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Ring-shaped Haptic Device with Vibrotactile Feedback Patterns to Support Natural Spatial Interaction

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Abstract

Haptic feedback devices can be used to improve usability, performance and cognition in immersive virtual environments (IVEs) and have the potential to significantly improve the user's virtual reality (VR) experience during natural interaction. However, there are only few affordable and reliable haptic devices that have a light-weight, unencumbering, simple and versatile form factor which does not prevent natural interaction with other objects or devices at the same time. In this paper we present such a ring-shaped wireless haptic feedback device, and we describe different vibrotactile signal patterns which can be used to provide proximity-based cues during 3D interaction with virtual objects. We present a usability study in which we evaluated the device and feedback patterns.

Categories and Subject Descriptors (according to ACM CCS): H.5.2 [User Interfaces]: Input devices and strategies—Haptic I/O I.3.3 [Computer Graphics]: Three-Dimensional Graphics and Realism—Virtual reality

1. Introduction

Providing haptic feedback through physiological responses in spatial interactive applications can provide benefits in terms of spatial cognition and performance when interacting with a virtual environment (VE), and generally enrich the user's experience. In particular, vibrotactile or force-feedback haptic information can be conveyed by a wide range of technologies such as devices composed of sets of actuators [BBLP13, LKAK12, OH14, SEWP10, SHL*14]. If combined with tracking technologies, such haptic feedback devices can be dynamically controlled according to interaction conditions to ensure spatially sensitive feedback such as collision responses or warnings or may be used to elicit physiological responses or behavior [SG08, CBS*14].

Even though new and varied input and output devices are constantly released for application domains that require interaction with VEs, such as wands, gamepads or touch-sensitive surfaces for video games or entertainment, few of these incorporate more complex haptics technologies than on/off vibration feedback as output methodology [GMPT13, MHF*14]. Moreover, few of these devices have a light-weight, simple and versatile form factor that supports haptic feedback during spatial interaction in mid-air, while keeping the fingertips free to use other tools or devices, such as touch-sensitive surfaces [LGH*14].

In this paper we describe a ring-like haptic device for which we designed spatially sensitive vibrotactile stimuli to effectively convey spatial information in the shape of timely responses [SG08, CBS*14, MHGS15], elicited as dynamic feedback patterns that can be combined with auditory and visual signals, producing improved user performance on 3D interactive tasks. This form of active haptic feedback for spatial interactive applications uses a set of proximity-based vibrotactile patterns to provide dynamic feedback signals. In this paper we present the novel hardware device, vibrotactile patterns, as well as a usability study, in which we evaluated the proposed patterns to support selection feedback when selecting 3D virtual objects by touching them with a fingertip. In the usability study we used a head-mounted display (HMD) as visual output and tracked the user's finger wearing the ring-like device using an optical tracking system with an infrared (IR) LED featured by the device.

The paper is structured as follows. Section 2 gives an overview of related work. Section 3 describes the haptic device. Section 4 presents the vibrotactile patterns which are evaluated in Section 5. Section 6 concludes the paper.

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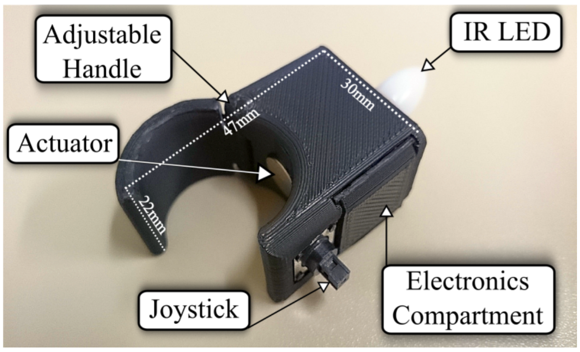


Figure 1: *Our ring-shaped haptic device featuring a lightweight form factor, actuator for vibrotactile feedback and IR LED for optical tracking.*

2. Related Work

Previous research on finger-worn devices focused mainly on the creation of input devices. For instance, uTrack [CLWP13] is a self-contained 3D pointing device composed of magnetometers similar to FingerPad [CLT*13] which uses the index finger and thumb to provide a 2D touch pad. RingMouse [BKLJP04], a ring-like device, uses ultrasonic tracking to generate position information only. FingerFlux [WWVB11] provides simulated haptic feedback to the fingertip during touch panel operation.

3DTouch [NB15], a more recent development, provides passive haptic feedback in a self-contained manner, using inertial measurement units (IMUs) and optical flow sensors to provide movement tracking over surfaces and 3D input. However, none of these devices had the goal to provide dynamic vibrotactile patterns in an interactive 3D environment.

Ergonomic and wireless haptic devices [SEWP10] provide collision feedback or guidance information to the human arm when interacting in an immersive virtual environment (IVE). Symmetrical haptic interaction systems with virtual creatures in mixed reality [THSM09] have been proposed, using vibration elements to provide haptic or vibrotactile feedback. Recent research work produced a solution for visually impaired people, providing a finger worn device that assists them reading text while providing real-time auditory and vibrotactile feedback [SHL*14].

Novel technologies in the field of haptic feedback use ultrasonic transducers to create focused ultrasound at a specific target, e. g., a user's fingertip, to create haptic feedback in mid-air [MHF*14]. A similar alternative [GMPT13] explores the use of air vortex rings that can be focused to travel several meters and impart perceptible feedback.

Beyond creating devices to provide haptic feedback, some studies explored illusory tactile feedback techniques using arrangements of vibrational elements, like Funneling and Saltation illusions [LKAK12], haptic stimulation of the feet to induce vertical illusory self-motion [NAN*12] and alteration of the perceived distance from hitting an object [OH14].

Recent research related to ergonomics and human factors proposed the use of dynamic vibrotactile warning signals in different contexts; collision avoidance [MHGS15] and prevention [SG08] during simulated driving. Pfeiffer and Stuerzlinger have found that vibration feedback in 3D Fitts' Law tasks does not significantly differ from visual feedback [PS15] and some studies have indicated the positive impact of vibration feedback on detection-reaction times [CBS*14].

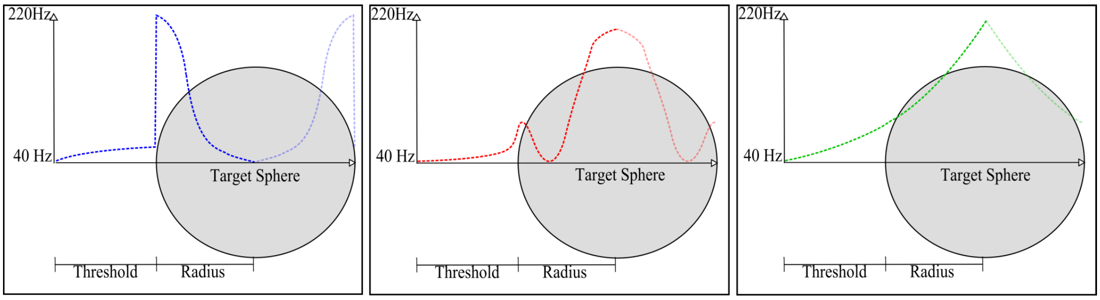
According to Mine et al. [MJS97], direct interaction leads to significantly higher performance than manipulation of objects at a distance from the user's hand. Most results from similar studies agree on the point that optimal performance may be achieved when visual and motor spaces are superimposed or coupled closely [Dja98, LL07, WM99]. Indeed, interacting with natural gestures in 3D space opens up new possibilities for exploiting the richness and expressiveness of the interaction. Users can control multiple degrees-of-freedom (DoFs) simultaneously, and exploit well-known real-world actions. However, as a matter of fact, interaction in the 3D mid-air is physically demanding and, therefore, often hinders user satisfaction and performance [CKC*10]. The increase in the DoFs that have to be controlled simultaneously as well as the absence of passive haptic feedback and resulting interpenetration and occlusion issues when "touching the void" [BSS13, CKC*10] are often responsible for reduced performance.

3. Ring-shaped Haptic Device

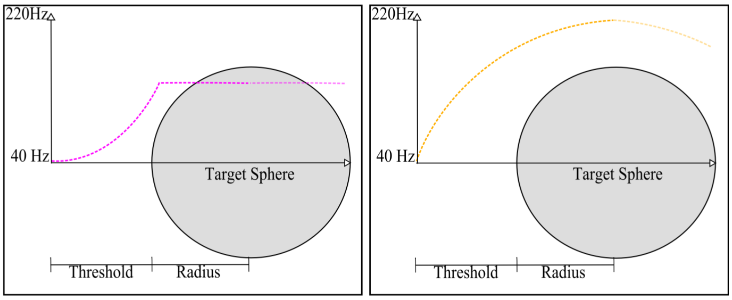
Our finger-worn device is designed in the shape of an adjustable ring and it is completely autonomous, i. e., avoiding cables using a wireless Bluetooth connection, a SoC microcontroller, a digital micro joystick for input commands, a small form factor rechargeable 2-hour battery and an IR LED with omnidirecitonal diffusor cap for external reference support (i. e., optical tracking systems).

It also contains an on-skin vibration element, managed and controlled by embedded software, which can be activated at different frequencies according to signals received from the computer to provide haptic feedback. Technical and design details of our wearable haptic device (HapRing) can be found in [ALS15].

Taking into account the designs of other finger-based wearables (see Section 2), in particular the designs by Chatterjee and Matsuno [CM06], we decided to place the ring on the first joint of the user's index finger. This allows for comfortable pointing gestures in IVEs, natural multi-touch gestures when using touch-sensitive interfaces, as well as comfortable control of the joystick. The prototype is illustrated in Figure 1.



(a) Pattern A (b) Pattern B (c) Pattern C



(d) Pattern D (e) Pattern E

Figure 2: *Illustrations of the interaction space and the signal patterns used to provide haptic feedback.*

4. Vibrotactile Patterns

In order to provide feedback with the *device* when a user is interacting with a 3D object, we defined a sphere-shaped interaction space which contains the object and matches its center. The interaction space exceeds the size of the 3D object, providing a threshold that enables the *device* to provide vibration cues when the user's finger is approaching, penetrating or moving inside the 3D object.

The haptic feedback changes accordingly to a vibrotactile signal pattern that varies the vibration frequency depending on the distance from the tracked finger to the center of the interaction space. Our proposed interaction space is also intended to offer haptic feedback in 3D interaction as in a typical 3D aimed movement [LvLNM09, LvL09]. In this way, with variations on the threshold and the radius, it is possible to provide vibrotactile feedback during the ballistic and corrective phases or any detected and significant submovement. The positive effect of the haptic feedback (e.g. the reduction of the error rate) in related 3D interaction tasks has been tested recently [PS15].

As shown in Figure 2, the threshold part of the signal pattern is used to define the behavior of the frequency when the finger is approaching the 3D object (a sphere in our test case), the rest of the signal could define that behavior for penetration and movements inside the sphere (e.g. if the user should receive specific feedback when touching the sphere's center). For the experiment, the radius of the sphere was defined in terms of the user's ergonomic space, enabling the user to interact comfortably. Consequently, the size of the threshold was defined as twice the radius in order to define a wide enough interaction space and elicit meaningful haptic feedback.

We defined five vibrotactile signal patterns (Figure 2) representing different cues in terms of the feedback provided in three phases: moving towards the sphere, penetrating the sphere and moving inside the sphere. For all of the patterns, the outcome frequencies range goes from 40Hz to 220Hz according to the capabilities of the device. The following listing shows a qualitative description of the patterns:

Pattern A This signal provides a subtle vibration during the approaching phase, then reaches the maximum vibration frequency when the finger is close to the sphere's bounds according to a steep peak. Then inside, the frequency decreases softly until no feedback is provided on the sphere's center.

Pattern B This signal provides an increasing and soft vibration during the approaching phase, goes until 55Hz on the sphere's bounds, then softly goes to zero to then increase quickly, providing the maximum frequency on the sphere's center.

Pattern C This signal increases softly according to an exponential function from the minimum to the maximum vibration frequency. No distinguishable changes between the three movement phases.

Pattern D This signal behaves as an exponential function during the approaching phase (0Hz to 110Hz), then provides the last reached frequency (110Hz) over the whole volume occupied by the sphere.

Pattern E This signal increases softly according to a logarithmic function. No distinguishable changes between the three movement phases.

5. Usability Study

In this section we describe the study we conducted to evaluate the qualitative effect of the different signal patters used to provide haptic feedback, as described in the previous section. The participants had to judge the quality of each curve after testing it in a head-mounted display (HMD) setup.

5.1. Participants

We recruited 16 participants for our experiment. Ten of them were male and 6 were female (ages 21 – 36, M = 26.38, SD = 4.272). The participants were professionals or students in the fields of human-computer interaction or computer science, who received class credit for the participation in the experiment. Two participants were left-handed, the others were right-handed. All but one of them had normal or corrected vision. One reported having Dyschromatopsia.

Using the technique proposed by Willemsen et al. [WGTCR08] we measured the interpupillary distance (IPD) before the experiment (M = 6.394 cm, SD = 0.386 cm). We calibrated the VE for each subject to ensure comfort. All but two subjects reported at least some experience with 3D video games (rating scale 1 = yes, 5 = no, M = 1.875, SD = 1.455). All subjects reported at least some experience with stereoscopic 3D, such as cinemas or TV (rating scale 1 = yes, 5 = no, M = 1.750, SD = 1.065). Twelve subjects reported that they had participated in HMD studies before.

All participants were naïve to the experimental conditions. The mean of the total time per subject, including questionnaires and instructions was about twenty minutes. Participants were allowed to take a break between the training and the main trials.

5.2. Materials

As illustrated in Figure 3, users wore an Oculus Rift DK2 HMD and our haptic device on the index finger of their dominant hand, tracked in 3 DoF with an optical WorldViz Precision Position Tracking (PPT X4) system with sub-millimeter precision. The Oculus Rift offers a nominal field-of-view of 100° at a resolution of 960 × 1080 for each eye. The visual stimulus consisted of a 3D scene (see Figure 3 inset), which was rendered with Unity3D on an Intel computer with a Core i7 3.4GHz CPU and Nvidia GeForce GTX780TI.

The participant's finger was represented by a yellow cube and the target was a semitransparent sphere. The sphere was red when the cube was outside and green when the cube was inside. During both the training and the experiment phases there was just one target in the scene. The targets were located depending on the calibrated finger position.

The participants received haptic feedback through the *device* depending on the distance of their finger to the center of the target sphere, as illustrated in Figure 2. The diameter of the target sphere was 21.876 cm, calculated by taking into account a distance of 40 cm and an index of difficulty of 1.5, and the size of the finger cube was 2.5 cm.

5.3. Methods

We used a within-subject design testing the five different patterns in an order given by a 5×5 Latin Square. After familiarizing themselves with all the patterns twice in a training part, the main trials followed. The training was excluded from the results. For each trial, the participant was instructed to move their finger through and around a sphere as long as they liked to acquire an understanding of the technique.

After a selection by pressing a button in the ring's joystick, the participants had to take off the HMD and answer a questionnaire evaluating the last used technique. The subjects were asked to evaluate the last used technique by the following sentences (rating scale 1 = Agree, 5 = Disagree):

- The haptic feedback provided is helpful to feel how the finger **penetrates** the sphere.
- The haptic feedback provided is helpful to feel how the finger **approaches** the sphere.
- The haptic feedback provided is helpful to keep the finger at the **center** of the sphere.
- The haptic feedback provided is appropriate in terms of **intensity**

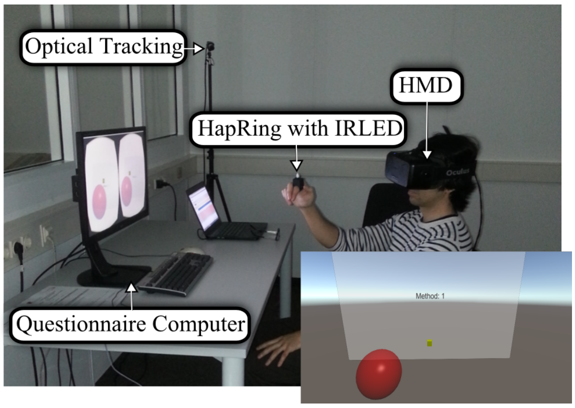


Figure 3: *Participant during the experiment with annotations explaining the setup. The inset shows the visual stimulus the user saw during the experiment.*

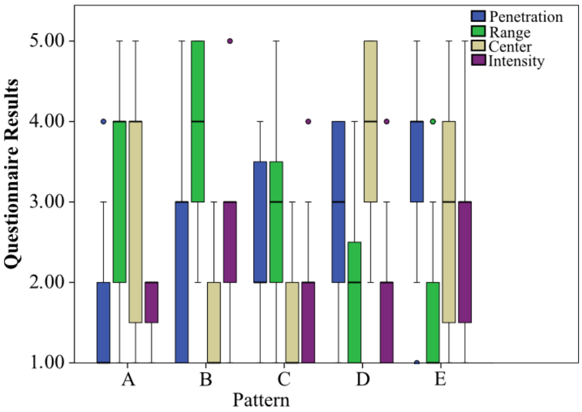


Figure 4: *Boxplots indicating experiment questionnaire results for each pattern concerning the questions described in Section 5.3 (rating scale 1 = Agree, 5 = Disagree)*

5.3.1. Hypotheses

We evaluated the following three hypotheses:

- **H1** Vibrotactile feedback patterns influence the user's awareness of virtual objects.
- **H2** Providing vibrotactile feedback around an object increases awareness of proximity.
- **H3** Lack of vibrotactile feedback in an object increases the awareness of the object's center.

5.4. Results

One subject misunderstood the task and was excluded from the results, so the results from the remaining 15 subjects were taken into account for the evaluation and were normally distributed according to a Shapiro-Wilk test at the 5% significance level. We analyzed the results with a repeated measure ANOVA and Tukey multiple comparisons. Degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity when Mauchly's test indicated that the assumption of sphericity had been violated. The results of the questionnaires are shown in Figure 4.

We found a significant main effect of the used pattern on penetration ($F(4,56)$=9.306, p<.001, η_p^2=.399). Post-hoc tests with Bonferroni correction revealed that pattern A was significantly better for penetration than patterns B ($t(14) = 2.229$ $p < .05$), C ($t(14) = 3.5$ $p < .05$), D ($t(14) = 3.228$ $p < .05$) and E ($t(14) = 4.83$ $p < .05$). Pattern E was also worse than B ($t(14) = 2.828$ $p < .05$), C ($t(14) = 3.552$ $p < .05$) and D ($t(14) = 3.287$ $p < .05$).

We found a significant main effect of the used pattern on range ($F(4,56)$=9.243, p<.001, η_p^2=.398). Post-hoc tests with Bonferroni correction revealed that pattern E was significantly better for range than patterns A ($t(14) = 3.190$ $p < .05$), B ($t(14) = 1.586$ $p < .05$) and C ($t(14) = 4.3226$ $p < .05$). Pattern D was significantly better than patterns A ($t(14) = 3.251$ $p < .05$) and B ($t(14) = 3.761$ $p < .05$). Pattern C was better than pattern B ($t(14) = 2.747$ $p < .05$).

We found a significant main effect of the used pattern on center ($F(2.091, 29.269)$=9.426, p<.001, η_p^2=.402). Post-hoc tests with Bonferroni correction revealed that pattern B was significantly better for center than patterns A ($t(14) = 3.286$ $p < .05$), D ($t(14) = 5.906$ $p < .05$) and E ($t(14) = 3.862$ $p < .05$). Pattern C was significantly better than patterns A ($t(14) = 1.6556$ $p < .05$), D ($t(14) = 5.145$ $p < .05$) and E ($t(14) = 4.394$ $p < .05$).

We found a significant main effect of the used pattern on intensity ($F(4,56)$=3.598, p<.001, η_p^2=.204). Post-hoc tests with Bonferroni correction revealed that pattern E was significantly worse for intensity than patterns A ($t(14) = 2.567$ $p < .05$), C ($t(14) = 2.750$ $p < .05$) and D ($t(14) = 2.197$ $p < .05$). Pattern A was also significantly better than pattern B ($t(14) = 3.055$ $p < .05$).

Additionally, before and after the experiment, we asked subjects to judge their level of simulator sickness with the Kennedy-Lane SSQ questionnaire [KLBL93]. While we measured an average pre-SSQ score of M = 10.721 (SD = 18.853), the post-SSQ score was M = 12.467 (SD = 14.531). We found no significant increase in simulator sickness over the time of the experiment ($t(14) = .401$ $p = .694$).

5.5. Discussion

Overall, the feedback patterns significantly influenced the subjective awareness of the users, which supports our hypothesis H1. The results show that every feedback pattern has their strengths in different areas.

Pattern A appears to be the best for the simulation of penetration. While some participants thought pattern B offered a good sense of penetration, others did not indicate that sensation. However, pattern A was judged badly for sensing the center of an object.

Pattern E showed the highest ratings for the sense of range, or being close to the object, as it offered relatively strong vibration throughout the threshold. However the sense of penetration was rated badly and especially the intensity received the worst ratings, as expected. Nevertheless, the haptic feedback increased the participants' awareness of proximity to the objects, supporting our hypothesis H2.

Patterns C and B equally gave the participants a good awareness of where the center is. The patterns offer different advantages. Pattern B offers a reasonable sense of penetration and a good hint for the determination on where the center is. This could enrich selection tasks and allow the execution of various tasks without the necessity to keep visual contact with the interactive object.

	A		B		C		D		E	
	M	SD	M	SD	M	SD	M	SD	M	SD
Penetration	1.600	.910	2.467	1.302	2.533	1.060	2.667	1.175	3.600	1.183
Range	3.400	1.298	3.933	1.223	2.800	1.082	2.067	1.033	1.733	1.100
Center	3.067	1.580	1.533	.640	1.600	.828	3.800	1.082	2.933	1.438
Intensity	1.733	.458	2.533	.990	1.800	.941	1.867	.915	2.533	1.246

Table 1: *Questionnaire Results: Means and Standard Deviation by technique used*

The fact that users gave mixed and negative ratings for the center question at pattern A indicated that the participants were inclined to focus on the active vibrotactile feedback and not the lack thereof. Despite being able to determine clearly when they penetrated the object, allowing them to stay within the target, they did not actively feel the center of the object as it offered no vibrotactile feedback, which disagrees with Hypothesis H3.

Being actively able to feel objects and their centers might have an influence on the distance perception and the errors caused by distance overestimation and underestimation in VE tasks, e. g., in selection tasks [LBS14]. It is thus necessary to further tune the parameters, depending on the desired use-case. However, a few recommendations for the use of vibrotactile feedback patterns can be derived:

- Vibrotactile peaks at the outline of objects allows users to feel the outline and the penetration thereof.
- Lack of vibrotactile feedback does not get detected as easily as vibrotactile peaks.
- Decoupling of vibrotactile feedback from visual cues can guide users to objects.

Some combinations of the patterns were used but in some cases produced misinterpretations related to the number of objects felt by users (i.e. some signal combinations behaved like the signals related to several objects close to each other). While the pilot study was conducted with spheres as targets, it is possible to determine the depth of arbitrary watertight 3D objects and thus calculate a center and the distance thereto for the determination of the correct signal strength based on the current pattern.

6. Conclusion

In this paper we presented a novel ring-shaped wireless haptic feedback device for spatial user interfaces, and we presented a usability study evaluating different vibrotactile feedback patterns. These feedback patterns differ from the common on/off approach for vibrotactile feedback used by most similar devices as they offer different strengths of feedback depending on the distance to a target or its hull.

Our usability study showed that these vibrotactile patters can improve the user's subjective awareness of a virtual scene, enriching it by providing haptic feedback when objects are penetrated or when their center is reached. Moreover, the results showed that there is no overall optimal pattern as each pattern provides advantages in different situations. We discussed recommendations for user interface designers to decide which pattern should be chosen for particular interfaces depending on their goals. Future work should evaluate the feedback patterns during pointing, touching, grasping or dexterous manipulation and determine how they may further support 3D selection and manipulation tasks (e. g., by designing a controlled Fitts' Law experiment which could also take into account error and performance measurement, as well as the comparison with the visual and even the audio feedback). Also, further studies should take into account the amplitude as another variation value of the vibrotactile pattern.

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