Haptic Redirection: Modulating Hand Movement Speed with Vibrotactile Feedback

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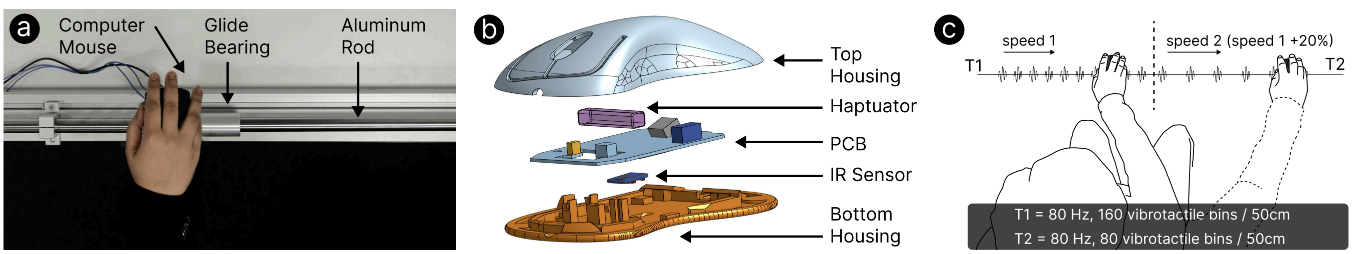

Figure 1: (a) Our experimental setup and apparatus where users move a mouse providing vibrotactile feedback along a slider; (b) an exploded view of the mouse generating vibrotactile feedback and measuring the hand's position; (c) an illustrative sketch of the experiment procedures using the apparatus to explore the relationship of vibrotactile feedback and movement speed.

Abstract

Redirecting user movement in Virtual Reality (VR) can expand perceived virtual space while accommodating limited physical space. Existing methods primarily rely on visual and auditory cues. This work explores the foundation for an alternative approach using haptic cues. We were inspired by the observation that vibrations arise when a finger moves over a textured surface, influenced by two factors: the scanning speed and the surface properties. While prior research has focused on using vibrations to modify texture perception, we investigate the second factor; modifying vibrations to influence movement speed. Through three psychophysical experiments, we show that: (1) Human movement speed is affected by the properties of vibrotactile feedback. (2) Movement speed remains unchanged during transitions if users are aware of vibrotactile feedback changes. However, we found that (3) movement speed increases by ∼20% when vibration pulses are reduced by 50%, provided users are unaware of the vibrotactile feedback change.

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CCS Concepts

• **Human-centered computing → Interaction techniques**; *HCI theory, concepts and models*; *Empirical studies in HCI*.

Keywords

Hand Redirection, Virtual Reality, Vibrotactile Haptics, Perception, Sensorimotor Contingencies

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1 Introduction

There is a growing interest in the HCI community to create redirected user movements in virtual reality (VR) to overcome the constraints of physical space. Redirection not only compresses a large virtual scene into a small physical space [5] but also helps enhance spatial interaction ergonomics [16, 29], enhance the scalability of passive haptic feedback [1, 6, 17, 25], and provide safe and natural ways of exploring virtual environments [12, 38]. Redirecting the hand is one of the key aims in this area: intentionally introducing an offset between the location of the real hand and its virtual representation without the user perceiving this misalignment [6, 32].

So far, research has dominantly focused on developing visual redirection techniques [9, 27, 32]. However, examples of acoustic redirection methods [44, 46] have highlighted the possibility of leveraging other sensory cues for redirection. Both hearing and vision provide distal cues. The sensory stimulus is perceived external from the body.

When we touch something, the experience is proximal, it is experienced at the location of the sensory organ (see also the account by Katz [22]. Furthermore, recent research has shown that feedback that correlates with human movement is attenuated, as if caused by one's own action [34]. This suggests that vibrotactile approaches to redirection might enable a more embodied redirection experience.

Further, haptic cues appear to be a natural choice for redirection, as they integrate with our proprioceptive systems [24, 51], and have been used to provide unconscious, pre-reflective feedback [33, 36]. For example, we instinctively withdraw our hand from a hot surface. Moreover, since vibrotactile feedback can be manipulated systematically [48, 49], they enable fine-tuned movement without any need for large-scale and complex input devices. Therefore, by leveraging vibrotactile feedback, we aim to create a more embodied approach to redirection in VR that can support established visual and acoustic redirection methods.

Our idea is based on the following observation: to evaluate a texture, we move our finger over its surface. Thereby, micro-level surface variations such as bumps or ridges create vibrations, providing information about the texture of the surface [21]. These vibrations have a frequency distribution that is affected both by (1) the tactile properties of the material [8] and (2) the speed with which we scan the texture [10]. Earlier work has focused on frequency distributions caused by material properties, showing how vibration patterns can simulate different textures without changing their actual physical properties [4, 42]. In contrast, we investigate how such patterns affect hand movement speed. We hypothesize that vibrotactile feedback can modulate not just texture perception but also influence movement execution.

To test our hypothesis and inspired by [42], we developed a custom-made slider mechanism to simulate the experience of vibrotactile feedback through vibrations in a 1D environment. In three psychophysical experiments, we systematically changed the frequency spectrum of the vibrations and the density of vibration pulses (grains) over the same spatial distance. We measured the movement speed of users over those different vibrotactile patterns and across conditions. The results demonstrate that (1) human hand movement speed can be modulated when perceiving different vibrotactile feedback, (2) the hand speed is not affected by vibrotactile feedback transitions when participants are aware of them, and (3) the hand speed increases by 20% when abruptly transitioning between relatively similar vibrotactile feedback as the amount of vibration pulses decreased by 50% when participants are unaware of the change in vibrotactile feedback.

2 Related Work and Background

We explore how vibrotactile feedback can modulate hand movement. Here, we first present the state-of-the-art redirection methods and then provide a review of relevant research on vibrotactile feedback perception.

2.1 Redirection in VR

Hand redirection is usually achieved through a visuo-haptic illusion that intentionally introduces visual offset between a user's hand position in physical and virtual space [32], thereby guiding user movement in a subtle and unnoticed manner. Redirection can increase presence [38] and create the illusion of greater movement in VR [28], which counteracts that the physical space is oftentimes more restricted than its virtual counterparts, addressing user safety concerns [12]. Further, redirection enables reusing a limited number of physical objects as proxies for multiple virtual counterparts, improving the scalability of passive haptic feedback [6, 17, 25].

Most redirection methods use visual cues due to their dominance over proprioceptive cues [9]. Applications include improving ergonomics [16, 29], bimanual redirection [18], and spatially decoupled haptic feedback [1, 15]. Other methods for redirection are underexplored. Examples of acoustic redirection include displaced tap sounds to simulate having extended limbs [45–47], and to alter object properties [37] and body perception [13, 44].

Both visual and auditory redirection methods face key limitations: they break down beyond certain misalignment thresholds [7, 18, 52], are less effective during unpredictable movements, often requiring additional strategies like forced blinking [19], and rely on indirect cues that can increase cognitive load [11]. Thus, we see the potential of expanding redirection methods with haptic cues, as they directly engage proprioceptive, kinesthetic, and tactile receptors [24, 26], while demanding less conscious attention [30]. *This paper takes a first step toward haptic redirection by exploring whether motion-coupled grain-based vibrotactile feedback can modulate hand movement.*

2.2 Tactile Perception

Sliding a hand over a surface generates vibrations shaped by both material properties [3] and movement dynamics [8]. The frequency spectrum of these vibrations is the dominant factor in distinguishing between different materials [8]. Interestingly, while changes in scanning speed of our fingertip alter these frequency spectra [2], the material perception remains stable [2, 10], indicating that perception relies on learned sensorimotor contingencies, that is both motor and sensory activity together, rather than absolute sensory input [43]. This aligns with sensorimotor theories of perception as discussed in the context of visual [31], and tactile perception [2, 24].

Vibrotactile cues closely coupled to actions – often referred to as grain-based vibration – can modify the perception of material properties [20, 41]. For example, it has been used to simulate materials [42], compliance [23, 50], flexible devices [20, 40], and in-air textures [39]. Many of these illusions, such as compliance illusion and simulated flexible devices require an assumption of human movement by the user. Ding et al. demonstrated that this could be used to create an illusion of movement, even when the user does not move [14]. *We extend upon this line of research by exploring if grain-based vibratile feedback can also influence the way in which a user executes a hand movement.*

3 Experimental Exploration

To better understand how bin density and frequency of grain-based vibration affect user movement speed, we conducted three experiments. First, we describe the shared apparatus, followed by each experiment and its results. All experiments followed the same protocol: participants gave informed consent, were informed that they could withdraw at any time without penalty, received 12 EUR compensation, and completed a brief training session. Conditions were counterbalanced using a Latin square. Participants always used their dominant hand to move a mouse along the slider (see Figure 1a)). The Shapiro-Wilk statistic suggested normally distributed data for all experiments.

3.1 Experimental Apparatus and Measurements

As shown in Figure 1, we developed a custom-made slider mechanism to provide vibrotactile feedback in a 1D environment. We constrained interaction to 1D linear motion, to study a simple base case, before expanding to more complex movement. A computer mouse was mounted on a low-friction 80 mm glide bearing attached to a 500 mm aluminum rod. Mouse acceleration was disabled for accurate tracking, and position data was sampled at 125 Hz via USB. This data was used for measuring user speed. Position data was sent to a Teensy 4.1, which generated vibrotactile grains using the TeensyAudio library. We used a PT8211 DAC to output the analog signals, before amplifying them with a Visaton 2.2LN. The vibration was played back with an Actronika Haptuator Mark II embedded in the mouse. We used grain-based vibrotactile rendering, triggering short pulses when position thresholds – uniformly spaced along the 50 cm rod – were crossed. For more details, see [14, 23, 35, 50].

3.2 Exp. 1: Effect of Frequency and Bin Density on Hand Movement Speed

In this experiment, we were interested in understanding how frequency and bin density of the vibrotactile feedback affect hand movement speed.

3.2.1 Participants and Procedure. 12 participants (7 females, 5 males; mean age = 25.66, SD = 4.43) participated in Exp. 1. We rendered 12 vibrotactile feedback patterns identified through a pilot study (see subsection A.1) in random order. Stimuli were repeated 3 times for each participant (see Figure 2 (a)). To shift focus away from movement speed, participants were tasked to identify how well each vibrotactile feedback condition enhanced their movement precision. White noise was played through headphones to mask any audio cues.

3.2.2 Results. To account for individual speed differences and unrestricted exploration, we standardized movement speed per participant using z-scores, as shown in Figure 3 (a). We found that participants moved faster under two conditions: when the frequency was low and bin density was high (80 Hz, 160 bins/50 cm) and when the frequency was high and bin density was low (200 Hz, 40 bins/50 cm). They moved the slowest when both frequency and bins were at intermediate levels (140 Hz, 100 bins/50 cm) (see Figure 3 (a)).

For further quantitative analysis, a two-way repeated-measures ANOVA was performed to evaluate the effects of frequency and bin density on participants' movement speed. The analysis did not find significant main effects of bin density ($F(2, 22) = 3.10, p = 0.07$), or frequency ($F(2, 22) = 0.83, p = 0.45$). However, the interaction between frequency and bin density was significant ($F(4, 44) = 03.53, p = 0.01$). Tukey's HSD post-hoc comparisons indicated a significant difference between bin densities 100 bins/50 cm and 160 bins/50 cm ($p = 0.040$), with no other bin density or frequency pairwise comparisons reaching significance.

We chose the two most different combinations in terms of user movement speed as parameters for the next experiment: (T1: 80 Hz, 160 bins/50 cm, T2: 140 Hz, 100 bins/50 cm).

3.3 Exp. 2: Effect of Transitions Between Vibrotactile Feedback Types on Hand Movement Speed

In this experiment, we investigated if hand movement speed changes when modulating three different transition types between two distinct grain-based vibrotactile feedback types.

3.3.1 Participants and Procedure. 6 participants took part in Exp. 2, who had already participated in Exp. 1 (4 females, 2 males: mean age = 26.83, SD = 6.11). We selected the two vibrotactile feedback types (T1 and T2) eliciting the most distinct movement speeds from Exp. 1 and rendered one on each side of the slider. We added three types of transitioning: *Abrupt transition* (sharp change in the middle of the slider), *Moderate transition*: (adding a short region where T1 and T2 are gradually interpolated), and *Gradual transition* (an extended region where T1 and T2 are gradually interpolated) (see Figure 2 (b)). Each condition was shown 3 times, with participants moving across the slider 3 times per trial. To divert focus from speed, participants were tasked to rate the effort of moving the slider. Again, white noise masked audio cues.

3.3.2 Results. The result of Exp. 2 is presented in Figure 3 (b). Using a one-way ANOVA, we found no significant effect of transition type on speed differences between T1 and T2 ($F(5, 30) = 0.12, p = 0.987$), confirmed by Tukey's HSD ($p > 0.05$). These results indicate that no matter the transition type, movement speed is not influenced when experiencing two *distinct* vibrotactile feedback next to each other. As users were aware that we rendered two different vibrotactile feedback and as we observed users watching their hands during the experiment, we hypothesized that participants might have focused on keeping a static movement despite the change in the stimuli. To prevent participants from becoming aware of stimulus changes in Exp. 3, we decided to reduce the visual input by using goggles and provide users with more similar vibrotactile feedback.

3.4 Exp. 3: Effect of Changes in Bin Density on Hand Movement Speed

In Exp. 3, we aimed to evaluate if movement speed is influenced when only the bin density of vibrotactile feedback is changed while the frequency remains the same.

3.4.1 Participants and Procedure. 8 participants (4 females, 4 males; mean age = 26, SD = 5.39) participated in this experiment. We selected the vibrotactile feedback eliciting the fastest speed from Exp. 1 (T1: 80 Hz and 160 bins/50 cm) and created another one by halving the bin density (T3: 80 Hz and 80 bins/50 cm), rendered on opposite

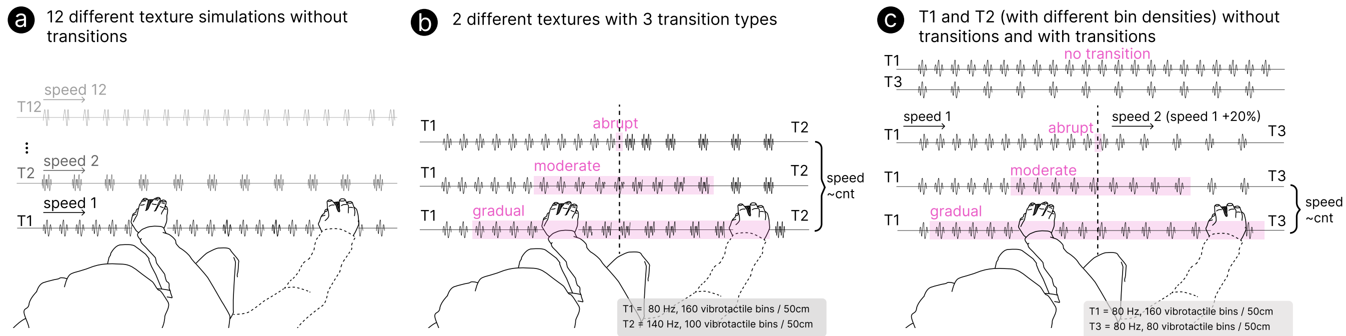

Figure 2: Study setup and main findings of all three experiments.

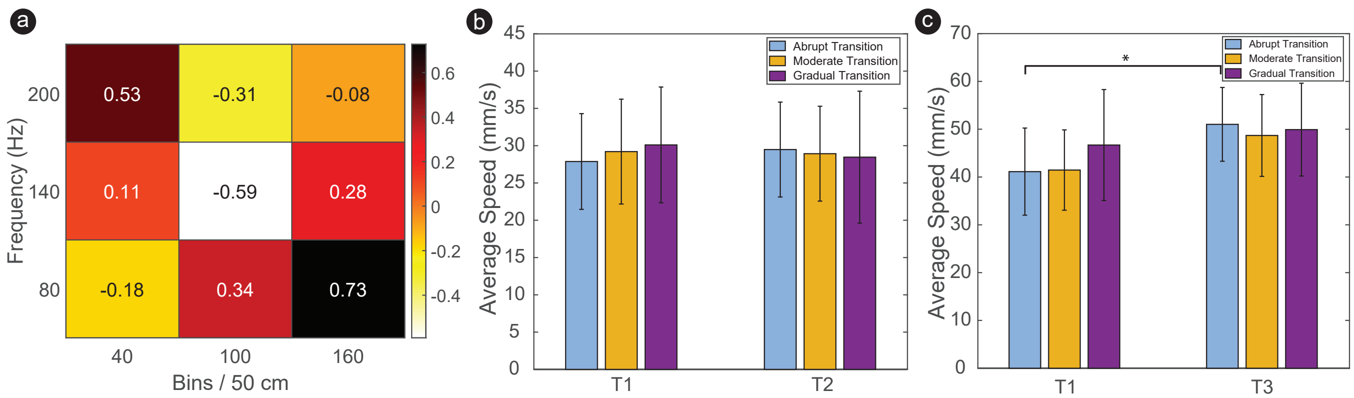

Figure 3: (a) Results of Exp. 1: Normalized average movement speed by bin density (x-axis) and stimulation frequency (y-axis). Average normalized movement speed differs significantly between the vibrotactile feedback with 140 Hz and 100 bins/50 cm and 80 Hz and 160 bins/50 cm. (b) Results of Exp. 2: We did not find a significant change in average movement speed when transitioning between vibrotactile feedback 1 (80 Hz, 160 bins/50 cm) and 2 (140 Hz, 100 bins/50 cm) under abrupt (blue), moderate (yellow), and gradual (purple) changes. (c) Results of Exp. 3: We found a significant change in average movement speed, which increased by 20% when transitioning between vibrotactile feedback 1 (80 Hz, 160 bins/50 cm) and 3 (80 Hz, 80 bins/50 cm) with an abrupt transition.

sides of the slider. Consistent with Exp. 2, we used the same three transition types and added two control conditions, where T1 and T3 covered the entire slider, measuring movement speed without stimulus changes. Therefore, the experiment included eight conditions: T1 only, T3 only, T1 left and T3 right with three transition types, and T3 left and T1 right with three transition types (see Figure 2 (c)). We also wanted to assess if hearing the vibration pattern has an effect on movement speed. Hence, participants experienced all eight conditions twice: once, audio cues were masked by white noise playing through headphones as in previous experiments, and once without, with the order being counterbalanced. In contrast to previous experiments, visual cues were masked by participants wearing goggles. Participants moved the mouse across the slider once per condition. Participants were tasked to move the slider from one end of the bar to the other while maintaining a constant movement speed.

3.4.2 Results. The result of Exp. 3 is shown in Figure 3 (c). Using a one-way ANOVA, we found a significant effect of transition type on differences in movement speed between T1 and T2 ($F(1, 7) = 0.12, p = 0.007$). Tukey's HSD with Bonferroni correction showed this difference was significant for abrupt transitions ($p = 0.038$). During abrupt transitions between T1 and T3, speed increased by 20% on the vibrotactile feedback with 80 bins/50 cm. This suggests users unconsciously adjust speed to compensate for bin density: they move faster with lower bin density and slower with higher density.

4 Discussion

In this paper, we performed three experiments to assess the possibility of haptic redirection by exploring the influence of vibrotactile feedback on hand movement speed. Our experiments showed that vibrotactile feedback can influence users' hand movement speed. First, we systematically observed varying speeds across different vibrotactile feedback (see Figure 3 (a)). In Exp. 2, we found that transitions between very distinct stimuli (in terms of frequency and bin density) did not affect movement speed when the stimuli were presented side by side on the slider (see Figure 3 (b)). In the final experiment, we kept the frequency constant and under abrupt transition condition, we found a 20% increase in average speed when bin density was reduced by half (see Figure 3 (c)).

Our results suggest that awareness of vibrotactile feedback transitions overrides haptic cues that would unconsciously affect the speed. This would explain the lack of significant effects in Exp. 2 in contrast to Exp. 3, where visual input was restricted by participants wearing goggles. It can also not be excluded that this was influenced by the participants in Exp. 2 having prior knowledge from Exp. 1. Results from Exp. 3 further suggest that participants adjusted their speed using tactile cues to compensate for changes in bin density, likely attempting to keep the timing between bins constant. We hypothesize that this effect occurred because participants assumed the vibrotactile feedback to be constant. Conversely, slow transitions might have given the participants time to adjust their mental model, preventing such an effect from occurring. This suggests that future work should explore using abrupt transitions between grain-densities while keeping the frequency of grains constant for optimal effect.

Our results highlight that humans use a broad range of sensory cues to construct the model of kinesthesia and movement. Based on the results in Figure 3 (c), we speculate that if vibrotactile feedback had no influence on our kinesthetic sense, we would not expect to find an effect of it. However, as we did find an effect of vibrotactile feedback, it suggests that humans use tactile information to shape their sense of kinesthesia. Furthermore, this demonstrates that similar methods could be used in the future to design multimodel redirection methods in VR.

Further, with this paper we provide a validation of the sensorimotor loop of human action and perception, as introduced in [24, 31].

Our experimental results also highlighted the complicated interplay between vibrotactile feedback and self-initiated movement speed. This paper thus contributes first insights into that relationship and suggests that investigating this correlation more systematically is a promising area for further exploration.

Our current study provides a foundation for future work to build on. We believe one promising direction is towards redirection in VR. To achieve this, it must be explored how our study transfers to less constrained, free-form movements. Additionally, there is still need for conceptual work to transform the changes in movement speed we observed to repeatable and precise changes in human hand position at the end of a movement.

5 Conclusion

This paper presents an initial approach to exploring whether and how vibrotactile feedback can be leveraged to intentionally alter movement speed without users noticing. These insights could potentially be used to extend visual and acoustic redirection methods by incorporating vibrotactile feedback. We contribute three psychophysical experiments that investigate this relationship, demonstrating that movement speed can be modulated by vibrotactile feedback under certain conditions and highlighting the complexity of the interaction between haptic cues and movement speed. Future work can build on our findings to explore this relationship more systematically.

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A Appendix

A.1 Initial Selection of Feedback Patterns

To select parameters for the first experiment, we conducted a pilot study. Two of the authors and one external expert in HCI were instructed to explore levels of frequency and bin density, to create combinations that felt distinctly different from each other. Following the individual selections, the authors collectively reviewed the results and agreed upon 12 vibrotactile feedback patterns based on the participants' choices. From this process, three frequency levels (80 Hz, 140 Hz, and 200 Hz) and four bin density levels per 50 cm (40, 100, 160, and 220) were selected for further study. We later excluded all combinations with 220 bins/50cm because the sensing resolution of our setup was insufficient to support them.