Pseudo-Haptic Button for Improving User Experience of Mid-Air Interaction in VR

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Abstract. Mid-air interaction is one of the promising interaction modalities in virtual reality (VR) due to its merits in naturalness and intuitiveness, but the interaction suffers from the lack of haptic feedback as no force or vibrotactile feedback can be provided in mid-air. As a breakthrough to compensate for this insufficiency, the application of pseudo-haptic features which create the visuo-haptic illusion without actual physical haptic stimulus can be explored. Therefore, this study aimed to investigate the effect of four pseudo-haptic features: proximity feedback, protrusion, hit effect, and penetration blocking on user experience for free-hand mid-air button interaction in VR. We conducted a user study on 21 young subjects to collect user ratings on various aspects of user experience while users were freely interacting with 16 buttons with different combinations of four features. Results indicated that all investigated features significantly improved user experience in terms of haptic illusion, embodiment, sense of reality, spatiotemporal perception, satisfaction, and hedonic quality. In addition, protrusion and hit effect were more beneficial in comparison with the other two features. It is recommended to utilize the four proposed pseudo-haptic features in 3D user interfaces (UIs) to make users feel more pleased and amused, but caution is needed when using proximity feedback together with other features. The findings of this study could be helpful for VR developers and UI designers in providing better interactive buttons in the 3D interfaces.

Keywords: Virtual reality; Mid-air interaction; User experience; Button; Pseudo-haptics

1. Introduction

Virtual Reality (VR) is a concept that has existed for several decades but has not gained much attention from the general public until the recent advancement of mass-market VR head-mounted displays (HMDs), which have renewed the interest in the design of 3D user interfaces (UIs) and 3D interaction techniques in immersive virtual environments. In such environments, head and hand tracking are often enabled by 6 degree-of-freedom tracking technologies that potentially provide natural and direct interaction with objects stereoscopically displayed in the virtual world. Consequently, the user can manipulate virtual objects within reach in a similar way to grabbing or selecting objects in the real world.

Selection is one of the fundamental tasks of user interaction in VR and 3D UIs (LaViola Jr. et al., 2017), and button is one of the fundamental widgets in UI both physically and digitally (Janlert, 2014), inevitably evolving to the 3D form in VR (Speicher et al., 2019; van Dam, 1997). However, current 3D UIs are usually designed by adapting directly from the paradigm of 2D UIs (Lee et al., 2018) which leads to a gap in the user experience (Bowman et al., 2012). Interacting with the 2D UI in 3D space is known to be demanding due to the inherent difficulty of understanding and performing actions in 3D space (Herndon et al., 1994).

In the HMD-based VR, head-gaze, hand-held controllers, and free-hand mid-air gestural inputs are considered typical interaction modalities (Speicher et al., 2018). Although the controller-based interaction
turned out to be more responsive than the free-hand mid-air interaction (Caggianese et al., 2019; Dudley et al., 2019), mid-air interaction is regarded as a natural and intuitive way of interacting with 3D UIs in VR (Lee and Hui, 2018). Since the release of the Leap Motion controller which supports real-time skeletal tracking of the user’s hands and fingers, steady efforts on technological advancements have been driven in the field of vision-based hand tracking. The current market-dominating VR and augmented reality (AR) HMDs such as Oculus Quest 2 and Microsoft Hololens 2 are coming out with a decent real-time hand tracking capability enabled by inputs from embedded monochrome (Han et al., 2020) or depth (Ungureanu et al., 2020) cameras, facilitating a simple and easy implementation of controller-free mid-air interactions in VR.

Although mid-air interaction in VR demonstrates the remarkable advantages of naturalness and intuitiveness, the usability of VR UIs is highly dependent on the availability of haptic feedback. Many studies have proven that the interaction suffers when no haptic feedback is provided (Benko et al., 2006; Dudley et al., 2019; Faeth and Harding, 2014; Hoggan et al., 2008; Shneiderman, 1997; Zhao et al., 2014). In order to provide the haptic feedback to inform users about the confirmation of their action, studies have used active haptics with wearable haptic devices such as smart gloves/thimbles (Blake and Gurocak, 2009; Bouzit et al., 2002; Bullion and Gurocak, 2009; Gabardi et al., 2016; Kim et al., 2016) and contactless modalities such as ultrasounds (Arafsha et al., 2015; Carter et al., 2013; Freeman et al., 2019; Shakeri et al., 2018), while passive haptics has been enabled by physical props (Azmandian et al., 2016; Joyce and Robinson, 2017; Strandholt et al., 2020). However, such approaches for providing the haptic feedback would eventually require compatible equipment, resulting in ineffective and bulky experience in real-life VR usages (Hwang et al., 2017), and not always available to users taking the practical considerations into account. Therefore, the lack of haptic feedback remains as the common problem of current mid-air button interaction.

The pseudo-haptic method which uses multi-sensory contradiction, where visual cues create haptic illusions without actual physical haptic stimulus (Hachisu et al., 2011) can be a breakthrough for compensating this issue (Chattopadhyay, 2016). Although it has been more than two decades since the first proposal of the concept of pseudo-haptics (Lecuyer et al., 2000), the adaptation of pseudo-haptic features into the design factors of buttons for modern VR is surprisingly lacking. A survey revealed that the design factors of buttons in VR such as sizes, positions, types, and shapes are not sufficiently addressed (Dube and Arif, 2019). Moreover, there have been very few comparative studies covering the fundamental factors of button design in VR (Bermejo et al., 2021). One recent preliminary study compared the planar (2D) and pseudo-haptic (3D) representations of UI widgets for menu interaction, and concluded the pseudo-haptic UI performs better in terms of workload, user experience, motion sickness, and immersion (Speicher et al., 2019). This demonstrates the potential of pseudo-haptic features for improving user experience thereby making other features worth studying in the domain of mid-air interaction in VR.

This study aims to investigate the effect of four pseudo-haptic features on the experience of the user touching the virtual button in mid-air. We conducted a user study to collect ratings on various subjective evaluation and user experience aspects when interacting with 16 buttons consist of different combinations of existence and nonexistence of four pseudo-haptic features. Then, we asked their preference towards each of the four pseudo-haptic features and the reasons behind their decisions.

2. Related Work

2.1. Free-Hand Mid-Air Interaction

Mid-air interaction is a type of kinesthetic interaction (Fogtmann et al., 2008), denoting touchless and gesture-based interactions with displays or devices (Koutsabasis and Vogiatzidakis, 2019). Free-hand mid-air interaction possesses great potential in enabling natural UI in many user scenarios such as VR/AR applications, human-robot interactions, smart homes, and autonomous devices. In comparison with controller-based interfaces, users are free from holding a device and are allowed to engage with virtual objects directly via hand
motions, promoting intuitiveness of the UI as spatial gestures are closely linked to the inherent manipulation skill of the human (Hinckley et al., 1994). Free-hand interfaces require tracking systems to detect mid-air hand gestures of the user as input. In virtue of extensive research on vision-based hand pose estimation (Ahmad et al., 2019; Erol et al., 2007; Supančič et al., 2018), modern commercial VR/AR HMDs are capable of detecting hands in real-time with embedded cameras.

Earlier works on free-hand mid-air interaction were explored across various modalities and application fields. Luo and Kenyon used scalable computing technologies to engage vision-based gesture interaction in a high-resolution tiled display setting (Luo and Kenyon, 2009). Hilliges et al. provided an easy way to handle digital contents in 3D by exploiting space above a standard interactive tabletop (Hilliges et al., 2009). Benko and Wilson combined free-hand pinch gestures with speech for the interaction of multiple users with a large curved display (Benko and Wilson, 2010). Nancel et al. developed a set of mid-air pan-and-zoom gestures to interact with graphics on a wall-sized display (Nancel et al., 2011). Song et al. studied designs of mid-air interaction in a free-hand setting for object manipulation in a 3D virtual space (Song et al., 2012).

Regarding direct interaction with floating virtual objects, several pioneering studies have explored using a Fresnel lens (Chan et al., 2010), a concave mirror (Butler et al., 2011), a see-through display (Hilliges et al., 2012), and a stereo projector (Benko et al., 2012), whereas later implementations occurred more in the context of VR HMD. Speicher et al. and Bermejo et al. tested design features of 3D UI for mid-air interaction in VR (Bermejo et al., 2021; Speicher et al., 2019), while Speicher et al. and Fashimpaur et al. emphasized improving user performance and experience for VR text entry (Fashimpaur et al., 2020; Speicher et al., 2018).

### 2.2. Pseudo-Haptics for Mid-Air Interaction

Most of the previous works on pseudo-haptics have simulated haptic properties by offering supplementary visual cues when the physical haptic cues were present by active devices or passive props (Abtahi et al., 2019; Abtahi and Follmer, 2018; Argelaguet et al., 2013; Ban et al., 2014; Dzidek et al., 2018; Hirano et al., 2011; Kimura and Nojima, 2012; Monnai et al., 2014; Punpongsanon et al., 2015, 2014; Samad et al., 2019; Sato et al., 2020; Ujitoko et al., 2015), thereby whether pseudo-haptic feedback could be made without a user's physical engagement with a tangible object remained uncertain. Interestingly, only a few studies attempted to create a haptic illusion in mid-air interaction when no external haptic inputs were given. Speicher et al. compared the experience of users for mid-air finger-based menu interaction with 2D and 3D UIs, and found 3D UI performed better (Speicher et al., 2019). Kawabe tested the stiffness of the virtual object with varied ratios of object deformation magnitude to the hand distance and found the deformation-to-distance ratio affected the perceived stiffness (Kawabe, 2020). Kang et al. revealed visual and auditory cues can influence perceived roughness on virtual mobile gadgets in mixed reality (Kang et al., 2021). These studies have shown the feasibility of pseudo-haptic feedback in mid-air interaction.

Haptic feedback supports interaction by providing users an important confirmation of a successful action. Therefore, visually augmented pseudo-haptic features can enhance haptic illusion or provide additional information to strengthen confirmation of the action to attain the same benefits. There is a large body of research investigating such features. One attempt was to use shadows as depth cues to enhance illusions when selecting or manipulating virtual objects. Herndon et al. visualized the spatial relationships between objects in 3D applications with shadows (Herndon et al., 1992), whereas Wanger investigated the effect of shadow sharpness and shape on the spatial relationships (Wanger, 1992). Chan et al. proposed the pseudo-shadow visual feedback which indicated the proximity of the finger on interacting with intangible displays, and found that feedback was helpful in improving user performance and satisfaction (Chan et al., 2010).
Another attempt was made in the design of UI widgets to adapt affordances of real-world objects. Planar 2D UIs were transformed into protruded pseudo-haptic 3D UIs following the look of real-world widgets (e.g. buttons, switches, sliders, and control knobs) in addition to the stereoscopic cues to further enhance the illusion like the user is interacting with tangible objects. The comparisons were made for the stereoscopic display (Zilch et al., 2014) and the VR HMD (Speicher et al., 2019), and reported superior performance of protruded 3D widgets in terms of usability and user experience ratings. Meanwhile, a recent study compared 2D and 3D buttons for the numeric keypad typing task, and their results implied the 3D buttons induced lesser button press depth when haptic cues are provided, while 2D buttons induced higher entry speed than the 3D counterparts (Bermejo et al., 2021).

One feature could be inspired from the field of gaming, where the game designers attempted to maximize the feeling of hit when the player attacks the enemy to improve enjoyment. This attempt bears resemblance to the pseudo-haptic approach in the sense that it creates a sensual illusion of collision with extra visual effects. Studies have examined the impact of various visual (e.g. particle, afterimage, vibration, and view adjustment) and auditory (e.g. shooting sound, explosion sound, and groan) effects in the 2D shooting game (Kim and Kim, 2004; Seo and Kim, 2010) and the 2D fighting game (Moon and Cho, 2012), and revealed significant improvements on the feeling of hit with such effects.

The other approach could be derived from the attempt to block the virtual hand from penetrating the virtual object, which eventually leads to the displacement between the real and virtual hands. This approach was first proposed by Lindeman et al. (2001), and was identified as evidence to prove visual dominance over proprioception (Burns et al., 2006) and haptic modality (Mensvoort et al., 2008). While extensive research has focused on utilizing hand displacement for the selection of the out-of-reach objects (Benda et al., 2020; Gonzalez and Follmer, 2019; Ogawa et al., 2020; Tian et al., 2020), limited efforts were made for pseudo-haptics. Pusch et al. applied hand displacement to provide haptic-like sensations by dynamically displacing the virtual hand in the simulation of force fields, and found most participants could feel force illusion that their hand was pushed inside the force field (Pusch et al., 2009). Rietzler et al. tested the pseudo-haptic feedback of the virtual hand not penetrating the static object, and reported a significant increase in immersion and enjoyment (Rietzler et al., 2018a). In this study, we adopt this feature to block the penetration of the finger in the context of button interaction in VR.

It is worthwhile to examine the pseudo-haptic features on their effect on the user experience for mid-air interaction in VR as the definitive conclusion cannot be made based on the prior works. In this study, we consider four aforementioned pseudo-haptic button design features: proximity feedback, protrusion, hit effect, and penetration blocking.

3. Methods

3.1. Participants

Twenty-one Korean young adults (13 males and 8 females) between the ages of 19 and 33 (M=23.8, SD=4.0) and with normal or corrected to normal vision participated in the experiment. All participants except one were right-handed. Eighteen participants have experienced a kind of headset-based VR applications before this experiment, but 16 of them used the VR headset no more than once a year, showing the majority of participants were light VR users. Six participants reported that they experienced mid-air interaction with the tracked virtual hand in VR. All participants gave consent for the experiment protocol approved by the University Institutional Review Board (IRB NO.: KH2021-009).
3.2. Experimental Design

Four pseudo-haptic features were investigated in this study (Figure 1). The first feature, proximity feedback (PF) provided visual feedback when the finger goes near the button by showing a circle that enlarges as the finger approaches the button. The use of pseudo-shadow was avoided to be independent of the direction of light of the virtual environment. The second feature, protrusion (PT) enabled the contact surface to be protruded then pushed into the base, mimicking the affordance of the real-world 3D button. The design of the button was adopted from the one proposed in a previous study (Speicher et al., 2019) and the example described in the guideline for Oculus developers (Facebook, 2021). The third feature, hit effect (HE) added an extra sparkling visual cue together with a small vibration of the button when triggered. Although shaking the screen induced the largest feeling of hit in a fighting game (Moon and Cho, 2012), it was not appropriate to be applied in VR since visually induced experiences of self-motion are known to cause motion sickness (Bonato et al., 2008). Therefore, two applicable effects: visual vibration and collision graphics were selected for this study. The last feature, penetration blocking (PB) prohibited penetration of the virtual hand which is shown to the user, although the real hand actually penetrated the button. Total 16 buttons with different combinations were created by enabling (O) or disabling (X) each of four features, and a 2 proximity feedback (PF₀, PFₓ) × 2 protrusion (PT₀, PTₓ) × 2 hit effect (HE₀, HEₓ) × 2 penetration blocking (PB₀, PBₓ) within-subject design was used to investigate the effect of those features (Figure 1).

![Figure 1](https://vimeo.com/548802500)

Figure 1. Four pseudo-haptic features investigated in this study. For penetration blocking, the location of the real hand, which is represented by a semi-transparent hand avatar, was invisible to the participants in the actual experiment. A video demonstration of 16 button combinations can be seen at the following link: https://vimeo.com/548802500.
3.3. Experimental settings

The participants experienced the virtual test environment with an Oculus Quest (resolution: 1440×1600 per eye; refresh rate: 72 Hz) VR headset, while the headset was connected to the PC through Oculus Link via a compatible USB 3.0 cable. The PC used to run the test environment was equipped with an Intel Core i7-7700 processor running at 3.6 GHz, 16 GB of RAM, and an NVIDIA GeForce GTX 1080 Ti GPU, running Windows 10. Hands were tracked in real-time by the four fisheye monochrome cameras embedded in the Oculus Quest headset with the help of an advanced hand detection network (Han et al., 2020). As hands were tracked by monochrome images, the background was covered by a black screen fence to prevent any potential deterioration of tracking performance (Figure 2-a). It is worth noting that although the virtual hand representation used in this study is not the most human-like hands, it does not severely violate the human-likeness thus does not significantly affect tactile experiences (Schwind et al., 2018). The screen fence was located 1.2 m away from participants, providing them enough space to freely interact with the virtual targets without any physical interruptions.

Inside the virtual test environment developed using Unity 2019.4.15f1, 16 circular buttons were placed in front of the participant in a 4×4 square grid (Figure 2-b). The center of the grid was located 0.2 m (scale unit in Unity) below the height of the VR headset when the participant was standing. The distance between two neighboring buttons placed in the same row or column was 0.1 m, and the diameter of the buttons was 5 cm. The participants were allowed to freely step back and forth to adjust the distance to the buttons to find the best setting for them to comfortably interact with the buttons. It is worthy to note that the location of buttons was determined to facilitate minimum ergonomic cost (Evangelista Belo et al., 2021) while taking the hand tracking range of the Oculus Quest headset into account to guarantee stable tracking performance at all times.

Figure 2. Experimental settings in (a) the real environment and (b) the virtual environment. The head avatar in the virtual environment was invisible to the participants in the actual experiment.

3.4. Experimental Procedure

First, participants filled in a pre-test questionnaire asking about their demographic information and prior experience with VR. After participants were explained about four pseudo-haptic features and the difference between 16 buttons, they were asked to press each of 16 buttons (Figure 2-b) with the index finger of their
dominant hand twice following the pre-defined randomized order. Then, 11 subjective evaluation items about haptic illusion, embodiment, sense of reality, presence, spatiotemporal perception, and satisfaction aspects (Gonzalez-Franco and Peck, 2018; Pusch et al., 2009; Schwind et al., 2018; Usoh et al., 2000) were asked and the responses were collected through 7-point Likert scales (Table 1). In addition, a short version of the User Experience Questionnaire (Schrepp et al., 2017) was used to collect pragmatic and hedonic quality aspects of user experience (Table 1). After participants were asked to answer their preference on each feature and the corresponding reasons, they were encouraged to select a single most preferred button, although multiple selections were allowed in case they did not have a clear preference on certain features. During the whole questionnaire session, questionnaire items were presented right next to the buttons all the time, and participants verbally gave the rating in their preferred order while freely interacting with buttons as many times as they wanted.

Table 1. Items of the subjective evaluation and user experience questionnaires used in this study. Answers were given through 7-point Likert scales (Subjective evaluation: 1=strongly disagree, 7=strongly agree; User experience: -3=fully agree with the negative term, +3=fully agree with the positive term)

| Aspect                  | No. | Item                                                                 |
|-------------------------|-----|----------------------------------------------------------------------|
| Haptic illusion         | 1   | I felt the haptic sensation like touching the tangible object.       |
|                         | 2   | It seemed as if I felt the touch of the button in the location where I saw the virtual button touched. |
| Embodiment              | 3   | I felt as if the virtual hand was my own hand while pressing the button. |
|                         | 4   | It felt like I could control the virtual hand as if it was my own hand while pressing the button. |
| Sense of reality        | 5   | My experiences in the virtual environment seemed consistent with my real-world experiences. |
|                         | 6   | Interacting with this button felt like interacting with the real-world buttons. |
| Presence                | 7   | I had a sense of “being there” in the virtual space.                 |
|                         | 8   | During the experience I often thought that I was really standing in the virtual space. |
| Spatiotemporal perception| 9   | I could perceive the distance between my hand and the button well when pressing the button. |
|                         | 10  | I could perceive the exact timing when the button will be pressed well. |
| Satisfaction            | 11  | I was satisfied with the overall experience of pressing the button.  |
| Pragmatic quality       | 1   | Obtrusive – Supportive                                              |
|                         | 2   | Complicated – Easy                                                  |
|                         | 3   | Inefficient – Efficient                                             |
|                         | 4   | Clear – Confusing                                                   |
| Hedonic quality         | 5   | Boring – Exiting                                                   |
|                         | 6   | Not interesting – Interesting                                       |
|                         | 7   | Conventional – Inventive                                            |
|                         | 8   | Usual – Leading edge                                                |

3.5. Data Analysis

Ratings for items of the subjective evaluation and user experience questionnaires were collected and arranged for statistical analysis. For all aspects, mean ratings within each category were used for the analysis. No outliers in ratings were detected according to the Grubbs’ outlier test. Analysis of variance (ANOVA) was conducted to check the statistical significance of each subjective evaluation item. Minitab 19 was used to conduct all statistical analyses at a significance level of 0.05. The variation from participants was blocked. The effect size in terms of eta-squared ($\eta^2$) was further calculated to check practical significance. A general rule on the magnitudes of the effect size with $\eta^2$ is as follows: small-$\eta^2$~0.01, medium-$\eta^2$~0.06 and large-$\eta^2$~0.14 (Cohen, 1988). For the selection of the most preferred button, the choices were normalized to keep the sum of frequency as 1 for each participant when multiple buttons were selected (e.g. 0.5 for selection of 2 buttons and 0.25 for 4 buttons).
4. Results

4.1. Subjective Ratings

4.1.1. Main effects

Table 2 shows the ANOVA results on the ratings of subjective evaluation and user experience questionnaires. Significant main effects of PF, PT, HE, and PB were observed on the haptic illusion (PF: $F_{1,300}=13.79$, $p<0.001$; PT: $F_{1,300}=276.59$, $p<0.001$; HE: $F_{1,300}=241.27$, $p<0.001$; PB: $F_{1,300}=41.3$, $p<0.001$), embodiment (PF: $F_{1,300}=7.28$, $p=0.007$; PT: $F_{1,300}=118.64$, $p<0.001$; HE: $F_{1,300}=99.19$, $p<0.001$; PB: $F_{1,300}=5.59$, $p=0.019$), sense of reality (PF: $F_{1,300}=10.06$, $p=0.002$; PT: $F_{1,300}=147.00$, $p<0.001$; HE: $F_{1,300}=114.37$, $p<0.001$; PB: $F_{1,300}=45.93$, $p<0.001$), spatiotemporal perception (PF: $F_{1,300}=177.81$, $p<0.001$; PT: $F_{1,300}=172.27$, $p<0.001$; HE: $F_{1,300}=99.67$, $p<0.001$; PB: $F_{1,300}=21.88$, $p<0.001$), and satisfaction (PF: $F_{1,300}=10.97$, $p=0.001$; PT: $F_{1,300}=94.54$, $p<0.001$; HE: $F_{1,300}=161.68$, $p<0.001$; PB: $F_{1,300}=21.11$, $p<0.001$), whereas the main effect of HE was solely significant for presence ($F_{1,300}=37.84$, $p<0.001$). Ratings increased by enabling PF, PT, HE, and PB in all subjective evaluation aspects except presence. Among significant measures, the effect size differed between different pseudo-haptic features. For PF, large effect size ($\eta^2=0.159$) was found at spatiotemporal perception while the rest had small effect size ($\eta^2=0.009-0.014$). Medium to large effect size for PT ($\eta^2=0.125-0.229$) and HE ($\eta^2=0.089-0.200$) and small to medium effect size for PB ($\eta^2=0.007-0.047$) was found at all subjective evaluation ratings except presence. Figure 3 depicts mean ratings and differences for subjective evaluation on four pseudo-haptic features.
Table 2. P-values and η² from ANOVA results of effects of four pseudo-haptic features on the ratings of subjective evaluation and user experience questionnaires

| Measure | Subjective evaluation | User experience |
|---------|-----------------------|-----------------|
|         | Haptic illusion | Embodiment | Sense of reality | Presence | Spatiotemporal perception | Satisfaction | Pragmatic quality | Hedonic quality |
| PF      | <.001*** 0.011 | 0.007** 0.009 | 0.002** 0.010 | 0.184 0.004 | <.001*** 0.159# | 0.001** 0.014 | 0.025* 0.011 | <.001*** 0.109# |
| PT      | <.001*** 0.229# | <.001*** 0.143# | <.001*** 0.152# | 0.630 0.001 | <.001*** 0.155# | <.001*** 0.125# | 0.393 0.002 | <.001*** 0.092# |
| HE      | <.001*** 0.200# | <.001*** 0.120# | <.001*** 0.118# | <.001*** 0.082# | <.001*** 0.089# | <.001*** 0.213# | 0.007*** 0.016 | <.001*** 0.403# |
| PB      | <.001*** 0.034 | 0.019* 0.007 | <.001*** 0.047 | 0.671 <.001 | <.001*** 0.020 | <.001*** 0.028 | <.001*** 0.033 | 0.012* 0.006 |
| PF×PT   | 0.077 0.003 | 0.444 0.001 | 1.000 <.001 | 0.552 0.001 | 0.001*** 0.010 | 0.455 0.001 | 0.823 <.001 | 0.012* 0.006 |
| PF×HE   | 0.821 <.001 | 0.765 <.001 | 0.950 <.001 | 0.843 <.001 | 1.000 <.001 | 0.915 <.001 | 0.742 <.001 | 0.001*** 0.010 |
| PF×PB   | 0.458 <.001 | 0.868 <.001 | 0.709 <.001 | 0.843 <.001 | 1.000 <.001 | 0.455 0.001 | 0.906 <.001 | 0.550 <.001 |
| PT×HE   | 0.001** 0.010 | 0.714 <.001 | 0.055 0.004 | 0.380 0.002 | 0.186 0.002 | 0.002** 0.013 | 0.086 0.007 | 0.232 0.001 |
| PT×PB   | 0.166 0.002 | 0.444 0.001 | 0.901 <.001 | 0.977 <.001 | 0.443 0.001 | 0.594 <.001 | 0.408 0.002 | 0.816 <.001 |
| HE×PB   | 0.420 0.001 | 0.765 <.001 | 0.154 0.002 | 0.184 0.004 | 0.126 0.002 | 0.594 <.001 | 0.365 0.002 | 0.790 <.001 |
| PF×PT×HE | 0.974 <.001 | 0.303 0.001 | 0.804 <.001 | 0.630 0.001 | 0.780 <.001 | 0.337 0.001 | 0.554 0.001 | 0.790 <.001 |
| PF×PT×PB | 0.540 <.001 | 0.485 0.001 | 0.495 <.001 | 0.843 <.001 | 0.780 <.001 | 0.749 <.001 | 0.906 <.001 | 0.618 <.001 |
| PF×HE×PB | 0.233 0.001 | 0.816 <.001 | 1.000 <.001 | 0.755 <.001 | 0.727 <.001 | 0.749 <.001 | 0.906 <.001 | 0.947 <.001 |
| PT×HE×PB | 0.583 <.001 | 0.816 <.001 | 0.901 <.001 | 0.887 <.001 | 0.889 <.001 | 0.337 0.001 | 0.823 <.001 | 0.973 <.001 |
| PF×PT×HE×PB | 0.540 <.001 | 0.572 <.001 | 0.852 <.001 | 0.515 0.001 | 0.727 <.001 | 0.915 <.001 | 0.927 <.001 | 0.868 <.001 |

* PF=Proximity Feedback; PT=Protrusion; HE=Hit Effect; PB=Penetration Blocking; **p<0.05, ***p<0.01, ****p<0.001, η²>0.06
Figure 3. Mean ratings (+SE) and p-values from ANOVA results for subjective evaluation on four pseudo-haptic features. Note: *p<0.05, **p<0.01, ***p<0.001

Regarding the user experience, significant main effects of PF (F\(_{1,300}=5.06, p=0.025, \eta^2=0.011\)), HE (F\(_{1,300}=7.28, p=0.007, \eta^2=0.016\)), and PB (F\(_{1,300}=14.66, p<0.001, \eta^2=0.033\)) were observed on the pragmatic quality but with small effect sizes. HE and PB affected the pragmatic quality positively, whereas PF affected negatively. For hedonic quality, all features were found to have a significant positive effect: PF (F\(_{1,300}=124.27, p<0.001, \eta^2=0.109\)), PT (F\(_{1,300}=105.05, p<0.001, \eta^2=0.092\)), and HE (F\(_{1,300}=457.83, p<0.001, \eta^2=0.403\)) with medium to large effect sizes, and PB (F\(_{1,300}=6.4, p=0.012, \eta^2=0.006\)) with a small effect size. HE had the largest mean difference of rating (MD=1.91) and PB had the smallest difference (MD=0.23). PF, PT, and HE had medium to large effect sizes and PB had a small effect size. Figure 4 illustrates mean ratings and differences for user experience on four pseudo-haptic features.

Figure 4. Mean ratings (+SE) and p-values from ANOVA results for user experience on four pseudo-haptic features. Note: *p<0.05, **p<0.01, ***p<0.001
4.1.2. Interaction effects and correlation

A few significant second-order interactions between PF, PT, and HE were found (Figure 5). More specifically, significant interaction effects were found in spatiotemporal perception ($F_{1,300}=6.57, p=0.001, \eta^2=0.010$) and hedonic quality ($F_{1,300}=4.30, p=0.012, \eta^2=0.006$) for PF × PT, hedonic quality ($F_{1,300}=7.59, p=0.001, \eta^2=0.01$) for PF × HE, and haptic illusion ($F_{1,300}=, p=0.001, \eta^2=0.01$) and satisfaction ($F_{1,300}=, p=0.002, \eta^2=0.013$) for PT × HE. The same tendency was found across all significant interaction effects where the degree of effect from these three features tends to decline when used together. However, it should be noted that the practical significances were considered negligible due to small effect sizes ($\eta^2=0.006-0.013$).

![Figure 5](image)

**Figure 5.** Mean ratings (+SE) and p-values from ANOVA results for subjective evaluation and user experience on ratings with significant interaction effects: (a-b) PF × PT, (c) PF × HE, and (d-e) PT × HE. Note: *p<0.05, **p<0.01, ***p<0.001

Table 3 shows the Spearman correlation matrix for collected eight different aspects of subjective ratings. The strongest correlation was found between haptic illusion and sense of reality ($\rho=0.78$), and the weakest correlation was found between presence and pragmatic quality ($\rho=0.11$). Aspects were moderately correlated to each other in general, although the correlation of presence and pragmatic quality with the rest tended to be weaker ($\rho=0.11-0.44$) compared to the correlation among the rest aspects ($\rho=0.48-0.78$). Satisfaction was correlated the most with haptic illusion ($\rho=0.75$) and the least with presence ($\rho=0.28$).
Table 3. Spearman correlation matrix for subjective ratings

|                      | (1)  | (2)  | (3)  | (4)  | (5)  | (6)  | (7)  | (8)  |
|----------------------|------|------|------|------|------|------|------|------|
| (1) Haptic Illusion  |      |      |      |      |      |      |      |      |
| (2) Embodiment       | 0.70 |      |      |      |      |      |      |      |
| (3) Sense of Reality | 0.78 | 0.67 |      |      |      |      |      |      |
| (4) Presence         | 0.30 | 0.40 | 0.22 |      |      |      |      |      |
| (5) Spatiotemporal Perception | 0.61 | 0.48 | 0.67 | 0.19 |      |      |      |      |
| (6) Satisfaction     | 0.75 | 0.61 | 0.69 | 0.28 | 0.60 |      |      |      |
| (7) Pragmatic Quality| 0.32 | 0.32 | 0.39 | 0.11 | 0.23 | 0.44 |      |      |
| (8) Hedonic Quality  | 0.61 | 0.51 | 0.51 | 0.31 | 0.61 | 0.62 | 0.17 |      |

4.2. User Preference

Figure 6-a shows the frequency of the preference on each of four pseudo-haptic features. HE and PT were most dominantly preferred (19 out of 21 participants, ~90%), followed by PF and PB with frequencies of 12 (57%) and 11 (52%), respectively. The number of participants who preferred to have the feature was larger compared to the number of participants who preferred to not have for all features. The number of participants who disliked the feature was the largest at PF with the frequency of 6 (29%), while the number of participants who did not have preference was the largest at PB with the frequency of 5 (24%). Figure 6-b further shows the frequency of the most preferred button among 16 buttons with different combinations of features. The button with all features enabled (PF₀, PT₀, HE₀, PB₀) was preferred the most with the normalized frequency of 8.75 (42%), followed by the button with all features but PF enabled (PFₓ, PT₀, HE₀, PB₀) and the button with all features but PB enabled (PF₀, PT₀, HE₀, PBₓ) with frequencies of 4.25 (20%) and 2.25 (11%), respectively. The top three buttons accounted for 73% of all selections.

![Figure 6](image)

**Figure 6.** Frequency (percentage) of (a) the preference on each of four pseudo-haptic features and (b) the most preferred button
5. **Discussion**

5.1. **Main Findings**

PF majorly contributed to spatiotemporal perception as it should be, adhering to its original intention of aiding the perception of distance between the finger and the button by providing additional visual cues. Visual feedback about motion pattern and position coordinates significantly influences early and later stages of hand movement (Saunders and Knill, 2004), and enhances parallel processing of the visual and kinesthetic information about the ongoing hand movement (Sigrist et al., 2013). This could be especially useful in the immersive virtual environment where distances tend to be underestimated (Interrante et al., 2006; Knapp and Loomis, 2004). However, the negative effect of PF on the pragmatic quality indicating less value in traditional usability aspects (Schrepp et al., 2006) should be noted. Detailed analysis on individual questionnaire items revealed that participants felt the button with PF slightly more supportive ($F_{1,300}=7.90$, $p=0.005$, $\eta^2=0.012$) but moderately more complicated ($F_{1,300}=42.73$, $p<0.001$, $\eta^2=0.087$), which eventually led to lower ratings on the pragmatic quality. Chan et al. warned that continuous feedback could easily distract users as it provides extra visual cues during the entire interaction process but fails to inform the exact time the button is touched (Chan et al., 2010). The same result was observed in this study that 29% of participants disliked PF because it was distracting and continually gave undesirable pressure like they should press the button. Nevertheless, PF was favored by twice the number of participants (57%) and contributed to a slight improvement on other subjective aspects and a considerable improvement in the hedonic quality.

The positive effect of PT on user experience was expected as shown in several prior studies. Studies have shown 3D buttons were better than 2D buttons in terms of overall usability and memorability (Zilch et al., 2014); overall user experience, workload, motion sickness, and immersion (Speicher et al., 2019); naturalness, perceived performance, and preference (Dube and Arif, 2020). On top of that, this study newly revealed the improvements from the 3D button in haptic illusion, embodiment, sense of reality, and spatiotemporal perception. Participants found the interaction more interesting and feel more like pressing the real-world button when PT is enabled, which is in line with the study of Speicher et al. (2019) where participants found the affordance-oriented design of the 3D button more exciting and motivating. Participants in our study claimed PT also helped knowing when the button will be pressed, as the distance between the protruded surface and the base offered an extra visual cue. The cue acts similar to PF in a sense, but unlike PF, it relies on the stereoscopic depth cue of the button surface protruded towards the user. In addition, some participants thought it was a good match with other features; for example, three participants conditionally preferred to have other features only when the button is protruded (one participant for each of PF, HE, and PB).

By combining two effects: visual vibration and collision graphics, HE successfully emulated the feeling of hit and corresponding pseudo-haptic sensation. Visual vibration has been applied to the cursor to evoke pseudo-haptic surface roughness of the touch screen (Costes et al., 2019), and stylized visual effects have been explored in simulating haptic properties of touching real and virtual objects in AR (Mercado et al., 2020), but to the authors’ knowledge, this is the first study investigated pseudo-haptics of these two visual effects in mid-air button interaction in VR. HE had a moderate to large impact on all subjective evaluation and user experience aspects except the pragmatic quality but especially, it induced the largest impact on satisfaction (MD=1.42) and hedonic quality (MD=1.91) among four investigated features. This result is reasonable considering this feature was inspired by special effects used in gaming, which put a huge emphasis on the entertainment and enjoyment of players. Interestingly, no participants disliked this feature. Participants claimed the hit effect not only made the interaction feel more interesting and tangible but also helped to know exactly when the button is pressed. Discrete feedback such as an instant visual transition or a sound effect is known to benefit interaction by clearly confirming a touch, yet provides little help before a touch (Chan et al., 2010). Therefore, the combination of PT and HE can be considered as a great harmony by offering advantages of both discrete and continuous feedback.
Notably, PT and HE were unconditionally preferred by 90% of participants, and buttons with both features enabled were chosen as the favorite by 79% of all choices (Figure 6-b).

The effect of PB was statistically significant but had a small practical impact on all subjective evaluation and user experience aspects except presence. 52% of participants who preferred PB claimed it enhanced haptic illusion and helped know when the button is pressed by checking the hand movement is blocked. They felt awkward, not realistic, and out of control when the hand penetrates the button because this is not what people with common sense will expect to happen in the real world. This becomes clear if we see the result that the sense of reality was influenced the most among all aspects, with the mean difference of 0.65 and eta-squared of 0.047. On the other hand, 19% of participants who did not like PB mentioned they felt their hand movement is restricted and awkward since it does not match with the movement of their real hand. This implies a caution is needed when applying this feature, as large offsets between the virtual and real hands over the threshold can place a big perceptional discrepancy between vision and proprioception (Burns et al., 2006). Although detection thresholds of hand redirection have been derived previously (horizontal/vertical offset: 4.5°, gain-based offset: 0.88-1.07; Zenner & Kruger, 2019), a further investigation to identify the offset threshold that can severely damage user experience in this specific case is needed, as even obvious perceivable offsets were accepted and preferred by VR users in some cases (Rietzler et al., 2018a, 2018b). 24% of participants who did not have a preference on this feature explained they could not identify an obvious difference caused by enabling PB. As participants were not requested to press the button beyond the base when they interact with the button, buttons with and without PB could be perceived as indistinguishable for some participants who always stopped their finger at the base before penetration.

It is worth mentioning the popular reasons for preference in all features were: (1) I felt an illusion of a reactive force or a touch (haptic illusion), (2) I felt like pressing the real-world button (sense of reality), (3) I easily knew the finger distance and the moment the button is pressed (spatiotemporal perception), and (4) I felt more interesting (hedonic quality). Haptic illusion ($\rho=0.75$), sense of reality ($\rho=0.69$), spatiotemporal perception ($\rho=0.60$), and hedonic quality ($\rho=0.62$) showed moderate to strong correlation with satisfaction. Our results provide a piece of empirical evidence that pseudo-haptic button design features could elevate such perception-related items thereby improve the user experience of free-hand mid-air interaction in VR.

According to the results, all four proposed pseudo-haptic button design features either majorly or minorly contributed to improving user experience. However, it is doubtful whether more features will always lead to a better user experience. Although the button with all features enabled was chosen by the largest number of participants as their favorite, some results proved otherwise. Some participants pointed out a certain feature (especially PF) feels distracting when too many features are used together, thereby either disliked or conditionally liked corresponding features. For instance, two participants preferred PF and HE under the condition of enabling only one of the two. Their concerns were also reflected in the ratings as significant interaction effects which indicated the decrease of feature impact at combined usage among PF, PT, and HE.

### 5.2. Design Implications

Our research findings implied that all four investigated pseudo-haptic features (PF, PT, HE, and PB) could benefit users in terms of user experience. VR developers can consider adapting proposed features into the design of 3D UI to improve perceived haptic illusion, embodiment, sense of reality, spatiotemporal perception, satisfaction, and hedonic quality of users. However, it should be noted that the effect of PF and PB were relatively minor along with a nonnegligible portion of disfavor compared to PT and HE. Therefore, an option to disable specific features could be beneficial for certain users, as individuals comprehend and interpret the haptic experience in different ways hence might want to tailor effects for their preferences (Schneider et al.,
The proposed features can be applied to general 3D UIs with interactive buttons in any type of VR application to provide a more satisfactory and enjoyable experience to users. Except for PB which relies on a virtual representation of the real hand, we expect the remaining three features: PF, PT, and HE can be applied to 3D UIs in other application domains (e.g. AR) to merit users.

5.3. Limitations and Future Work

This study has some limitations. First of all, since this study mainly focused on investigating the effect of pseudo-haptic features on user experience, the effect on task performance was not considered. A recent study from Bermejo et al. reported that the users with 2D buttons unintuitively achieved faster key entry speed than the 3D buttons in the numeric keypad typing task (Bermejo et al., 2021), showing the possibility that button protrusion may result in worse performance in certain task scenarios, although Dube and Arif reported contradictory results that 3D keys yielded lower error rate compared to 2D keys in the VR text entry task (Dube and Arif, 2020). Future work can further verify the effect of proposed features on the task performance for interacting with 3D UI or virtual keyboard where mid-air touch interaction with virtual buttons can frequently occur. Second, this study attempted to investigate the pure effect of visual cues hence excluded the auditory cues which were proven to be effective in addition to visual cues for multi-modal conditions (Bermejo et al., 2021; Chan et al., 2010; Kobayashi et al., 2016; Lecuyer et al., 2001). The addition of auditory cues with proper sensory integration strategy to further improve the user experience of mid-air interaction in VR can be investigated in future work. Third, the hit effect consisted of two visual components: a visual vibration effect and a collision graphics effect, so it is unclear whether the positive impact mainly came from the particle effect or the vibration effect. These two effects could not be investigated separately to keep the number of factors and experimental conditions manageable in this study, but a more concrete investigation on individual effects deserves consideration in the future.

6. Conclusion

We conducted a user study with 21 young subjects to investigate the effect of four pseudo-haptic button design features (proximity feedback, protrusion, hit effect, and penetration blocking) on user experience for free-hand mid-air button interaction in VR. All investigated features significantly and positively affected user experience in terms of haptic illusion, embodiment, sense of reality, spatiotemporal perception, satisfaction, and hedonic quality. In addition, protrusion and hit effect were more beneficial in comparison with the other two features. It is suggested to use the four proposed pseudo-haptic features for designing 3D UI to make users feel more satisfied and entertained, but caution is needed when using proximity feedback together with other features. The findings of this study may serve as a useful input for VR developers and UI designers to create better interactive buttons in 3D UI.

Acknowledgments

This work was supported by the Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT and Future Planning (NRF-2020R1F1A1048510).
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