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Increasing Sense of Agency in VR by Providing Non-Contact Collision Haptics

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I. Introduction

Sense of agency (SoA) is *"the experience of controlling one's own actions, and, through them, events in the outside world."* [4]. In a virtual environment, sense of agency plays a crucial role in the sense of embodiment, which ultimately affects users' overall experience [6]. Previously, researchers have increased SoA by visual [1], auditory [7], and tactile [2] cues. These works focused on the first part of SoA's definition to increase SoA. The sensory cues in these works reinforced additional detail of one's body and own action to heighten SoA.

We propose a novel method to increase SoA, focusing on the second part of the definition: events in the outside world. We emphasized the result of the users' actions that cause changes in virtual reality (VR). Hence, we deliver haptic feedback from collision events of non-contact virtual objects caused by users' actions (Figure 1a). For instance, when a user throws a ball in VR, the user's action causes the ball to hit a wall. We generate vibration patterns based on the collision sound and deliver these vibrations to the user when the ball hits the wall. By providing appropriate vibrations, we highlight the result of the user's action and consequently, increase SoA.

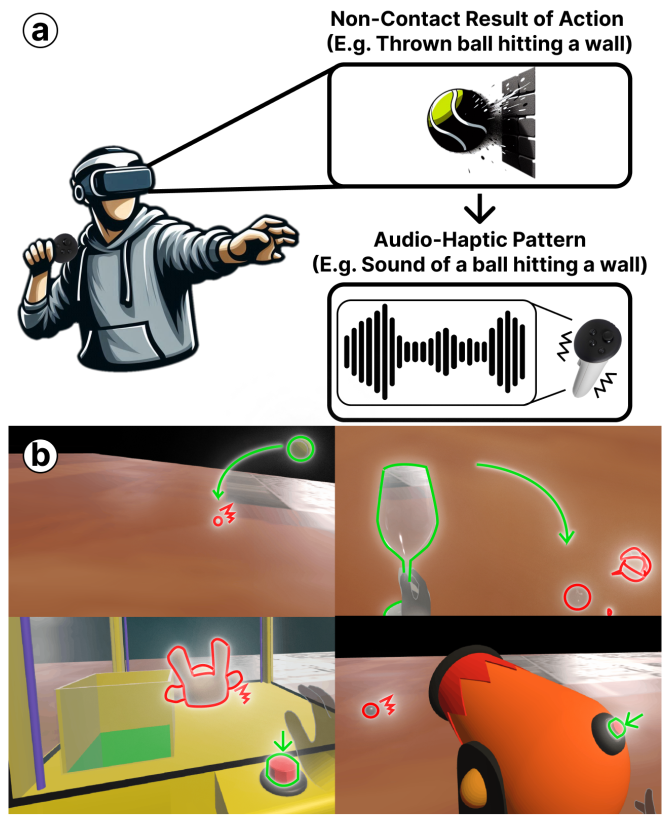

Fig. 1. (a) We deliver haptic feedback from collisions between virtual objects caused by the users' actions, emphasizing the consequences of the users' actions. (b) We developed 4 collision scenarios. The green outlines show user interaction and action. The red outlines highlight the affected virtual object and the collision. The user causes the collision directly by throwing a ball or a wineglass, or indirectly by pushing a button that triggers a claw to drop a doll or a cannon to fire.

II. Collision Scenarios

We developed 4 example collision scenarios demonstrating our idea (Figure 1b). We used a Meta Quest 3 for our head-mounted display (HMD) and provided the vibrations through the Quest 3 controllers. We developed the scenarios through Unity 3D (2022.3.43f1).

We first organized the different types of actions and collisions for our scenarios to cover a wide range of possible collisions. We categorized the actions causing the collision into direct and indirect. Direct interaction occurs when the user directly interacts with the target virtual object and causes it to collide with other objects. Indirect interaction occurs when the user manipulates another object, which affects the target virtual object. We also categorized the type of collision into soft and hard depending on the loudness of the collision.

For a direct, soft collision, we used a tennis ball. When the user throws the tennis ball, the vibration is applied when the ball hits the floor. For a direct, hard collision, we used a wineglass. When the user drops the wineglass, the wineglass shatters, and we apply vibration as it shatters. For an indirect, soft collision, we used a claw machine dropping a doll. When the user presses the button, they release the claw, and the doll drops. When the doll contacts the floor, the controller vibrates. Lastly, for an indirect, hard collision, we used a cannon. When the user presses the button, the cannon fires and shoots a cannonball. We deliver the vibration when the

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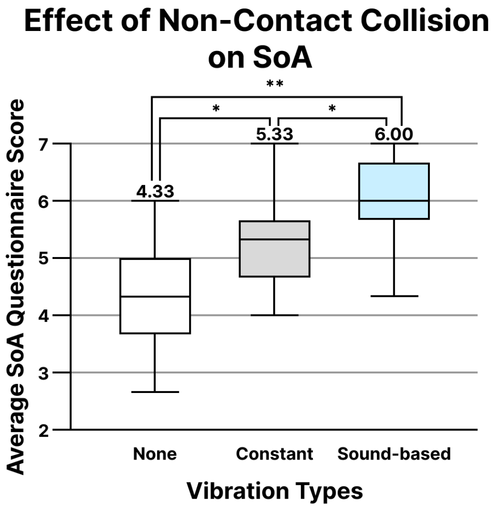

Fig. 2. Boxplots of the average SoA questionnaire scores. Numbers above the boxplot indicate the median. * indicates $p < 0.01$ and ** indicates $p < 0.001$.

cannonball lands on the floor. We found sounds for each scenario online[1] and used the sounds to generate haptic patterns through Meta Haptic Studio (Ver. 1.3.1).

III. Sense of Agency Pilot Study

Here we test whether SoA increases by highlighting results of users' actions through haptic feedback. We recruited 6 participants (2 males, 4 females; Mean age: 25.2, SD:2.56). We used the 4 collision VR scenarios (Figure 1b) for our pilot study. We tested these VR scenes with 3 vibration settings: *None*, where there was no vibration; *Constant*, where the vibration was constant; and our implementation, *Sound-based*, where we generated the vibration pattern based on the sound produced during collision.

To measure SoA, we used the feedback reasoning category of the game sense of agency questionnaire [3]. The questionnaire consists of 3 7-point Likert scale questions which were: 1) *How the virtual environment reacts to my control is responsive*; 2) *The interaction between other objects and me appears to be reasonable*; and 3) *My actions and its effects on other objects appear to be coherent*. Participants experienced the 12 combinations of collision scenarios and vibration settings in a random order. After each combination, participants answered the questionnaire. The pilot study took no longer than 20 minutes.

To analyze the results, we first averaged the 3 questionnaires and conducted a Kruskal-Wallis test using the vibration types as the factor (Figure 2). We found that there is a significant difference between the medians of the 3 vibration types (χ^2(27.3,2), $p < 0.001$). A post-hoc Dunn's test showed that there was a significant increase from *None* to *Constant* (Z=2.62, $p < 0.01$), from *None* to *Sound-based* (Z=5.23, $p < 0.001$), and from *Constant* to *Sound-based* (Z=2.60, $p < 0.01$).

[1] `https://freesound.org`

From these results, we conclude that haptic feedback from collision events of non-contact virtual objects increases SoA. More specifically, there was a greater increase when the vibration mirrored the sound produced during the collision compared to a constant vibration.

IV. Future Works

During the pilot study, participants had visual feedback of their actions, but we did not include auditory details. By extending the study to different situations where certain sensory cues are absent or present, we would be able to observe how cross-modal groupings would affect user SoA when emphasizing user action results [5]. These additional studies would shed more light on how to apply non-contact collision haptic to improve SoA most effectively during a multimodal interaction.

Also, to apply non-contact collision haptics, haptic designers would have to find the exact trigger when the collision happens, retrieve the relevant sound, and save the haptic pattern, complicating the process when there are several virtual objects involved. We are currently developing an authoring tool where the author simply acts out the action in situ, and the system detects applicable locations for these non-contact collision haptic.

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