winDirect: Studying the Effect of a Wind-Based Haptic Bracelet on Presence and the Detectability of Hand Redirection

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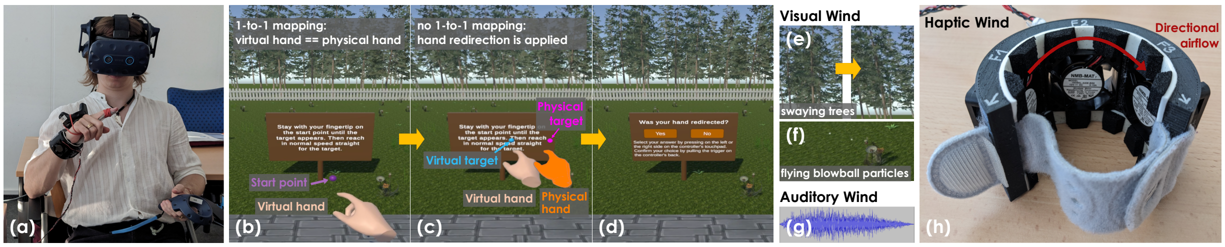

Figure 1: We conducted a psychophysical study to investigate the influence of multimodal stimuli on the feeling of presence and the detection thresholds of hand redirection. Users experienced different magnitudes of hand redirection while reaching out towards a virtual target (a through d). During redirection, they experienced simulated wind either visually, auditorily, haptically, or through combined multimodal feedback (e through h). To provide haptic feedback, we developed *winDirect*, a wearable air-based haptic bracelet (h). (The physical hand in (c) is shown for illustration only, but was not visible in VR.)

Abstract

We developed a wind-based wearable haptic feedback device called *winDirect* to investigate if multimodal stimuli can be used to disguise hand redirection (HR) by increasing corresponding perceptual detection thresholds (DTs) in users. Our investigation was motivated by the findings of two previous works, which showed multimodal stimuli to increase presence, and indicated an increased feeling of embodiment to increase the DTs of HR. In contrast to our expectations, we found that the integration of multimodal stimuli did not guarantee increased HR DTs, even when increasing presence – highlighting the need to study correlations between presence and HR more deeply.

Index Terms: Virtual reality, hand redirection, haptic wearable.

1 Introduction

Hand redirection (HR) is an illusion-based interaction technique used in immersive virtual environments (IVEs) that introduces offsets between a user's real and virtual hands to redirect the trajectory of the real hand, enabling improved haptic experiences [6]. However, redirecting users' hands by magnitudes greater than their perceptual detection thresholds (DTs) can lead to users noticing the illusion and experiencing breaks in presence, degrading their virtual reality (VR) experience. To prevent this, research actively investigates methods that allow greater magnitudes of HR to go unnoticed, focusing on haptic feedback [1] and embodiment [7].

In this paper, we investigate a novel approach to disguise the application of HR based on the findings of previous research by Fröhlich and Wachsmuth [4], who showed that the integration of multimodal feedback in IVEs increases the feeling of presence, and Ogawa et al. [7], who showed an increase of the HR DTs when the sense of embodiment, an important contributing factor to presence, is increased. Motivated by these findings, we developed a wearable device, called *winDirect*, which provides air-based haptic feedback at the wrist. We combined haptic feedback provided by *winDirection* with matching visual and auditory stimuli to simulate virtual winds, making use of the metaphor that the user's virtual hand is moved by the wind (instead of the HR algorithm) just like wind moves light objects like leaves or sheets of paper.

We investigated the effect of the multimodal feedback on the feeling of presence and on the HR DTs in a user study. Based on the findings of previous research [4, 7] we hypothesized that exposing the participants to multimodal stimuli leads to (**H1**) an increase in their feeling of presence, and (**H2**) an increase of their HR DTs.

2 winDirect: A Wind-Based Haptic Bracelet

To provide localised haptic wind feedback at the wrist, we developed *winDirect*, a novel wearable device that delivers haptic feedback via airflow. As shown in Fig. 1 (h), our device consists of a flexible 3D printed case in the form of a bracelet with three fans ($diameter = 4$ cm, model: NMB-MAT 1608KL-04W-B59) which are activated sequentially to generate airflow in the direction of the virtual hand offset. The fans are controlled by a Wemos D1 mini that communicates with the IVE via a serial connection. *winDirect* had a total weight of approximately 125 g, which the participants of the user study did not perceive to be uncomfortable.

3 Experiment

To investigate **H1** and **H2**, we conducted a psychophysical experiment using a within-subjects design with $N = 23$ volunteers (22 right-handed, 1 ambidextrous; $7f$, $15m$, $1nb$) between 21 and 44 years of age ($M = 30.39$, $SD = 5.89$).

We investigated the type of wind feedback as independent variable, with the following five implementations: baseline (no wind stimulus provided), visual (visual animations of wind depicted in Fig. 1 (e and f)), auditory (sound of wind), haptic (haptic feedback provided by *winDirect*), and multimodal (all wind stimuli together).

For each of these five conditions, we measured two central dependent variables, namely the feeling of presence using the SUS presence questionnaire [8], and the corresponding DTs for HR determined by an 1 up/1 down method [5]. The stimulus in our psy-

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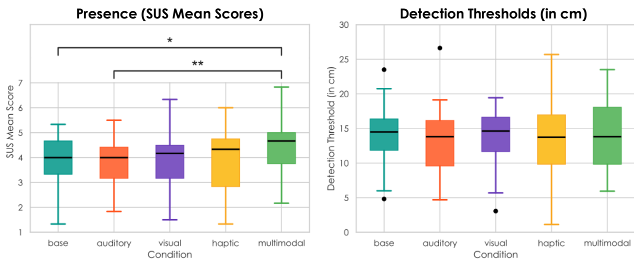

Figure 2: Box plots of the SUS mean scores [8] which measured the feeling of presence (left) and the HR DTs measured in an interleaved staircase procedure [9] (right). Significant differences of the SUS scores are indicated ($p' = 0.048$ ($*$), $p' = 0.008$ ($**$)).

chophysical study was the magnitude of the HR, ranging from a minimum offset of 0 cm to a maximum offset of 40 cm. To redirect the user's hand, we utilised the redirection method developed by Cheng et al. [2] with gradually increasing offsets. Also, the virtual hand was always drifted in the same direction, i.e. to the left. We implemented the procedure using the *Staircase Procedure Toolkit* by Zenner et al. [9], which interleaved an ascending sequence starting at 0 cm and a descending sequence starting at 20 cm. Each sequence was completed after eight reversal points. The step size of the sequences was decreased in three stages from 4 cm (until 2 reversals have been reached) over 2 cm (until the 4^{th} reversal point has been reached) to 1 cm (until the last reversal point), to speed up convergence. Once a sequence finished, its DT was calculated by averaging the stimuli at the last four reversal points. The overall DT was then determined by averaging the DTs of the two sequences [9].

The study was performed by the participants wearing an HTC Vive Pro Eye head-mounted display, a Vive tracker for hand tracking, a finger splint to maintain hand calibration, and *winDirect*. The setup and trial procedure is depicted in Fig. 1 (a through d). *winDirect* was worn by the participants the entire time, regardless of whether it was activated during the conditions or not.

After the staircase procedure of a feedback condition terminated, participants completed the SUS presence questionnaire [8] and answered a custom questionnaire inquiring about their perception of wind, assessed using the *Virtual Reality Questionnaire Toolkit* [3]. The order of the feedback conditions was counterbalanced according to the first five rows of a 5x10 sized Latin square (Williams Design). The study was approved by the Ethical Review Board of the Faculty of Mathematics and Computer Science at Saarland University.

4 Results & Discussion

Fig. 2 illustrates the results regarding the measured feeling of presence and the HR DTs for each condition. **H1** was supported by a RM ANOVA ($F(4,88) = 4.24$, $p = 0.003$) and a post-hoc paired t-test comparing the participants' feeling of presence in the baseline condition ($M = 3.78$, $SD = 1.06$) and in the multimodal condition ($M = 4.44$, $SD = 1.16$), which showed a significant difference ($t(22) = 2.98$, Bonferoni corrected $p' = 0.048$). Regarding **H2**, a Friedman test could not determine any significant differences between the DTs of the different conditions ($Q = 4.42$, $p = 0.35$).

These results support **H1**, indicating that haptic feedback with synchronized visual and auditory cues has a positive impact on the feeling of presence, in line with previous research [4]. However, our results did not support **H2**, which is surprising as it stands in contrast to the expectations derived from previous insights [7]. Consequently, our findings call for further investigation on the correlations between the feeling of presence and HR DTs in order to find other possibilities to increase the magnitude of unnoticeable HR.

5 Conclusion

In this work, we investigated the impact of multimodal stimuli simulating wind on both the user's feeling of presence and their detection thresholds (DTs) regarding hand redirection (HR).

To provide multimodal feedback and to study if it can reduce the noticeability of HR by increasing presence, we decided to investigate the metaphor of wind. Specifically, we chose the simulation of airflow because of the similarity of wind that moves light objects such as leaves or sheets of paper, and the virtual hand drift experienced during redirection. For appropriate stimulation, we developed *winDirect*, a wind-based wearable haptic feedback device that was combined with matching visual and auditory feedback to simulate wind in VR.

Conducting a psychophysical user study, we found multimodal wind feedback to increase the feeling of presence in line with our expectations. Yet, in contrast to our expectations, our statistical analysis did not indicate significant differences between the HR DTs of the different feedback conditions. While this does not allow drawing the conclusion that there is no effect of presence on HR DTs, this result makes a case for further investigations on the correlations between the feeling of presence and the detectability of techniques like HR in order to find new and effective methods for disguising HR. By this, we could enable future VR applications to unnoticeably redirect hands by magnitudes that previously could lead to disruptions of users' VR experiences.

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