved < 150 stimulations over a total of 10 min per participant. Also, this research was conducted in accordance with experienced ophthalmologists and the corresponding ethics committee. The effect of stimulation over longer periods (several hours) and frequent use may need further investigation.

6 CONCLUSION

In a comprehensive VR experiment we highlighted the potential of EMS-based blink stimulation to enhance hand redirection (HaR) and, thereby, increase users' VR experience. In this work, we proposed a novel stimulation model that can effectively and safely stimulate eye blinks for instantaneous displacements of virtual hand models that go unnoticed for VR users. The model requires only three electrodes and applies counter-currents for highest efficiency. Beside the main objective, our study revealed intriguing insights to a variety of unexplored factors in the domain of HaR including new methods, key considerations of EMS, and gender effects. In future designs, blink-controlled instant HaR can extend conventional redirection to provide a decisive advantage in complex conditions by repositioning the hand geometry unnoticed and without temporal delay.

ACKNOWLEDGMENTS

We would like to thank Dr. Leon von der Emde and Priv.-Doz. Dr. med. Thomas Ach of the University Hospital Bonn for their kind support and medical advice in this project. The authors gratefully acknowledge funding by the German Science Foundation (DFG MA2555/15-1 "Immersive Digital Reality"), and under Germany's Excellence Strategy within the Cluster of Excellence PhoenixD (EXC 2122, Project ID 390833453).

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