Beyond the Blink: Investigating Combined Saccadic & Blink-Suppressed Hand Redirection in Virtual Reality

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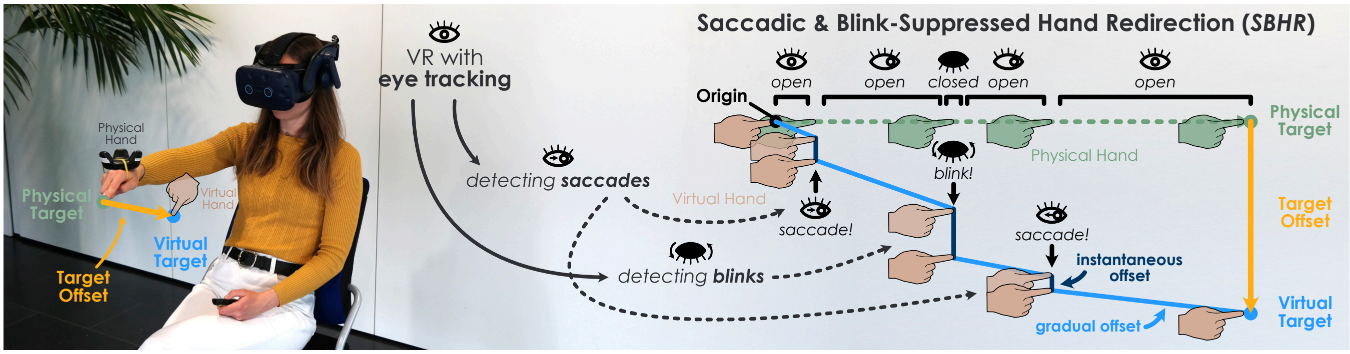

Figure 1: We introduce *Saccadic & Blink-Suppressed Hand Redirection* (*SBHR*), the first algorithm redirecting the physical hand of a VR user by taking advantage of saccade-induced change blindness. The image shows a participant in our psychophysical study comparing different hand redirection techniques. As sketched on the right, *SBHR* leverages eye tracking to combine saccadic redirection with the conventional approach of gradual hand drifting and the previously proposed approach of blink-suppressed redirection. Results show *SBHR* to allow for more unnoticeable redirection than the conventional approach of hand drifting.

ABSTRACT

In pursuit of hand redirection techniques that are ever more tailored to human perception, we propose the first algorithm for hand redirection in virtual reality that makes use of saccades, i.e., fast ballistic eye movements that are accompanied by the perceptual phenomenon of change blindness. Our technique combines the previously proposed approaches of gradual hand warping and blink-suppressed hand redirection with the novel approach of saccadic redirection in one unified yet simple algorithm. We compare three variants of the proposed *Saccadic & Blink-Suppressed Hand Redirection* (*SBHR*) technique with the conventional approach to redirection in a psychophysical study ($N = 25$). Our results highlight the great potential of our proposed technique for comfortable redirection by showing that *SBHR* allows for significantly greater magnitudes of unnoticeable redirection while being perceived as significantly less intrusive and less noticeable than commonly employed techniques that only use gradual hand warping.

CCS CONCEPTS

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

KEYWORDS

virtual reality, hand redirection, saccades, eye blinks, detection thresholds, change blindness

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1 INTRODUCTION

As a high-end human-computer interface, virtual reality (VR) is uniquely tailored to the human senses [33]. VR systems leverage head-mounted displays (HMDs) that track the user's head, hand,

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and eye movements, and control what the user sees, to make them feel present inside immersive virtual environments (IVEs) [64]. This, in turn, leads to users behaving realistically inside the simulated scenes [63], making VR a valuable tool for a variety of use cases ranging from therapy [32] to training [22] or education [81].

The unique levels of immersion achievable with modern VR systems give rise to exciting and unique opportunities when it comes to interaction. Since human perception relies extensively on vision [23], VR systems can use their control over what the user sees to their advantage by enhancing the user's VR experience through visual illusion techniques [44]. Such techniques have seen great interest in the VR and human-computer interaction (HCI) research communities lately. Approaches that have been proposed and investigated range from pseudo-haptic techniques that convey haptic perceptions by means of visual manipulations (e.g., [2, 13, 19, 43, 59]), to redirection techniques that alter the user's real walking paths (e.g., [51, 56, 67, 72]) or reaching motions (e.g., [3, 11, 16, 38, 46, 80, 82]) without users noticing it.

Illusion techniques help modern VR systems solve a variety of problems that occur when users experience IVEs that differ from their real surroundings. A prominent example is the technique of *hand redirection* (HR). Analogous to how redirected walking (RDW) redirects the user's walking path, HR redirects the user's real hand movement when the user moves their hand in VR. Past research could make use of this type of illusion to solve crucial challenges of modern VR systems, and used HR, for example, to enable more flexible haptic feedback [3, 11, 18, 24, 38, 46, 52, 85] and improved ergonomics [20, 48, 49].

HR is commonly realized by *gradually drifting away* the virtual hand from the real hand as the user reaches forward, breaking with the 1-to-1 mapping of the user's real and virtual bodies (a concept known as body warping [3, 11, 77]). Due to the phenomenon of *visual dominance* [23], this displacement leads to users perceiving their hand to be located rather where it is *shown* than where it physically is, which, in turn, leads to users compensating for the displacement by moving their real hand in the direction opposite to the introduced offset. The displacement is controlled by a HR algorithm and can remain unnoticed when not exceeding the perceptual detection thresholds (DTs) of the user [5, 15, 16, 18, 80, 82]. As a consequence, HR grants the VR system control over the user's real hand movement.

The illusion, however, works best and avoids the risk of semantic violations [27] when it remains undetected. Traditional HR algorithms, such as the widely used approaches by Kohli [38], Azmandian et al. [3], or Cheng et al. [11], however, introduce the entire offset by gradually displacing (i.e., drifting away) the virtual hand from the real hand in plain sight, disregarding the state of the user's eyes and not taking advantage of any perceptual phenomena other than visual dominance. By this, traditional HR techniques risk detection of the manipulation as users might become aware of large drift magnitudes [5, 15, 16, 80]. Moreover, past research has missed the opportunity to compare the perceived intrusiveness of gradual hand drifting to alternative strategies of introducing hand offset for HR, such as sudden hand offsets.

As a reaction to this and to minimize the noticeability of HR, researchers have started to investigate HR algorithms that, in addition to visual dominance, also leverage the perceptual phenomenon of *change blindness*. In this line of research, Zenner et al. [82] recently proposed the first HR algorithm that makes use of eye blinks, which are known to cause change blindness [54]. The approach of *Blink-Suppressed Hand Redirection* (*BHR*) works by injecting sudden hand offsets for redirection (i.e., "jumps" of the virtual hand) when the user is blinking. The authors could show that with this approach users can unnoticeably be redirected without manipulating the virtual hand in front of their opened eyes. Yet, while representing an important step towards more advanced and less noticeable HR techniques, the algorithm introduced by Zenner et al. [82] comes with three central limitations: Firstly, the algorithm only successfully redirects users when a blink occurs in time during the interaction. This, however, only rarely happens as reaching usually takes no longer than $2s$ [24] while spontaneous blinks occur only every $3s$ – $6s$ [21, 83]. Secondly, in situations where multiple blinks would occur during a redirection, the algorithm would only make use of the first blink while leaving all further opportunities for injecting offset unused. Thirdly, previous evaluations of the *BHR* technique have failed to show that leveraging blinks allows for greater unnoticeable redirections than conventional hand drifting [82].

It is these limitations and the lack of more advanced HR algorithms that centrally motivate this work. Inspired by previous research on *BHR* [82] and related techniques in the domain of RDW [6, 39, 50, 73], in this paper, we propose the next step in the evolution of HR algorithms. We build upon the algorithms of Cheng et al. [11], which stands out for its elegant and simple implementation, and the work by Zenner et al. [82], which introduced the idea of leveraging blink-induced change blindness, and propose a novel, more advanced and unified HR algorithm that is tailored to human perception. Central motivation for the HR algorithm introduced in this paper is provided by the observation that change blindness accompanies not only blinks but also saccades [29], which are fast rotations of the eyeballs that occur between visual fixations (i.e., much more frequently than blinks). In an attempt to take advantage also of this – yet unexplored – opportunity for unnoticeable HR, in this paper, we contribute:

- *Saccadic & Blink-Suppressed Hand Redirection* (*SBHR*) – the first HR algorithm taking advantage of saccades and blinks.
- A psychophysical experiment ($N = 25$) comparing the common approach of gradual drifting as a baseline [11] to blink-suppressed HR (*BHR*), saccadic HR (*SHR*), and the combined *SBHR* approach. Our results reveal the advantages of leveraging saccades for redirection over previously published techniques in terms of redirection performance, intrusiveness, and noticeability.

2 RELATED WORK

We revisit conventional HR techniques, change blindness and the physiology of human eye blinks and saccades. Finally, we review related VR techniques that take advantage of blinks and saccades.

2.1 Conventional Hand Redirection

Our eyes play a pivotal role when we perceive our environment and visual information frequently dominates our perception [23]. This phenomenon of *visual dominance* is the cornerstone of visual illusion techniques in VR [44] – from pseudo-haptics [43, 58, 59] over RDW [51, 56, 67] to HR [3, 38].

To redirect the user's real hand, the most common approach is based on tampering with the representation of the user's virtual body inside the IVE. Such body warping-based HR [3] makes use of how humans combine visual information (specifically: the *seen* hand position; perceived with the eyes) and haptic sensations (specifically: the *felt* hand position; perceived with muscles, tendons, and joints [34]). During multisensory integration, the different estimates for hand position are weighted according to their reliability and combined [14], with vision usually receiving highest weights and dominating the overall perception [23].

HR algorithms intentionally introduce a discrepancy between visual and proprioceptive hand location by displacing the hand inside the IVE [3, 38]. Due to visual dominance, this displacement leads to the user perceiving their hand to be rather where it is *shown* than where it physically is. The misled perception, in turn, leads to users issuing motor commands to the physical hand based on the manipulated position of the virtual hand, which provides means for the VR system to control the user's real hand movement.

Different algorithms have been proposed by previous research to introduce such hand offsets for redirection. By far the most common approach is to gradually increase the displacement (see review in [77]), and only very few exceptions use constant hand offsets (e.g., [5, 30, 41, 69]). Widespread algorithms, such as those proposed by Azmandian et al. [3] or Cheng et al. [11], linearly interpolate from an initial offset (e.g., a zero-offset when a 1-to-1 mapping is applied) to a target offset as the user reaches out [47]. By this, conventional HR algorithms keep computations simple and can achieve unnoticeable redirection. The magnitude of unnoticeable warping thereby depends on a couple of factors and has been subject to intense psychophysical research [77]. While perceptual detection thresholds (DTs) can differ with the HR algorithm employed [82], direction [15, 31], movement restrictions [18], distraction [10, 15], the presence of haptic feedback [1, 16], the number of hands being redirected [25], and avatar realism [53], conservative estimates have shown that in desktop-scale settings, HR based on gradual hand drifting goes unnoticed within a couple of centimeters [40, 80, 82].

2.2 Change Blindness, Eye Blinks, & Saccades

Apart from relying on visual dominance, conventional HR techniques do not consider the user's visual awareness. Yet, the user's visual perception plays a pivotal role in detecting HR. Thus, it seems reasonable to consider the workings of visual perception beyond visual dominance when designing new HR techniques.

To this end, a perceptual phenomenon known as *change blindness* has received significant attention in the VR research community. Change blindness is described by Simons and Levin as *"the inability to detect changes to an object or scene"* [62] and occurs when the user's view of a scene is briefly interrupted [57], even in stereoscopic VR [66]. When a visual change is made to an observed scene during this interruption, users are likely to miss the change as a result of our perceptual system assuming that *"if the gist [of a scene] is the same, [...] the details are the same"* [62].

By utilizing moments in which users are change blind, suitably designed HR techniques could inject hand offset without drawing attention to the change [82]. By this, change blindness-based HR might allow for greater redirection to go unnoticed than conventional HR techniques, which do not specifically take advantage of change blindness. The practical value of change blindness-based HR is further reinforced by *eye blinks* (i.e., rapid closings and re-openings of the eye lids) and *saccades* (i.e., fast ballistic eye movements between fixations). Both occur regularly under normal viewing conditions and usually go unnoticed as they are accompanied by visual suppression [8, 74]. As such, both blinks and saccades lead to change blindness in users [29, 54].

Blinks occur every $3s$ to $6s$ on average [21] and can also be triggered on demand [83], with blink-induced suppression lasting for approximately $100ms$ to $200ms$ [74]. Saccades, in contrast, occur every $300ms$ to $400ms$ [6] as the visual system rotates the eyeballs to bring points of interest into the fovea. Saccades last for $20ms$ to $200ms$ [4], with mid-sized saccades lasting approximately $50ms$ [74]. Thus, saccades are shorter than blinks but occur much more frequently. During normal saccades, the eyes rotate at velocities of $300\frac{\circ}{s}$ to $400\frac{\circ}{s}$ [75]. Both blinks and saccades can be detected using eye tracking, for example, by monitoring the visibility of the pupil [83], leveraging spatial boundary techniques, or velocity-based algorithms [60].

2.3 Using Eye Blinks & Saccades for Redirection

Several techniques have used change blindness for redirecting users in VR. Suma et al. [70–72], for example, changed the geometry of the virtual room outside the user's field of view (e.g., behind the user's back) to redirect their walking paths. Similarly, Lohse et al. [42] and Patras et al. [55] remapped virtual objects to physical props when they were outside the user's view for change blindness-based haptic remapping. To covertly inject scene manipulations inside the field of view, Marwecki et al. [45] proposed a system that takes advantage of eye tracking and attention models to apply scene manipulations when they are outside the user's visual attention.

Apart from these approaches, previous work also explored the use of blinks and saccades for RDW. Langbehn et al. [39] and Nguyen and Kunz [50] could show that by leveraging blinks to inject translations and rotations of the IVE, the performance of RDW can be improved and the required space be reduced. Along the same line of research, Bolte and Lappe [6] explored the use of saccades for hiding translations and rotations of the IVE. Their results showed that users are considerably more sensitive to detecting manipulations during fixations than during saccades. A little later, Sun et al. [73] proposed a first RDW technique leveraging saccadic suppression and found saccades to improve RDW performance.

Based on these promising results in the field of RDW, Zenner et al. [82] recently proposed the first algorithm that takes advantage of blink-induced change blindness for HR. In contrast to blink-based techniques for RDW, the technique does not translate or rotate the IVE during a blink, but modifies only the location of the virtual hand (i.e., body warping). Their results showed that blink-suppressed HR allows for redirecting users' reaching motions without manipulating the hand in front of their opened eyes. Moreover, their results indicated that combining gradual drifting with instantaneous shifts of the hand during blinks allows for more unnoticeable redirection than using only blinks to accumulate offsets. Yet, while representing

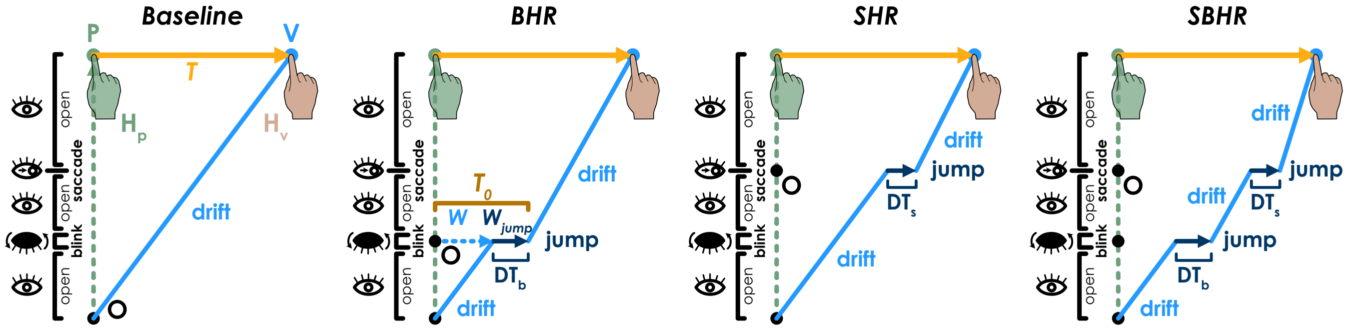

Figure 2: Comparison of four different HR algorithms. *Baseline* represents conventional HR using only gradual hand drifting. The remaining three represent variants of our proposed technique: *BHR* uses drifting and blink-induced hand jumps, *SHR* uses drifting and saccade-induced jumps, and *SBHR* combines all three offset injection methods. Central variables from Algorithm 1 and the parameters DT_b and DT_s are illustrated. As jumps inject offset, drifting angles become shallower.

a valuable step forward, the algorithm by Zenner et al. still suffers from a couple of central limitations [82], motivating this work:

1. Although combining gradual drifting and blink-suppressed shifts, users can miss their target when not blinking in time [82] as the algorithm depends on at least one blink to occur during redirection. Given average blink frequencies of $3s$ to $6s$ [21] and average reaching times of only up to $2s$ [24], this assumption is likely violated in practical applications [83], calling for fail-safe alternatives.
2. If multiple blinks happen to occur, the algorithm only makes use of the first blink, ignoring subsequent blinks.
3. The algorithm misses to take advantage of saccades.
4. The study of Zenner et al. [82] did not find blink-suppressed HR to allow for more unnoticeable redirection than conventional techniques that only apply gradual warping. Given previous findings on RDW, this comes at a surprise and motivates further investigations of the potential of blink-suppressed HR and alternatives such as saccades.

3 COMBINED SACCADIC & BLINK-SUPPRESSED HAND REDIRECTION

We introduce a novel HR algorithm called *Saccadic & Blink-Suppressed Hand Redirection* (*SBHR*). *SBHR* is the first algorithm combining:

(a) continuous hand *drifting* [11]
(b) instantaneous hand offsets injected during *blinks* [82]
(c) instantaneous hand offsets injected during *saccades* [78]

SBHR advances the state-of-the-art in change blindness-based HR as it is the first algorithm to consider saccadic suppression in addition to drifting and blink-induced shifts [82].

3.1 Concept

SBHR is based on the algorithm by Cheng et al. [11] and represents a simple extension thereof: *SBHR* applies gradual hand drifting and opportunistically takes advantage of all moments of change blindness detected by an eye tracking system during the redirection. Specifically, every time a blink or a saccade is detected, *SBHR* injects an additional, instantaneous hand offset that is below perceptual DTs and thus likely to go unnoticed as illustrated in Figure 3. By this, the algorithmic concept of *SBHR* differs slightly from that of blink-suppressed HR as presented previously by Zenner et al. [82]: In contrast to their technique, *SBHR* does not constrain the amount of gradual warping. Instead, *SBHR* constrains the saccadic and blink-suppressed shifts to be subliminal, i.e., below perceptual thresholds. This change makes *SBHR* fail-safe and overcomes limitation (1) of the previously introduced blink-suppressed HR [82]. The behavior of *SBHR* will equal that of the original algorithm by Cheng et al. [11] if no blink or saccade is detected, always guaranteeing that users will reach their targets. Moreover, since *SBHR* can exploit every blink and saccade detected during redirection, the algorithm also overcomes limitations (2) and (3) of the previous state-of-the-art.

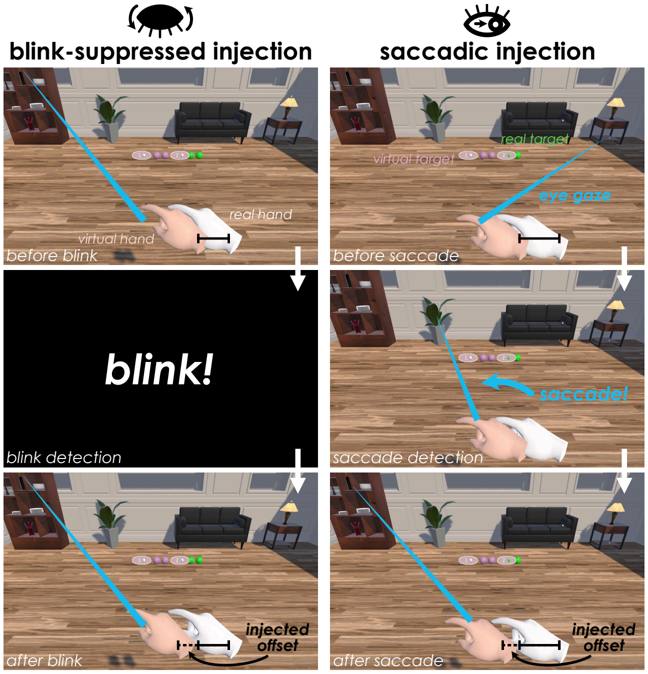

Figure 3: Illustration of the blink-suppressed (left) and saccadic offset injection methods (right).

Algorithm 1 Saccadic & Blink-Suppressed Hand Redirection

```
Input: Locations: physical target $\vec{P}$, virtual target $\vec{V}$;
    Blink-Parameter: DT for jumps during blinks ($DT_b$);
    Saccade-Parameter: DT for jumps during saccades ($DT_s$);
    Frame-Wise: physical hand position $\vec{H_p}$, eye tracking $eyes$.
Output: virtual hand position $\vec{H_v}$

1: procedure INIT($\vec{H_p}$,$\vec{P}$,$\vec{V}$)                ▷ called once
2:     $\vec{O} \leftarrow \vec{H_p}$      ▷ origin set to physical hand position at start
3:     $\vec{T} \leftarrow \vec{V} - \vec{P}$                              ▷ target offset
4:     $\vec{W} \leftarrow \vec{0}$      ▷ frame-wise warp, i.e., offset of virtual hand
5:     $\alpha \leftarrow 0$                    ▷ frame-wise gradual warp ratio
6:     $\vec{T_0} \leftarrow \vec{0}$                ▷ "Extension 1" of Cheng et al. [11]
7: end procedure

8: procedure UPDATE($\vec{H_p}$, $eyes$)                ▷ called every frame

9:     // SBHR-Extension of Cheng et al. [11]:
10:    // injecting unnoticeable offsets during saccades and blinks
11:    if $eyes.blink$ or $eyes.saccade$ then             ▷ onset detection
12:        $\vec{T_{remain}} \leftarrow \vec{T} - \vec{W}$                  ▷ remaining offset
13:        $\vec{W_{jump}} \leftarrow \vec{T_{remain}}$        ▷ instantaneous offset to inject

14:        // ensure hand jumps remain unnoticed
15:        if $eyes.blink$ then                              ▷ blink detected
16:            if $|\vec{T_{remain}}| > DT_b$ then              ▷ noticeable jump
17:                $\vec{W_{jump}} \leftarrow \frac{\vec{T_{remain}}}{|\vec{T_{remain}}|} \cdot DT_b$              ▷ clamp jump
18:            end if
19:        else if $eyes.saccade$ then                     ▷ saccade detected
20:            if $|\vec{T_{remain}}| > DT_s(eyes.\vec{sac}_{dir}, \vec{T_{remain}})$ then
21:                $\vec{W_{jump}} \leftarrow \frac{\vec{T_{remain}}}{|\vec{T_{remain}}|} \cdot DT_s(eyes.\vec{sac}_{dir}, \vec{T_{remain}})$
22:            end if
23:        end if

24:        // inject offset using "Extension 1" of Cheng et al. [11]
25:        $\vec{O} \leftarrow \vec{H_p}$
26:        $\vec{T_0} \leftarrow \vec{W} + \vec{W_{jump}}$
27:    end if

28:    // Original Cheng et al. [11] with "Extension 1":
29:    $\alpha \leftarrow \frac{|\vec{H_p}-\vec{O}|}{|\vec{H_p}-\vec{O}|+|\vec{H_p}-\vec{P}|}$            ▷ update gradual warp ratio
30:    $\vec{W} \leftarrow \alpha \cdot \vec{T} + (1-\alpha) \cdot \vec{T_0}$          ▷ interpolate from $\vec{T_0}$ to $\vec{T}$
31:    $\vec{H_v} \leftarrow \vec{H_p} + \vec{W}$              ▷ update virtual hand position
32: end procedure
```

3.2 Algorithm

Algorithm 1 presents the pseudo-code of *SBHR* following the established notation used by Cheng et al. [11] and Zenner et al. [82]. The algorithm is a direct extension (lines 11–27) of the original algorithm by Cheng et al. [11] (lines 29–31). The extension is responsible for instantaneous offsets introduced during blinks and saccades, while the original algorithm takes care of the drifting.

Upon starting the redirection with `INIT()`, the `UPDATE()` method is called every frame to compute the virtual hand position $\vec{H_v}$ by adding a warp vector $\vec{W}$ to the physical hand position $\vec{H_p}$ [11]. $\vec{W}$ is thereby computed as a linear interpolation (line 30) from an intermediate offset $\vec{T_0}$ (initially: $\vec{0}$) to the target offset $\vec{T}$ representing the displacement of the virtual from the physical target. The interpolation is driven by the progression of the physical hand $\vec{H_p}$ from the current origin $\vec{O}$ towards the target $\vec{P}$ (line 29).

To realize additional, instantaneous offsets, the *SBHR* algorithm takes advantage of an extension introduced in the original article by Cheng et al. [11]. This "Extension 1" was originally meant to allow for smooth transitions between redirections and resets the warp origin $\vec{O}$ to the physical hand location $\vec{H_p}$ when a new target offset $\vec{T}$ is set. To prevent a warped virtual hand from snapping back to a zero offset in such cases, the extension proposes to save the offset vector $\vec{W}$ that was already applied when switching targets as $\vec{T_0}$. As a consequence, the linear interpolation maintains this offset during the reset despite the warp ratio α changing to 0.

It is this reset mechanism that the *SBHR* algorithm takes advantage of to inject hand offsets when a blink or a saccade is detected. In every frame, in which the eye tracking detects the onset of a blink or saccade (line 11), *SBHR* computes the remaining offset $\vec{T_{remain}}$ that is still to be added to complete redirection. Depending on whether a blink or saccade was recognized, the magnitude of the remaining offset $|\vec{T_{remain}}|$ is then clamped to the corresponding perceptual DT for blink-suppressed (DT_b) or saccadic hand jumps (DT_s), respectively (lines 15–23), to ensure the hand jump remains unnoticed. The clamped offset $\vec{W_{jump}}$ is then to be injected instantaneously. For this, the redirection is reset following "Extension 1" [11] by updating $\vec{T_0}$ to the sum of the already applied offset $\vec{W}$ and the offset to be injected $\vec{W_{jump}}$ (line 26). Leveraging this reset mechanism, *SBHR* leaves a minimal footprint on the algorithm of Cheng et al. [11], maintaining its elegant and lightweight algorithmic design while additionally exploiting change blindness.

Figure 2 illustrates the four different modes *SBHR* can operate in. When disabling blink- and saccade-induced shifts, the algorithm equals the algorithm by Cheng et al. [11] implementing conventional hand drifting (*Baseline*). Using only blink- or saccade-induced shifts in addition to drifting, the algorithm implements either a variant of the previously proposed blink-suppressed HR (*BHR*) [82] or the novel approach of saccadic HR (*SHR*), respectively. Leveraging both blinks and saccades to hide offsets realizes *SBHR*.

3.3 Parameters

SBHR introduces two central parameters sketched in Figure 2, DT_b and DT_s, which define the maximum size of individual blink- and saccade-induced hand jumps, respectively. To ensure *unnoticeable* jumps, we instantiate these parameters based on perceptual data.

The *Blink-Parameter* DT_b can be informed by the results of Zenner et al.'s psychophysical study on blink-suppressed HR [82]. The authors investigated blink-suppressed hand jumps in their condition $BSHR_{+0\%}$ and derived mean DTs of up to $3.83\ cm$. Based on these findings, we set the parameter DT_b to $3.83\ cm$ in this work.

Similarly, also the *Saccade-Parameter* DT_s can be informed by psychophysical research. For this work, we base DT_s on the findings of a recent study on the detectability of saccadic hand jumps in VR, which found DTs to vary with the screen-space angle between saccade and hand jump direction [78]. Consequently, DT_s is a function that takes into account the direction of a saccade, tailoring hand jumps to each individual eye movement. After extensive informal testing, we ended up using the DT estimation model $t_{75\%}(\beta)$ derived in previous research [78] for DT_s since it trades off the effectiveness of the hand jumps for HR and their detectability well:

$$DT_s(\beta) = 4.8 \cdot 10^{-7} \cdot \beta^2 - 3.71 \cdot 10^{-6} \cdot \beta + 1.5 \cdot 10^{-3} m \qquad (1)$$

DT_s predicts the DT (in m) of saccadic hand jumps for individual saccades [78] based on the screen-space angle β (in degree) between saccade direction ($eyes.\vec{sac}_{dir}$) and remaining offset ($\vec{T_{remain}}$).

4 EVALUATION

To evaluate our novel HR technique we conducted a psychophysical study. We compared Cheng et al.'s [11] HR technique that only applies hand drifting (*Baseline*) to three variants of our new algorithm which additionally apply either blink- (*BHR*) or saccade-induced hand shifts (*SHR*), or both (*SBHR*). The *objective* performance of the HR algorithms was captured by deriving the respective perceptual DTs, which describe how much redirection goes unnoticed when a technique is used. In addition, we also evaluated the *subjective* quality of the redirection by assessing the perceived intrusiveness and noticeability of the three investigated offset injection strategies: hand drifting, blink- and saccade-induced hand jumps.

In contrast to previous studies [78, 82], in which the user's blink and saccade behavior was strictly controlled for, our goal was to assess the techniques in a more realistic and less constraining setting (in line, for example, with Esmaeili et al. [15]). Our study scenario was inspired by real-world applications and classic HR use cases, like the simulation of cockpit procedures [38], which involve active visual behavior during interactions. For this reason, we decided to not control for the user's eye gaze behavior during the trials but to let participants look around freely and naturally, while incentivizing visual search through a game-like task. Consequently, our study allows us to analyze the performance of the four HR techniques under supporting yet natural conditions and without enforcing any potentially unnatural blink or saccade behavior [78, 82]. The study was approved by the Ethical Review Board of the Faculty of Mathematics and Computer Science at Saarland University.

4.1 Hypotheses

Based on previous results in the domain of RDW [6, 39, 50, 73], we initially expected blink- and saccade-induced shifts to inflate DTs, i.e., to allow for more unnoticeable redirection compared to using only hand drifting [11, 80]. Yet, taking into account the results of Zenner et al. [82], who did not find blinks alone to increase DTs for HR, we refrained from this expectation for *BHR*. As a result, we ended up expecting that only those techniques increase the range of unnoticeable HR that utilize saccades:

H1 *SHR* allows for more undetectable HR than the *Baseline*.
H2 *SBHR* allows for more undetectable HR than the *Baseline*.

Moreover, with blinks and saccades both being accompanied by change blindness [29, 54], we also hypothesized:

H3 Hand jumps during blinks and saccades are *perceived* as *less intrusive* than continuous hand drifting.
H4 Hand jumps during blinks and saccades are *perceived* as *less noticeable* than continuous hand drifting.

4.2 Participants

The study was conducted with 26 volunteers from the local campus, out of which $N = 25$ ($21m, 4f$; median age 24, min. 18, max. 37) completed the experiment. All participants had normal or corrected-to-normal vision, and all were right-handed except for one participant, who was ambidextrous, but performed the study with the right hand. Most participants had a background in computer science or related fields. We also assessed how often participants use VR on a scale from 1 (= never) to 5 (= daily) and found previous experience to differ widely ($M = 2.20$, $SD = 1.08$, min. 1, max. 5). Each participant received a compensation of 10€ for their time.

4.3 Apparatus

The study was conducted in a quiet lab room. Participants remained seated throughout the experiment and were immersed using a *HTC Vive Pro Eye*[1] HMD with $120Hz$ eye tracking, using *Base Stations 2.0* for spatial tracking. The participant's dominant hand was tracked with an *HTC Vive Tracker* (v2018) attached to the back of the hand as depicted in Figure 1. Participants maintained a pointing hand posture supported by a splint. The position of the fingertip relative to the tracker was calibrated by touching the touchpad of an *HTC Vive Pro Controller* following the calibration procedure outlined by Zenner et al. [80, 82]. A presenter in the non-dominant hand was used to record answers and the IVE was rendered using a laptop with an *NVIDIA GeForce RTX 3070* graphics card.

The study was implemented with *Unity*[2] (v2021.3.7f1) and the *SRanipal SDK*[3] (v1.3.3.0) was used for eye tracking. Our saccade and blink onset detection is based on the heuristic approaches of previous work [73, 82, 83], with the blink detector comparing the *eye openness* values (in $[0, 1]$) of the SDK to a threshold value of 0.2, and the saccade detector applying an eye velocity- and acceleration-based thresholding approach. To account for the eye tracker's frame rate, our implementation was tuned to reliably detect medium to large saccades, sacrificing the detection of small saccades for increased accuracy and a low false-positive rate. The settings were determined during extensive pre-testing with our team and are also published, together with the detection algorithm, in an open-source repository[4]. For the implementation of the experiment, we made use of the *Unity Experiment Framework*[5] [9], the *Unity Staircase*

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[1] https://www.vive.com/us/product/vive-pro-eye/specs/
[2] https://unity.com/
[3] https://developer.vive.com/resources/vive-sense/eye-and-facial-tracking-sdk/
[4] https://github.com/AndreZenner/saccade-detection
[5] https://github.com/immersivecognition/unity-experiment-framework

Figure 4: The virtual room participants were immersed in. During each task execution, participants were to indicate whether one or two eggs are shown in the room.

Procedure Toolkit[6] [84], and *LimeSurvey*[7]. The HR techniques were implemented with the *Hand Redirection Toolkit*[8] [79].

4.4 Procedure

Participants were informed about the course of the experiment and signed a consent form. Participants were told about the general concept of HR and that the goal of the study was to compare DTs of different HR techniques. Moreover, to ensure conservative results, participants were made aware that during the experiment, they were to pay attention to all sorts of hand movement manipulations, including drifting and jumping, but they were intentionally not informed about the workings of the four techniques compared. After answering potential questions, the experimenter helped participants putting on the tracker, splint, and HMD, and guided them through the calibration of the eye tracking and the fingertip. When calibration was completed, participants familiarized themselves with the task in a couple of practice trials. Once they felt comfortable with the task, the experiment and data recording was started.

During the experiment, participants were immersed in a virtual room. To start the experimental task, participants touched a start sphere located 30 *cm* below and 20 *cm* in front of their head while a 1-to-1 hand mapping was applied. The location of the start sphere was chosen to ensure that the hand was well inside the participant's view throughout the trial. Upon touching the start sphere, four furniture items appeared 3.7 *m* in front of the participants as shown in Figure 4. The participants' task then was to answer whether one or two white eggs are hidden in the room. The number and location of the eggs was randomized, which incentivized a brief visual search of the furniture, during which participants could naturally perform blinks and saccades. Participants then reached forward with their hand to answer the egg-question by touching one of two virtual buttons located 30*cm* below and 65 *cm* in front of them, labeled "*1 egg*" and "*2 eggs*", respectively. This task was then repeated a second time in each trial as outlined in Figure 5. Following the two executions of this task, participants were to answer the question "*Did both hand movements feel the same?*" by selecting either "*same*" or "*different*" with a presenter in their non-dominant hand. After answering, the experiment continued with the next trial.

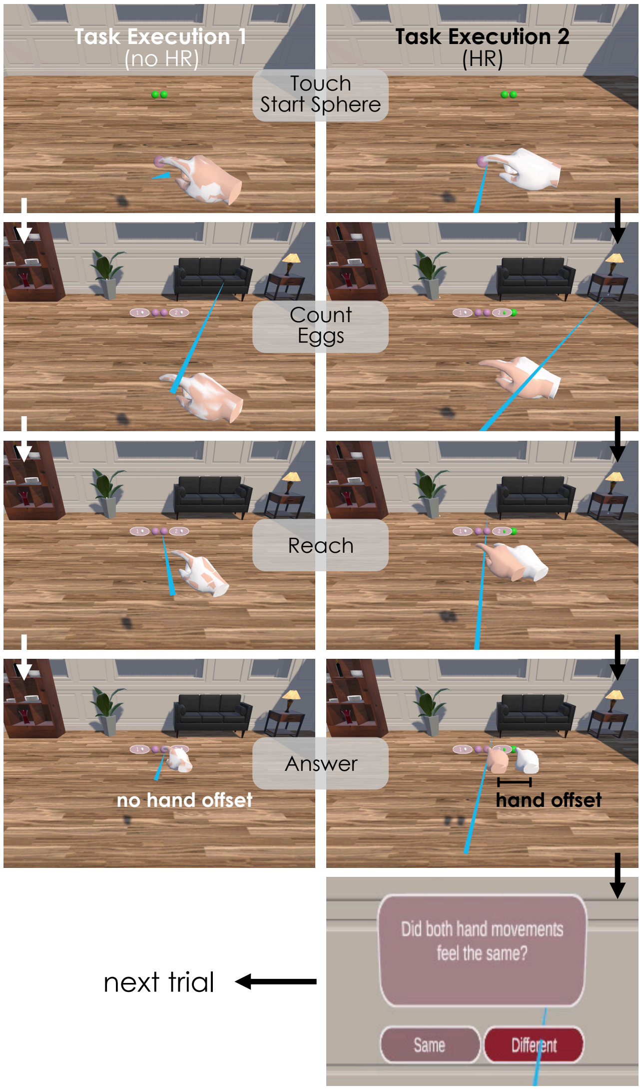

Figure 5: A trial consisted of two consecutive task executions. During the first execution participants re-calibrated to a 1-to-1 hand mapping. During the second, the tested HR algorithm was applied and a *same-different* question recorded the participant's perception. Real hand (white) and targets (green), and gaze ray (blue) are shown only for illustration.

By comparing the two reaching movements of the two task executions in each trial, the procedure followed an adapted *one alternative forced-choice* (1AFC) *same-different* design [37]. Participants were informed that the virtual hand was not manipulated, i.e., no HR was applied, during the first execution of the task in each trial. This allowed participants to re-calibrate to the 1-to-1 mapping, preventing unwanted adaptation to HR as observed in previous studies [17]. Participants were further told that during the second execution of the task, manipulations might or might not occur. Unknown to the participant, however, the HR algorithm

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[6] https://github.com/AndreZenner/staircase-procedure
[7] https://www.limesurvey.org/
[8] https://github.com/AndreZenner/hand-redirection-toolkit

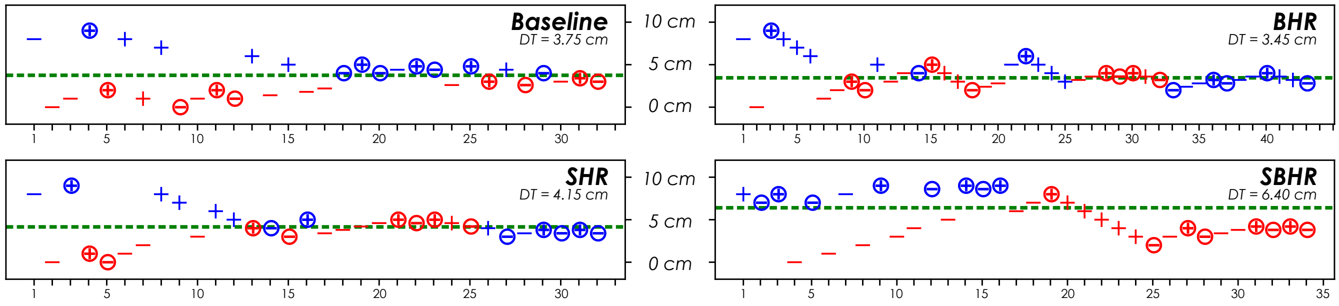

Figure 6: Staircase results of participant #22. The stimulus (y-axis) represents the magnitude of applied HR per trial (x-axis). + indicates the participant noticed HR in a trial, - indicates that the redirection was not noticed. Circles mark reversals. The derived DTs are indicated in green. In this example, *SBHR* allowed for more unnoticed redirection than the other HR techniques.

tested in the trial was always activated during the second task execution and the physical reach was redirected horizontally towards the right. The magnitude of this redirection, i.e., the stimulus tested in the trial, was determined by the staircase procedure.

The study was finished once the staircase for each tested HR technique was terminated and the participant's DT computed. Upon completion of all trials, participants took off the VR equipment and filled a demographics questionnaire, the SUS presence questionnaire [64], an adapted version of the embodiment questionnaire by Gonzalez-Franco and Peck [28], the Simulator Sickness Questionnaire (SSQ) [35], and a set of custom questions on a laptop. The study was concluded with a debriefing and took around 60 minutes.

4.5 Design

The experiment was designed as a within-subject study with HR technique serving as the independent variable. We tested four conditions, namely the HR technique by Cheng et al. [11] as the *Baseline* that only applies gradual warping, and three variants of our novel algorithm: *BHR* applying gradual warping and blink-suppressed shifts, *SHR* applying gradual warping and saccadic shifts, and *SBHR* combining all three offset injection methods.

As dependent variables we assessed for each HR technique the corresponding DT in *cm*, i.e., the magnitude of redirection that goes unnoticed with the technique. For this, we applied an adaptive *1 up/1 down method* [36] with a *1AFC same-different* question [37]. We used an interleaved staircase consisting of an ascending (starting with a stimulus of 0 *cm*) and a descending sequence (starting with 8 *cm*), both using a step-size of $\Delta_{start} = 10\ mm$ until the 4th reversal occurred and a step-size of $\Delta = 4\ mm$ after that. Each sequence terminated after 8 reversals. The final DT was computed by averaging the stimuli at the last 4 reversals of both sequences. Figure 6 shows an example. The staircases of all HR techniques ran in parallel and for each trial, a random, non-terminated staircase and sequence was selected to prevent anticipation. Moreover, we captured the perceived intrusiveness and noticeability of the three offset injection methods (drifting, blink-, and saccade-induced shifts) on a 7-point scale through post-experiment questions. To prevent excessive fatigue, we restricted the investigation to the most common spatial direction for HR, which is horizontal redirection; here: redirecting the real hand towards the right.

4.6 Results

In the following, we present the results of our study. To investigate the hypotheses, we applied a significance level of $\alpha = .05$.

4.6.1 *Trials.*

Participants completed 160 trials on average (SD = 25.7, min. 130, max. 217). The %-correct in the egg-search task was very high across all participants (M = 96.9%, SD = 3.5%, min. 85.4%, max. 100%).

4.6.2 *Blinks and Saccades.*

On average, participants blinked 0.67 times (SD = 0.66, min. 0.02, max. 2.62) and performed 4.87 saccades (SD = 0.91, min. 3.19, max. 7.40) during a reaching task. Tracked saccades lasted $35ms$ ($SD = 5ms$, min. $27ms$, max. $46ms$) on average while tracked blinks lasted $80ms$ ($SD = 50ms$, min. $23ms$, max. $282ms$). Table 1 summarizes for all tested HR techniques the percentage of reaching motions that took advantage of blink- and saccade-induced hand offsets (left columns), as well as the average aggregated amount of blink- and saccade-induced offset per reach (right columns), considering only trials where blinks or saccades were used for offset injection.

4.6.3 *Detection Thresholds (DTs).*

The mean DTs of the four HR techniques are shown in Figure 7 (left). To investigate **H1** and **H2**, we compared the DTs for significant differences among the conditions. To this end, we applied Shapiro-Wilk tests, which did not show the DT data to violate the assumption of normality, and Levene's test verifying the homogeneity of variance (all $p \geq .05$). Consequently, we conducted a parametric repeated-measures ANOVA with pairwise post-hoc t-tests and a Holm correction (corrected p-values denoted as p') to investigate the differences in DTs. The ANOVA showed the DTs to differ statistically significantly among the HR techniques ($F_{(1.93,46.38)} = 7.181, \eta^2_G = .027, p = .002$). The pairwise t-tests found the DTs for *SHR* ($M = 8.00\ cm, SD = 4.09\ cm$) ($t(24) = -3.278$, $p' = .019$, $d = -.656$) and for *SBHR* ($M = 8.04\ cm$, $SD = 4.03\ cm$) ($t(24) = -3.041$, $p' = .028$, $d = -.608$) to be significantly greater than the DTs of the *Baseline* algorithm ($M = 6.65\ cm$, $SD = 3.12\ cm$). All other pairwise differences were not found to be significant, although two comparisons can be interpreted as close to significance, namely, *BHR* ($M = 7.04\ cm$, $SD = 3.35\ cm$) vs. *SHR* ($t(24) = -2.487, p' = .064, d = -.497$), as well as *BHR* vs. *SBHR* ($t(24) = -2.591$, $p' = .064$, $d = -.518$).

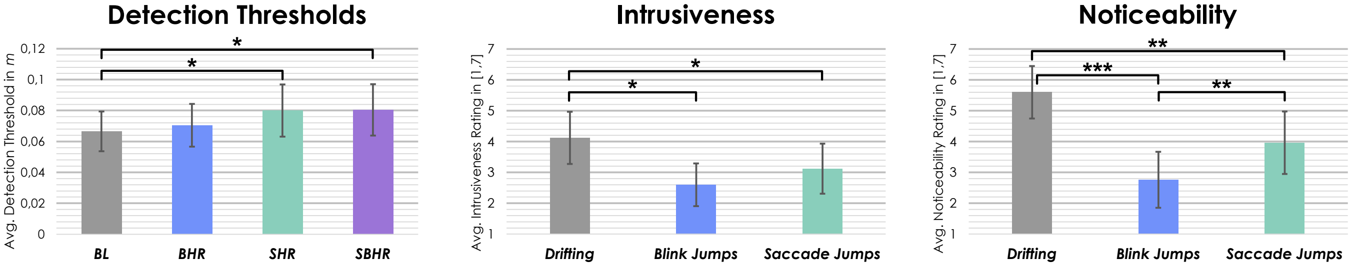

Figure 7: Left: Average DTs of the four tested HR techniques. Center: Intrusiveness of the three tested approaches for offset injection (hand drifting, hand jumps during blinks/saccades). Right: Noticeability of the same. Brackets indicate pairwise significant differences ($p' < .05$ (*), $p' < .01$ (**), $p' < .001$ (***)). Error bars show 95% confidence intervals.

4.6.4 Perceived Intrusiveness & Noticeability. We assessed the subjectively perceived intrusiveness and noticeability of the three offset injection methods by asking participants post-experiment to state their agreement with the following statements (1 = not at all; 7 = very intrusive/clearly):

- ... I perceived this as intrusive.
  - When I noticed my hand to jump while I was looking around in the room, ...
  - When I noticed my hand to jump while I was blinking, ...
  - When I noticed my hand to drift sideways while I was reaching forward, ...
- I noticed that in some trials, my virtual hand ...
  - ... jumped when I was looking around in the room.
  - ... jumped when I was blinking with my eyes.
  - ... drifted sideways when I was reaching forward.

The results are shown in Figure 7 (center and right). Shapiro-Wilk tests indicated the data for intrusiveness and noticeability to violate normality (all $p < .005$). As a result, we used non-parametric Friedman tests with pairwise post-hoc Wilcoxon signed-rank tests applying Holm corrections to investigate **H3** and **H4**.

For **H3**, the Friedman test found intrusiveness to differ significantly among the offset injection methods ($\chi^2(2) = 7.892$, $p = .019$, $W = .158$). Pairwise tests indicated hand offsets applied during blinks ($M = 2.60$, $SD = 1.68$) ($Z = -2.652$, $p' = .023$, $r = .375$) and saccades ($M = 3.12$, $SD = 1.96$) ($Z = -2.273$, $p' = .047$, $r = .322$) to be significantly less intrusive than gradual hand drifting ($M = 4.12$, $SD = 2.05$). Differences in intrusiveness between blink- and saccade-induced offsets were not found to be significant ($p' = 0.128$).

Table 1: Statistics for blink- and saccade-induced offset. *Amount* shows how much blink- and saccade-induced offset was applied on average per reach (sum of all injections), considering only trials where blinks or saccades were exploited.

	Blink-Induced Offsets				Saccade-Induced Offsets			
	Used in [% of trials]		Amount [*cm*]		Used in [% of trials]		Amount [*cm*]	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
BHR	34%	31%	3.78	0.88	–	–	–	–
SHR	–	–	–	–	96%	2%	2.75	0.58
SBHR	26%	24%	3.09	0.99	95%	4%	2.54	0.56

For **H4**, the Friedman test likewise found noticeability to differ significantly among the offset injection methods ($\chi^2(2) = 19.972$, $p = .00004$, $W = .399$). Post-hoc tests indicated all pairwise differences to be significant, with drifting ($M = 5.60$, $SD = 2.06$) being significantly more noticeable than instantaneous offsets injected during saccades ($M = 3.96$, $SD = 2.46$) ($Z = -3.090$, $p' = .003$, $r = .437$), and blink-induced offsets ($M = 2.76$, $SD = 2.20$) being less noticeable than saccade-induced shifts ($Z = -2.807$, $p' = .005$, $r = .397$).

4.6.5 Post-Experiment Questionnaires. The virtual embodiment of users was assessed using an adapted version of the questionnaire by Gonzalez-Franco and Peck, for which we selected a subset of 13 applicable questions as proposed by the authors [28]. Based on the original embodiment score computation, we aggregated the answers into an adapted total embodiment score (TES') in the range $[-3, +3]$ with the following formula:

$$TES' = \frac{\left(\frac{Owner'}{3} \cdot 2 + \frac{Agency}{4} \cdot 2 + \frac{Location}{3} \cdot 2 + \frac{Appear'}{3}\right)}{7} \qquad (2)$$

with $Agency$ and $Location$ being equal to the original scores, $Owner'$ being equal to the original *Ownership* score without questions 4 and 5 (not applicable as our IVE did not have a virtual mirror), and $Appear'$ being equal to the original *Appearance* score without question 20 (not applicable as the virtual avatar only consisted of a hand without clothes). Questions regarding *Tactile Sensations* and the *Response to External Stimuli* did not apply. The results show that users experienced embodiment towards the virtual hand according to the obtained positive TES' scores ($M = +1.07$, $SD = 0.62$). Moreover, the SUS count ($M = 2.20$, $SD = 1.78$) and SUS mean ($M = 4.42$, $SD = 1.24$) presence scores confirmed the IVE to be generally immersive and the SSQ total scores confirmed the absence of sickness issues ($M = 46.8$, $SD = 29.5$).

5 DISCUSSION

After the experiment, participants could leave written comments to provide insights about their experience of being redirected. One participant (male, 34 years) used this opportunity to comment that "*When the virtual hand was manipulated, the sensation of moving my hand caused my stomach to feel uncomfortable*" – a statement highlighting the need for HR techniques that redirect users in comfortable or unnoticeable ways. With *SBHR* and its variants *BHR* and *SHR*, we aim to achieve this by improving redirection performance and comfort compared to the current state-of-the-art.

5.1 Saccades Improve Performance

SBHR takes advantage of eye tracking and change blindness to an extent previously known only from the domain of RDW [39, 73]. To enable a direct comparison with the current state-of-the-art algorithm by Cheng et al. [11], we designed *SBHR* as a simple extension to conventional hand drifting as outlined in Algorithm 1. Doing so, we could overcome central limitations of the previously proposed blink-suppressed HR [82]. Our novel *SBHR* algorithm, for example, is now fail-safe and able to take advantage of arbitrarily many blinks and saccades, making the technique more widely applicable and easier to use than previous solutions [82].

These improvements, which are by design of the algorithm itself, are further accompanied by advances in terms of performance. The results of our comparative user study show support for both **H1** and **H2**, indicating that the exploitation of saccades (in addition to gradual drifting, and optionally blink-induced shifts) inflates DTs, i.e., allows for more redirection to go unnoticed than when using only the conventional approach of gradual drifting. These findings are in line with those in the domain of RDW [6, 39, 50, 73], highlighting the value of considering the state of the user's visual system when applying illusion techniques like HR.

Our study could also shed light onto the advantages of saccades over the previously introduced approach of leveraging blinks [82] for HR. The results outlined in Table 1, for example, suggest that saccade-based redirection is more reliably applicable than blink-based offsets. Independent of the technique, i.e., both when applying *SHR* and *SBHR*, saccades contributed to the redirection in almost all trials while blinks could be used only in every third (*BHR*) or fourth (*SBHR*) trial. The reason for that – as already discussed and targeted in previous work [83] – is that blinks occur less frequently. In addition, we observed that blinks are sometimes unfavorably timed and might occur, for example, at the very end of the reach when all the offset has already been applied by gradual drifting (*BHR*) or saccade-induced methods (*SBHR*). Potentially due to these reasons, our results did not show blink-suppressed shifts to yield a statistically significant advantage over conventional drifting. These observations are also in line with previous findings by Zenner et al. [82], who did not find the addition of blink-induced offsets alone to notably inflate DTs for HR. Comparing blink- and saccade-induced shifts further, the results outlined in Table 1 also show that despite the smaller offset magnitudes per individual saccade (originating from DT_s [78]), the high number of saccades during a reach led to aggregated saccade-induced offsets of a similar magnitude compared to those induced by blinks (originating from DT_b [82]). Taking into account also the high probability of saccadic offset to be injected renders saccadic shifts (*SHR*) the more valuable extension to conventional HR compared to blink-induced shifts (*BHR*) – at least when relying solely on the user's natural blinking behavior and not using blink trigger methods [83].

5.2 Blinks and Saccades Reduce Intrusiveness & Noticeability

The comparison of the psychophysical DTs revealed the advantages of saccadic HR in terms of objective performance. Yet, besides that, our study also revealed that exploiting moments of change blindness increases the subjective quality of redirection. As outlined in Figure 7 (center and right), the results support both **H3** and **H4**. User responses indicate that both blink- and saccade-induced hand jumps are perceived as significantly less intrusive and less noticeable than a gradually drifting hand. Differences were especially considerable for noticeability as hand drifting was perceived as rather clearly noticeable receiving a mean score of $M = 5.60$ on a 7-point scale. Saccade-induced hand jumps, in contrast, were rated medium concerning noticeability and blink-induced jumps rated medium-to-low, with mean scores of $M = 3.96$ and $M = 2.76$, respectively, and all differences being statistically significant. These findings highlight the value of making use of blinks and saccades for HR as an alternative strategy to purely drift-based techniques like Cheng et al.'s [11] *Baseline*. Moreover, the results support our proposed algorithmic design, which is to take advantage of every single eye-based change blindness opportunity that occurs during interaction.

5.3 Getting the Most out of *SBHR*

From our observations and our own experiences gained when testing the *SBHR* algorithm, we obtained the impression that when instantaneous hand jumps were timed well, chances were good that users would miss the manipulation as a result of blink- and saccade-induced change blindness. In these cases, the feeling of being redirected sometimes arose only later as the hand drifted sideways while reaching forward. These impressions led us to suspect that as long as instantaneous offsets are injected out of the user's attention, the amount of unnoticeable HR achievable with mixed techniques like *SBHR* is bound primarily by the detectability of the gradual drifting or the absolute accumulated offset magnitude. This might potentially hold up to the point where unnoticed instantaneous hand jumps have accumulated to the DTs for fixed positional hand offset revealed by Benda et al. [5], beyond which users might notice the hand displacement even before drifting starts – a hypothesis to be investigated in future research.

Under this assumption, however, interaction designers could adopt as a rule of thumb that: *the more instantaneous offset is unnoticeably added before drifting begins, the later users notice redirection and the more redirected interactions become possible.* While other mechanisms might exist that cause detection of HR, it seems advisable to design interactions and IVEs in ways that facilitate early offset injection, for example, by incentivizing saccades and blinks at the start of a redirected interaction. Saccades can be incentivized relatively conveniently, for example, by cleverly designing the spatial layout of the IVE, tasks, and interactions (such as in this experiment), or by utilizing subtle gaze direction methods [73]. For optimal conditions, saccade trigger methods should also consider the dependency of DT_s on saccade direction. Moreover, soft- and hardware-based methods compatible with VR could be used to trigger blinks on demand [83]. By combining these techniques, developers could optimize their applications to get the most out of the proposed *SBHR* technique.

5.4 Limitations

While our study could demonstrate the advantage of *SBHR* over conventional hand drifting, it is important to highlight that the performance of our algorithm crucially depends on the parameters

DT_b and DT_s, i.e., the maximum offsets injected during blinks and saccades. For our experiment, we configured the parameters based on the findings of previous psychophysical experiments [78, 82] and the promising results of our study generally support this choice. However, we see potential for further tuning of the algorithm by optimizing the maximum jump sizes. The parameters could, potentially, be tailored to the perceptual sensitivity of individual users [17] or to specific IVEs and tasks. By this, the advantage of a combined technique like *SBHR* and its variants over conventional approaches could become even more significant at the expense of a more sophisticated calibration. Likewise, however, a bad choice of DT_b and DT_s could compromise any performance benefits. Besides that, *SBHR* might also profit from improved eye tracking hardware. Since the delay of the eye tracker used in our study is in the order of magnitude of 50 *ms* [65], the benefit in redirection performance shown in our study can be considered a conservative estimate of the full potential of *SBHR*. *SBHR* might potentially perform even better if eye tracking hardware with less delay is employed as this would allow for offset to be injected even closer to saccade onset, i.e., where saccadic suppression is strongest [7].

Further limitations of our work concern the generalizability of our results. Firstly, due to an open recruiting campaign at the local campus, we ended up with a slight gender bias towards male participants. As a result, we can only draw limited conclusions about how well *SBHR* performs for non-male users. For this reason, we encourage future studies to investigate if there are any gender-specific differences concerning performance, intrusiveness, or noticeability of *SBHR*. Considering such differences seems especially important in light of previous studies that observed increased blinking rates in women [61, 76]. Secondly, the task and IVE tested in our study were developed with typical VR applications like simulations or games in mind. As such, our scenario was designed to be less controlled and more realistic than many previously conducted studies, and at the same time incentivized active eye movement through the visual search task. The results of our study are thus linked to our tested scenario. In other interaction contexts, users might perform less or even more eye movement. For example, users might perform only few saccades when reaching for an object the position of which is known, or might need to perform even more extensive visual search in cluttered scenes, which could potentially reduce or increase the performance benefits of *SBHR* to a yet unknown extent, motivating further research. Moreover, in our study, offsets were injected early in the trials, with ca. 75% of the blinks and saccades that caused offsets having occurred within the first 20% of normalized trial runtime (latest blink occurrence used for offset injection at 55%, latest saccade occurrence used for injection at 63%). This aligns with our observation that offsets were frequently injected before reach onset. It is important to note that, in actual applications, applying offsets that early requires appropriate reach target prediction [11, 12]. If such prediction is not available, it is likely that the performance benefit of *SBHR* will be impacted since the technique could then only rely on offset injections during the reach. Such injections are likely fewer in number and might potentially differ also in terms of how they are perceived from offsets injected while the hand is "idle".

6 CONCLUSION & FUTURE WORK

To enable more flexible hand-based interactions in VR, we advanced the technique of HR by tailoring it more to human perception. To this end, we contributed *Saccadic & Blink-Suppressed Hand Redirection* (*SBHR*), the first HR algorithm that utilizes saccade-induced change blindness for redirecting the physical hand movements of a user. Besides introducing saccades to the domain of HR, *SBHR* is also the first unified algorithm that combines saccadic redirection with the conventional approach of hand drifting [3, 30, 38] and the previously proposed, but only partially successful, approach of blink-suppressed HR [82]. To facilitate the usage and adaptation of our algorithm by other researchers and VR developers, we designed *SBHR* as an extension to the fail-safe state-of-the-art algorithm by Cheng et al. [11] and provided the corresponding pseudo-code as well as pointers to supporting code repositories. In a comparative user study then, we could show that our proposed approach outperforms the current state-of-the-art in HR in terms of (1) the amount of redirection that can be applied without users noticing it, and (2) the subjectively perceived intrusiveness and noticeability of the redirection. As such, *SBHR* enhances the applicability of HR in VR applications and enables redirected interactions that would likely be noticed by users if conventional algorithms were employed.

Our work can serve as a starting point for future research. To further optimize *SBHR*, future work could, for example, explore what factors other than saccade angle have an impact on the detectability of saccadic hand jumps. As a result, future iterations of *SBHR* might use parametrizations for DT_b and DT_s that take into account additional blink- and saccade-features, such as speed and duration, or make use of attention models [45], to tailor injected hand jumps to individual interactions or users. Besides that, HR techniques like *SBHR* could be evolved to take advantage also of change blindness opportunities that occur, for example, when user's look away from their hand or when their view of the hand is occluded – approaching the vision of an *ultimate redirection technique* that can exploit every change blindness event. Moreover, future research should investigate how well methods that trigger blinks [83] and saccades [73] integrate with *SBHR*, how blinks and saccades can help to re-establish a 1-to-1 hand mapping and align dislocated hands again after redirection [31], and whether there are any side-effects or gender-specific differences relevant to *SBHR*. In these contexts, it might also be worthwhile to make use of simulation models for hand redirection that take into account visual uncertainty [26], and to consider the prediction of blinks and saccades for redirection planning. We also encourage a more in-depth comparison of *SBHR* leveraging pre-reach offset injections and *SBHR* leveraging only mid-reach injections. Finally, the conceptual approach of *SBHR* might also be of value for related hand-based illusion techniques like pseudo-haptics [19, 44, 68], and for HR techniques based on world or hybrid warping [3, 42, 55], encouraging further research on VR interactions that consider the particularities of visual perception.

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