Vibrotactile Feedback in Virtual Reality

Subjects: Others
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While substantial progress in computer graphics and sound rendering has resulted in highly realistic visual and auditory experiences in virtual reality (VR), achieving genuine immersion, interactivity, and the stimulation of imagination necessitates the integration of realistic tactile experiences, often facilitated through haptic feedback. The incorporation of vibrotactile feedback in VR allows users to fully engage their sense of touch, enabling them to explore, grasp, and manipulate virtual objects as if they were interacting with them in the physical world.

Keywords: vibrotactile funneling illusion ; virtual reality ; haptic devices ; auditory feedback ; localization task ; multisensory environments ; avatar hands

1. Introduction

Creating a seamless integration of various sensory inputs poses a notable challenge in the domain of virtual reality (VR) [1]. While substantial progress in computer graphics and sound rendering over the past five decades has resulted in highly realistic visual and auditory experiences in VR [1][2], achieving genuine immersion, interactivity, and the stimulation of imagination [3] necessitates the integration of realistic tactile experiences, often facilitated through haptic feedback [4]. Haptic feedback encompasses diverse tactile stimulation methods, including vibrations, forces, and motions, all aimed at conveying information and enriching user experiences [5]. This text's specific focus lies in vibrotactile feedback, a haptic feedback form utilizing controlled vibrations to replicate sensations on the skin [6]. This technology seamlessly integrates into various devices, such as touchscreens, game controllers, and wearables, offering users realistic and immersive sensations that closely mimic physical attributes like texture, shape, weight, temperature, or resistance [7][8][9]. Consequently, the incorporation of vibrotactile feedback in VR allows users to fully engage their sense of touch, enabling them to explore, grasp, and manipulate virtual objects as if they were interacting with them in the physical world [9][10][11].

In the domain of haptic perception, a noteworthy area of research explores the ‘funneling effect,’ initially observed by v. Békésy [12]. The ‘tactile funneling illusion’ is characterized by the emergence of phantom tactile sensations through the application of vibrotactile feedback [13]. In this context, ‘phantom’ sensations refer to illusory tactile experiences, often perceived as occurring between distant points of skin stimulation [14][15][16][17]. This research aims to better understand and manipulate the tactile perception of users by exploring how vibrotactile feedback can create these intriguing illusory sensations. The tactile funneling technique has regained significant attention, especially in the contexts of virtual and augmented reality [8][13][18][19][20][21][22][23][24]. It has the potential to expand users’ perception of touch to virtual objects they interact with. For instance, in VR environments, when handheld controllers deliver vibrotactile sensations, the funneling illusion creates a compelling sensation for users. It makes them feel as if they are genuinely touching virtual objects or sensing the impact on a virtual object caused by interactions with other virtual objects, simulating forces [13][20][21][22]. This unique phenomenon significantly elevates the immersive quality of VR experiences by effectively bridging the gap between the digital and physical worlds.

The robustness of the funneling effect has been evident across various skin locations, including the palms, fingers, arms, and even the forehead [18]. However, despite its demonstrated reliability, prior research on the tactile funneling illusion has exhibited limitations in its scope. The majority of studies have primarily focused on a limited set of skin locations, typically involving just five intended illusory points [8][13][19][20][21][22][23]. In a few instances, researchers have expanded their investigations to include up to seven points [18][25]. Nevertheless, these studies have often overlooked multisensory environments, particularly neglecting audio stimulation. As a result, a notable gap remains in our understanding of how the tactile funneling illusion operates in multisensory contexts, where the integration of various sensory modalities has the potential to enhance its effectiveness. Furthermore, our current knowledge gap extends to understanding how these factors may interact and potentially reduce the perceived workload, a crucial aspect of enhancing user experiences in such settings [26].

2. Assessing Tactile Funneling in VR: An Objective Approach

The funneling effect, a phenomenon achieved by delivering tactile stimuli to various areas of the skin in a specific pattern, intensifies tactile sensations and directs them toward a central point on the skin [12][15][16][17]. For example, equal intensity delivered to both the right and left hands creates a phantom sensation centered between them. However, by varying the intensity, such as increasing it in the left hand while keeping it lower in the right hand, the perception of touch appears to shift towards the left side, with the reverse occurring when the intensity is higher on the right side. This phenomenon demonstrates how we can manipulate the perception of touch by adjusting the intensity of vibrotactile feedback across different body areas, even including the forehead [18].

In previous research, participants' descriptions of their experiences with phantom haptic events in VR settings have often been subjective. Many studies have relied on subjective questionnaires, administered in either virtual scenes or physical setups, to assess participants' perceptions, often through Likert scale responses [8][13][20][21][23]. These questionnaires included inquiries such as, 'I could locate where the events seemed to occur on the stick'. Alternatively, some studies adopted a raycasting method [19][22], requiring participants to utilize a foot pedal to accurately pinpoint the location where they sensed this phantom tactile sensation. These assessment methods introduced notable delays between experiencing the illusion and reporting it, potentially affecting response accuracy and our understanding of the illusion's intricacies.

Another study [8] emphasized the significance of incorporating bimodal feedback (visual–haptic) to enhance both presence and haptic perception in VR. They conducted a study to investigate the impact of different feedback modalities (visual only, haptic only, and visual plus haptic) on users' sense of presence. Surprisingly, their findings challenged the common assumption that visual feedback alone offers a better experience than haptic feedback alone, ultimately supporting the role of bimodal feedback (visual–haptic) in enhancing presence. However, none of the previous studies have investigated the potential of trimodal stimulation in VR experiments to further enhance haptic perception and presence when utilizing the tactile funneling technique.

Research on the funneling effect also extends to the design of cost-effective virtual haptic systems. For instance, Wang's study [27] has highlighted the customization of haptic feedback in real time, considering events in the virtual environment. The research prioritizes key elements such as haptic feedback in collisions and responsive force algorithms, fostering engaging virtual experiences. Importantly, Wang's study introduces a personalized approach, laying the groundwork for diverse haptic applications.

3. Multimodal Stimulation and VR: Performance Insights

Recent research investigated the influence of multimodal stimulation and perceptual load on human performance, workload, and presence in a VR target detection task [26]. To investigate these aspects comprehensively, the study employed a range of methodologies, including questionnaires, behavioral assessments, and neurophysiological measures such as Electroencephalography (EEG) and Galvanic Skin Response (GSR). EEG assessed task difficulty, while GSR objectively measured body illusions, as observed in earlier studies [28][29]. The study presented participants with various multimodal stimuli, including auditory and vibrotactile cues, either in isolation or in combination with visual targets. The research found that combining visual, auditory, and vibrotactile cues (trimodal) or using visual–vibrotactile stimulation (bimodal) significantly improved performance in high-perceptual-load VR tasks compared to visual stimulation alone. EEG data analysis showed that multisensory integration, especially with visual–audio–tactile and visual–audio cues, enhanced stimulus processing speed (i.e., faster detection of stimuli). However, this effect was not observed with visual–tactile stimulation. Both trimodal and bimodal stimulation reduced EEG-based workload, but only trimodal reduced subjective workload according to the NASA Task Load Index (NASA-TLX) (i.e., perceived workload). Interestingly, high-demand VR tasks increased the sense of presence, with trimodal stimulation being more effective than bimodal or unimodal. Additionally, skin conductance levels increased with task demands in VR, aligning with real-world task observations.

In a related systematic review by Melo et al. [1], which examined 105 studies on human senses in virtual environments, it was shown that 84.8% of these studies reported positive outcomes for multisensory VR experiences when compared to bimodal or unimodal experiences. Haptic feedback emerged as a dominant feature, featured in 86.6% of the studies, highlighting its crucial role in enhancing sensory immersion within virtual settings. These findings collectively help us understand how different types of stimulation and task complexity in VR impact performance, workload perception, and the sense of presence, providing insights for improvement.

4. Avatar Embodiment in VR: Effects on Tactile Perception

Avatar embodiment is a multifaceted concept encompassing ownership perception, appearance realism, sensory integration, and responsive interactions [30]. Previous work emphasizes the importance of full-body avatars in VR, particularly in enhancing vibrotactile [22] and visual–vibrotactile stimulation [31][32]. The presence of a virtual body significantly improves users' spatialization of touch, crucial in scenarios involving ambiguous haptic feedback.

Interestingly, participants' objective and subjective reports of touch illusion sometimes differ, suggesting that subjective measures of immersion may not always align with users' internal cognitive states [22]. Objective measures like haptic localization tasks are proposed to gain deeper insights. Additionally, embodying different avatars or adjusting virtual body characteristics (e.g., size, gender, or race) can lead to shifts in haptic perception [30].

Hence, integrating avatar bodies or avatar body parts into VR environments offers a unique opportunity to enhance avatar embodiment. Matching skin tones further strengthens the connection between users and their avatars, improving the VR experience [33].

5. The Neural Mechanisms behind Tactile Illusions: Insights from VR

Vibrotactile stimulation has gained popularity in recent years for enhancing human–computer interaction (HCI), particularly in VR. This often involves using vibrators in game controllers, but more advanced tactile grids with multiple vibrators pose cost and usability challenges. To address this, tactile illusions have emerged as a promising solution, creating 'phantom' vibrotactile sensations seemingly originating from non-contact points [13][20]. One technique, saltation, induces pseudo-tactile sensations between two body locations through timed stimuli [34], while funneling generates similar sensations by simultaneously stimulating two skin locations with varying amplitudes [16].

Despite their significance for effective use in human–computer interaction, there has been limited research into the physiological and neural mechanisms underlying tactile illusions. To address this gap, Lee et al. [21] conducted a study focusing on the brain activation patterns associated with the tactile funneling illusion—a phenomenon where tactile sensations are perceived as originating from external locations without any physical stimulator present. Using EEG to measure brain waves, the researchers compared illusory tactile sensations generated by the funneling technique to non-illusory sensations. Surprisingly, their results revealed that both non-illusory and illusory sensations involved the parietal lobe despite the absence of a corresponding body map area for an external object. Furthermore, illusory sensations exhibited additional processing, resulting in delays in event-related potential (ERP), and involvement of the limbic lobe. These findings suggest a possible connection to memory and recognition tasks.

In summary, this research reveals the complexities of tactile illusions and their neural basis. It suggests that humans may have limitations in recognizing multiple illusory sensations due to the constraints of working memory. Additionally, the study shows that the speed of brain responses (ERP latency) can affect how well these illusions work, especially when using different-sized devices or virtual objects in VR.

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