MotionRing: Creating Illusory Tactile Motion around the Head using 360° Vibrotactile Headbands

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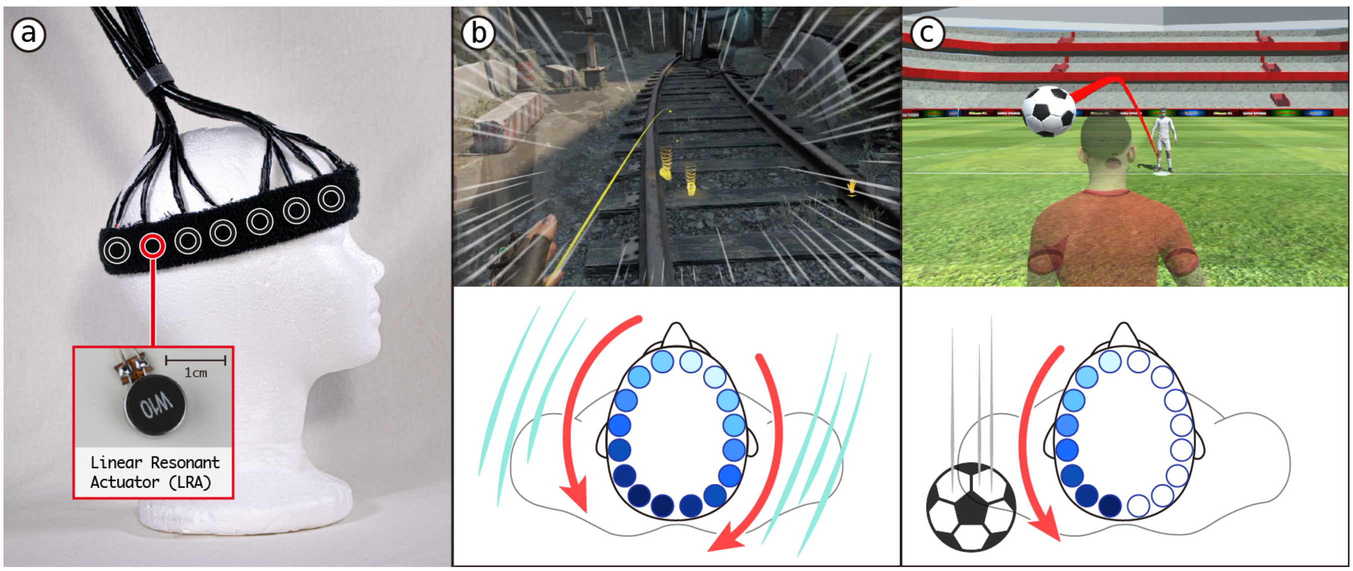

Figure 1: (a) MotionRing controls the timing of a sparse array of vibration motors to create 360° apparent tactile motion (ATM) around the head. Its ring shape enables motion-based haptic experiences around the users in any directions, e.g. (b) teleportation in VR, with *symmetric* tactile motion patterns, and (c) dodging footballs, with *asymmetric* tactile motion patterns.

ABSTRACT

We present MotionRing, a vibrotactile headband that creates illusory tactile motion around the head by controlling the timing of a 1-D, 360° sparse array of vibration motors. Its unique ring shape enables symmetric and asymmetric haptic motion experiences, such as when users pass through a medium and when an object passes nearby in any direction. We first conducted a perception study to understand how factors such as vibration motor timing, spacing, duration, intensity, and head region affect the perception of apparent tactile motion. Results showed that illusory tactile motion around the head can be achieved with 12 and 16 vibration motors with angular speed between 0.5-4.9 revolutions per second. We developed a symmetric and an asymmetric tactile motion pattern to enhance the experience of teleportation in VR and dodging footballs, respectively. We conducted a user study to compare the experience of MotionRing vs. static vibration patterns and visual-only feedback. Results showed that illusory tactile motion significantly improved users' perception of directionality and enjoyment of motion events, and was most preferred by users.

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CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**.

KEYWORDS

apparent tactile motion, vibrotactile, haptic feedback

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1 INTRODUCTION

The sensation of tactile motion results from relative motion between objects and the skin [26] and is part of our everyday experiences. It was discovered over a century ago that this experience can be simulated through Apparent Tactile Motion (ATM), which is a tactile illusion when consecutive vibration at two discrete points on the skin can be perceived as tactile motion [3]. Prior studies have investigated how different duration, shapes, and types of motion affect the occurrence of ATM on various parts of human body [18, 19]. More recently, haptic device researchers have explored ATM on forearms and the back [11, 12] to simulate 1-D tactile motion using 2-D, rectangular-shaped vibrotactile arrays.

With the growing popularity of VR and AR headsets, a variety of head-worn haptic devices have recently been proposed to enhance virtual experiences by simulating impact, wind, temperature, and acceleration [5, 21, 35, 37]. However, whether and how tactile motion can be simulated on the head, and the types of virtual experiences that it can support remain unexplored.

We present MotionRing, a vibrotactile headband that creates 360° illusory tactile motion around the head by controlling a sparse 1-D array of vibration motors (shown in Figure 1a). Its unique ring shape, compared to prior 2-D rectangular shapes, enables *symmetric* and *asymmetric* haptic motion experiences around the user, such as when users pass through a medium and when an object passes nearby in any direction.

To understand the feasibility and limitations of apparent tactile motion around the head, we first conducted a perception study (n=48) to quantify how factors such as vibration motor timing, spacing, duration, intensity, and head region affect the perception of apparent tactile motion. Results from our study showed that ATM is feasible with 12 and 16 vibrotactile motors around the head. The interval between the actuation time of two subsequent actuators, called inter-stimulus onset asynchrony (SOA) [12] or interstimuli onset interval (ISOI) [18], is significantly affected by duration, intensity, angular spacing, and by the interaction between vibration intensity and angular spacing.

Based on this perceptual model, MotionRing is able to create ATM around the head with 12 and 16 vibration motors with angular speed ranging from 0.5-4.9 revolutions per second, which is equivalent to surface speed of 28-276cm/sec around the head (average circumference: 56.3cm). Furthermore, the ring shape of MotionRing enables ATM to start from any area of the head and move: 1) symmetrically in both directions, and 2) asymmetrically in one direction.

To evaluate the user experiences of MotionRing, we designed symmetric and asymmetric tactile motion patterns for two common virtual experiences. The first experience is teleportation, which is a popular VR locomotion technique. The symmetric ATM pattern, as shown in Figure 1b, simulates the experience of airflow on both sides of users' heads while they teleport from their current location to the target location. The second experience is dodging footballs. The asymmetric ATM pattern, as shown in Figure 1c, simulates footballs passing by the corresponding side of users' heads.

We conducted a 12-person study to understand how these apparent tactile motion patterns around the head affects immersion, enjoyment, and realism vs. two baseline conditions: 1) static vibration (ie. without ATM), and 2) visual-only (ie. without vibration). Results showed that illusory tactile motion significantly improved users' perception of directionality in both experiences and enjoyment in the football experience. In terms of overall preference, MotionRing was preferred by 92% and 75% of participants, respectively.

Our main contributions are as follows:

- We present MotionRing, a vibrotactile headband which creates the sensation of 360°tactile motion around the head.
- We summarize a perceptual model for creating apparent tactile motion around the head that includes the following factors: vibration timing, duration, intensity, motor spacing, and head region.
- We propose symmetric and asymmetric tactile motion patterns around the head for virtual experiences. User evaluation showed significant improvement in directionality and enjoyment over static vibration patterns and visual-only feedback, as well as being the most preferred by users.

2 RELATED WORK

To place MotionRing in the context of related work, we focus our discussion on illusory tactile motion and tactile feedback on head.

2.1 Illusory Tactile Motion

The observation of tactile illusions of motion dates back to 1917 [3], where the time relations of two sequential tactile stimuli presented at different points on the skin were controlled to create the illusion that there is movement between two points. This illusion of movement is later known as "apparent tactile motion" (ATM) in the field [32]. The effects of the interstimulus onset interval (ISOI), stimulus duration, shape, and the type of motion on the occurrence of ATM [10, 18, 19] have been investigated through a series of perceptual studies, and a perceptive model to control ATM has been proposed [11].

ATM has been used for providing haptic feedback not only on contiguous parts of the body, e.g., along the fingers, hands, forearms, face, and back [12, 23, 34, 39], but also on non-contiguous parts, e.g., from one hand to the other [27, 28]. ATM has also been induced using different mediums, including physical tactile stimuli, e.g., vibrotactile actuator [12, 13], and mid-air stimulation, e.g., ultrasound [27] and air vortices [34].

Despite over a century of research on ATM, it is only recently attempted to apply ATM to haptic feedback to enhance virtual experiences. In this work, we conducted perception studies to understand the effects of vibration motor spacing, vibration duration, vibration intensity, and head region on the occurrence of ATM. Based on the result, we built up the perceptive model around the head. We then proposed MotionRing, a headband with evenly distributed vibrotactile actuators that creates the sensation of tactile motion around the head during virtual experiences.

2.2 Tactile Feedback on Head

Because the human head is highly sensitive to touch, careful implementation of tactile feedback is imperative. In general, stimulation at low frequencies [24] and short duration [14] are used to avoid unpleasant perceptions. Additionally, the VibrationCap study provided recommendations on how to localize individual vibrations on the head accurately [8].

Prior researchers have attached actuators to many different head-worn devices, e.g., glasses [2, 25, 29], hats [1], helmets [22], and headbands [6, 7, 9, 30, 33], to create tactile feedback for users. These devices are mainly used for conveying information about the surroundings to users [15, 16, 22]. For instance, devices have been used to provide users intuitive navigation guidance [25], help obstacle avoidance [1] and provide clues during search tasks [30]. In addition, tactile feedback is also used for simulating haptic events during virtual experiences [31, 38]. In this work, we presented MotionRing, which creates the sensation of tactile motion around the head to enhance realism, immersion, and enjoyment in virtual experiences.

3 IMPLEMENTATION

3.1 Linear Resonance Actuators

Vibration actuators are commonly used to provide haptic feedback due to their reasonable cost and portable size. We selected Linear Resonance Actuators (LRA) over other types of actuators for its response time, energy consumption, cost, and availability. Eccentric Rotating Mass vibration motors (ERM) have slow response time (50-100ms) which can't support short durations. Compared to LRAs, piezoelectric actuators have faster response time (~1ms), but consume 2x more energy for our use case [36] and are significantly more expensive for models with comparable displacement. Dielectric Elastomer Actuators (DEA) is a promising technology, but we could not find commercially available DEA actuators.

We evaluated several LRAs and selected the one used by LG for their flagship smartphones (part number: PH-VI-LG-00014 R3) for its small size, max force (0.2N), response time (10ms), and cost (USD$3 each).

3.2 MotionRing

MotionRing is an elastic headband with LRAs stuffed in evenly distributed pouches, which were sewed inside the headband. The length of the headband is approximately 34 cm, which can be stretched to the average adult head size (roughly 56 cm)[4]. The distribution of LRAs can generate ATM along the headband, following various ring-shaped motion pattern.

We used an Arduino UNO as the hardware component to program the vibration intensity and duration of each LRA. Haptic motor drivers (DRV2605L) control the LRAs independently, and the drivers receive signals from two 8-channel I2C multiplexers (TCA9548A) connected with the Arduino board.

4 INTERSTIMULUS ONSET INTERVAL STUDY

To better design MotionRing and understand the range of angular travel speeds suitable for vibration patterns, we investigate the factors of interstimulus onset interval (ISOI), a critical control variable of ATM. ISOI is defined as the delay between the start-up time of adjacent actuators. If the ISOI is too large, users will feel a series of discrete vibrations; whereas, if the ISOI is too small, users feel a single vibration event without motion. Between the two extremes, variation of ISOI introduces ATM with different speeds. We design a user study to understand how the optimal range of ISOI is affected by vibration motor spacing, vibration duration, vibration intensity, and head region.

4.1 Study Design

As areas of the human head differ in sensitivity, we partition the contact area of the headband into three regions: *forehead*, *headSide*, and *headBack*. By symmetry, we combine the left and right side of the head into one partition, *headSide*. To explore the effect of vibration motor spacing, we implemented our prototype with three different numbers of vibration motors, 8, 12, and 16. With the motors evenly spaced, the corresponding angular spacings are 45°, 30°, and 22.5°. However, pilot users reported that with the 45°-design, a series of discrete actuation is perceived instead of ATM, leaving two the vibration motor spacings, 30° and 22.5°. For vibration intensities, we select 50% and 100% of the LRA's maximum force limit, which corresponds to 0.1N and 0.2N. As for vibration intensities, we based our study design on that of [12], which used durations of 40ms and 160ms. We adopted the 1:4 ratio and increased the durations slightly to 50ms and 200ms to explore a wider range of ISOI.

Overall, the lower and upper thresholds of ISOI are determined for two vibration motor spacing (30° and 22.5°), two vibration durations (50ms and 200ms), two vibration intensities (0.1N and 0.2N), and three head regions (*forehead*, *headSide*, and *headBack*).

With two prototype versions of the device, one with 30° angular spacing and the other with 22.5° angular spacing, we conducted a between-subject study. A total of 48 participants are recruited, 24 for each. The participants for the 30°-spacing device consists of 13 females and 11 males, with ages 20-26 (Mean = 23.04, SD = 1.68) and head circumference ranging from 52.8cm to 60cm. The other group of participants for the 22.5°-spacing device have ages 20-24 (Mean = 23.04, SD = 1.60) and head circumference 54-61cm. 13 of them are females, 10 are males, and one prefers not to say.

The combinations of different vibration durations, vibration intensities, and head regions are fully counterbalanced. It takes about an hour for a participant to finish the tasks. Every participant receives 5.75 dollars as nominal compensation.

4.2 Procedures

First, we briefly introduce the study procedures to the participants and inform that they can drop out whenever they feel sick. Participants are then instructed to sit down and wear both our headband device and noise-cancelling earbuds. To prevent them from being influenced by the discrete vibration noises upon actuation, white noise is played through the earbuds.

Each participant goes through two sections. The first section searches for ISOI lower thresholds, while the second searches for upper thresholds. Participants are instructed to take a ten-minute break between sections. Both sections consist of 12 subsections, with each corresponding to a duration-intensity-region combination. Similar to the study methods introduced in Tactile Brush [12],

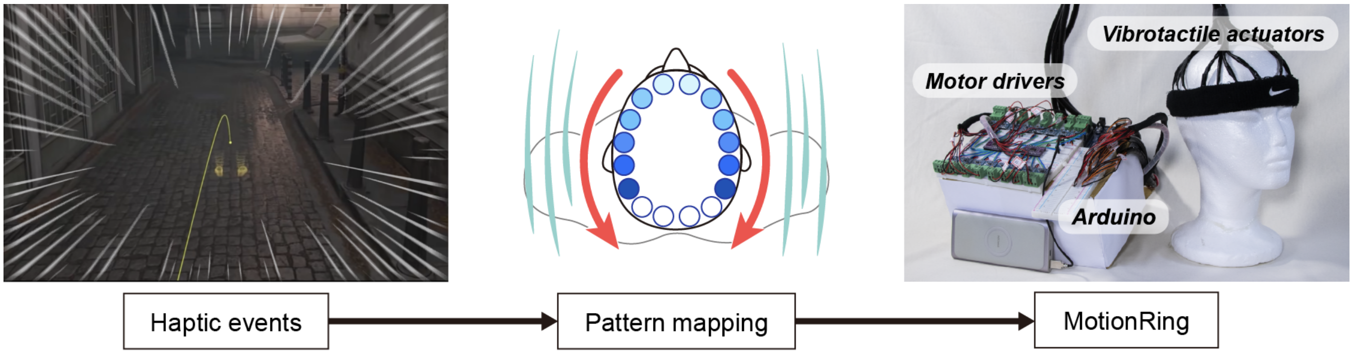

Figure 2: System diagram and control flow. When a tactile motion event is triggered, the system will determine the tactile motion pattern of the event and control the corresponding actuators via Arduino.

a one-interval two-alternative forced-choice paradigm combined with one-up one-down adaptive procedure [20] is applied to determine ISOI.

When measuring lower thresholds, the initial ISOI is set to 0. In this case, all LRAs start and end synchronously. In every trial, participants are asked if they perceived a single vibration with a fixed position. If they answer "yes", the value of ISOI is increased by a step size in the next trial. If they answer "no", i.e. ATM is perceived, the value of ISOI is decreased by a step size. Participants can freely trigger the vibration feedback arbitrary times before answering the question. Subsection ends after the sixth reversal of the ISOI value.

The procedure for measuring upper thresholds is similar to that for measuring lower threshold. The two differs in the initial ISOI value, the question asked, and the adjustments corresponding to each answer. The initial ISOI is set to 300 ms, with which all participants perceive a series of discrete vibrations. Participants are asked if they perceived multiple discrete actuators. If the answer is "yes", the ISOI value is decreased by a step size. If the answer is "no", i.e. ATM is perceived, the ISOI value is increased by a step size.

The initial step size is 20 ms in each subsection. After two reversals, the step size is decreased to 5 ms. If participants cannot perceive ATM during the reversal point, we record the previous value to ensure that participants can perceive ATM at every recorded value. This recording method may result in a smaller ISOI range if the true lower/upper bounds lie between step points. However, it ensures that ATM is always perceived when ISOI is between the two recorded thresholds. At the end of each subsection, the average of the last four reversal points is documented as the participant's ISOI threshold for this duration-intensity-region combination.

4.3 Perceptive Model of Tactile Motion on Head

We proposed the following hypotheses: *{Angular spacing, vibration duration, vibration intensity, head region} affect the {lower, upper} ISOI threshold.* To investigate this hypothesis, we applied four-way ANOVA to quantitatively determine the possible effects of these parameters.

For the lower and upper threshold of ISOI, angular spacing (lower: p-value=2.6e-27 < 0.05, upper: p-value=6.42e-8 < 0.05), vibration duration (lower: p-value=5.0e-4 < 0.05, upper: p-value=1.46e-14 < 0.05), and vibration intensity (lower: p-value=3.23e-7 < 0.05, upper: 5.12e-15 < 0.05) are shown to be significant factors. As angular spacing or vibration duration increases, the thresholds of ISOI also increase. With other factors fixed, as intensity increases, the thresholds decreases (Figure 3). However, head region does not show significance in both threshold types (lower: p-value=0.54 > 0.05, upper: 0.49 > 0.05). Moreover, the interaction of angular spacing and vibration intensity is shown to be a significant factor for ISOI thresholds (lower: p-value=1.18e-4 < 0.05, upper: 1.88e-5 < 0.05).

Based on the result of the perceptive studies, the perceptive model can be simply written as the following linear regression form:

$$ISOI = c_0 + c_1 d + c_2 i + c_3 s + c_4 i \times s$$

where d is the vibration duration (ms), i is the vibration intensity (N), and s is the angular spacing (°). After fitting, the lower/upper bounds of ISOI are:

$$ISOI_{upper} = -252.09 + 0.34d + 1419.28i + 15.77s - 73.85i \times s$$
$$ISOI_{lower} = -116.93 + 0.04d + 380.14i + 6.02s - 18.88i \times s.$$

To better compare the perception model to prior work on other body parts, we convert the angular spacing in our model into linear distances using the average head circumference of our participants (56.3cm). The converted perceptive model is shown below:

$$ISOI_{upper} = -252.1 + 0.34d + 1419i + 100.8\bar{s} - 472.1i \times \bar{s}$$
$$ISOI_{lower} = -116.9 + 0.04d + 380.1i + 38.48\bar{s} - 120.7i \times \bar{s},$$

where $\bar{s}$ denotes the linear distance (cm) between LRAs.

Finally, the angular travel speed of ATM and the ISOI have the following relation:

$$\alpha = \frac{\frac{360°}{s}}{ISOI}(°/sec)$$

For example, with duration $d = 100$ ms, intensity $i = 0.2$ N, and angular spacing $s = 22.5°$, the lower bound of ISOI = 13.59 (ms) and the upper bound of ISOI = 88.26 (ms). In this case, the maximum of angular speed $\alpha_{max} = 4.60(rps)$ and the minimum of angular speed $\alpha = 0.71(rps)$.

5 USER EXPERIENCE EVALUATION

To evaluate the user experience of MotionRing, we developed tactile motion patterns for 2 common events in two virtual experiences,

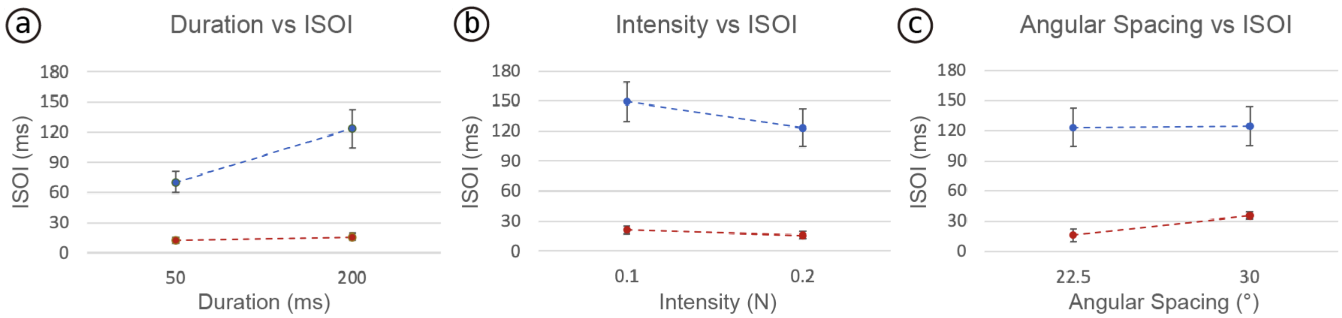

Figure 3: Upper (blue) and lower (red) bounds of ISOI, with error bars shown in standard error. (a) Relationship between duration and ISOI when intensity is 0.2N and angular spacing is 22.5°. (b) Relationship between intensity and ISOI when duration is 200ms and angular spacing is 22.5°. (c) Relationship between angular spacing and ISOI when duration is 200ms and intensity is 0.2N.

namely, teleportation in Half-Life: Alyx and object passing by in Football Dodging. For haptic feedback conditions, we compared MotionRing with tactile motion against two control conditions, static vibration and visual-only scenarios. Participants rated each experience regarding its enjoyment, realism, and immersion, and ranked their preference in the end.

5.1 Designing Tactile Motion Patterns

We divide the tactile motion events into "symmetric tactile motion" and "asymmetric tactile motion". Symmetric tactile motion starts from one area and travels in both direction on the 1-D sparse array, while asymmetric tactile motion starts from one area and travels in a single direction on the 1-D sparse array. For the purpose of demonstrating MotionRing and its two motion scenarios, we implemented two common game events, rapid self-movement (teleportation) and relative object motion (dodging footballs).

For the teleportation event, we presumed that users can feel the air resistance from the sudden acceleration. Air flow comes from the traveling direction, hence the tactile motion pattern starts with the 2 LRAs closest to the user's teleportation destination. As the user moves forward in the virtual environment, tactile motion shifts along both sides of the headband.

In the football dodging game, the football applies wind pressure on the user's head, allowing the user to sense its motion trajectory. Depending on the trajectory of the football, the tactile motion pattern starts from the front LRA, and the vibrotactile shifts along one side of the headband with only 8 LRAs operating.

To make the vibrotactile feedback convincing, we conducted two pilot studies to map out the vibration pattern design. The vibration duration and ISOI were adjusted based on users' perception. Vibration duration of 50-120 ms and ISOI of 8-30 ms is used in the teleportation event, while vibration duration of 100 ms and ISOI of 20 ms is used in the football dodging event.

5.2 User Studies

We conducted two within-subject studies to evaluate user experience of MotionRing in comparison to two control baselines, visual-only and static vibration. In the visual-only condition, users experience the games as is, where no haptic feedback will be applied to game events. In the static vibration condition, the selected LRAs on the headband will be actuated and stopped simultaneously when game events (teleportation, dodging) occur, without creating tactile motion. The three conditions were conducted with neither noise-cancelling earphones nor white noise, so that participants can experience and compare them with all the sensory feedback.

Ordering for the three feedback conditions and two virtual experiences was counterbalanced by a Latin square. We recruited 12 participants, 6 females and 6 males with age 21-25 (Mean = 23.33, SD = 1.07). Their head circumference ranged from 55.0 to 59.1 cm. The user studies took 40 minutes in total, and every participant received five dollars as nominal compensation.

5.3 Application: Half-Life: Alyx

Half-Life: Alyx is a commercial VR game known for its high quality graphics, complex interacting system, and realistic environment. Among different types of player locomotion it supports, the shift teleport method allows player to move rapidly toward the designated destination. This multi-directional sudden acceleration can be implemented with MotionRing to create the sense of motion. To receive real-time information about teleportation distance and direction, we utilized game mods to send in-game information via a Socket connection.

5.3.1 Tasks and Study conditions. In order to experience the teleportation fully, we designed a treasure hunting game in one of the levels of Half-Life: Alyx. We examined several game levels to locate one region most suited to conduct our user study. The study scene is an open area with collectables scattered around the field and no hostile characters showing up. Participants can explore this area freely by using the shift teleport method, and search for hidden resins. The static vibration condition in this application delivers a full-ring vibration when the teleportation starts, and its duration is the same length as MotionRing's tactile motion pattern.

5.3.2 Experimental procedure. Participants were asked to sit on a stool in the middle of a spacious room. We assisted them to wear the MotionRing headband underneath the VIVE Pro VR headset.

Participants were given sufficient time to learn the controls of teleportation around the area, changing their orientation, and picking up distant objects.

To more accurately conduct the user study, we would like the number of times each user teleports to be similar. A pilot study was conducted beforehand to calculate the average teleportation frequency throughout the treasure hunting game. We then designed the study procedure based on the collected data, such that the participants teleport around 30 times per condition to obtain the required number of resins. After each feedback condition, we asked the participants to rate the enjoyment, realism, and immersion regarding the movement experience on a 7-point Likert-scale questionnaire, as well as their ability to perceive the direction of wind resistance when teleporting regardless of the visual. When all three conditions were completed, participants were asked to provide a preference ranking along with their reasons, and an overall qualitative feedback.

5.3.3 Results. Figure 4(a) shows the average Likert-scale ratings for teleportation with MotionRing, static vibration, and visual-only conditions. We analyzed the results of the three conditions with the Friedman test. For pairwise comparison, the Wilcoxon signed-rank sum test including Bonferroni correction was applied. MotionRing outperforms the visual-only condition in directionality, enjoyment, realism, and immersion.

Participants gave significantly higher ratings in enjoyment with MotionRing then with static vibration feedback ($p<0.01$), and there is also a significant difference in directionality between MotionRing and static vibration ($p<0.05$). 92% of the participants preferred MotionRing's haptic feedback in the teleportation event.

Qualitative feedback. Participants showed appreciation toward the sense of motion MotionRing provided. We received comments like "MotionRing is great for letting me know where I am heading" (P4, P7, P10) and "The motion feedback matches the visual perfectly. It feels like the whole world is moving around your head" (P3). As for static vibration, participants commented that "Static vibration does not provide directional information, so adding this haptic feedback to such a frequent event seems useless or even disruptive" (P8, P12).

5.4 Application: Football Dodging

We made a third-person view football game using Unity 2018.4.1f1, which was inspired by Wii Fit Soccer Heading game.

5.4.1 Tasks and Study conditions. In our game, a non-player character kicks footballs toward the player's avatar. The participants' task is to control their avatar with an Xbox controller to dodge those footballs. For each haptic feedback condition, the participants are asked to dodge ten footballs to end the game.

The static vibration condition in this game delivers a half-ring vibration when a football flies by the avatar's head. If the football grazes the left-side of the avatar's head, the 8 LRAs on the left part of MotionRing will vibrate simultaneously, while conversely on the right-side. The duration of the static vibration is the same length as MotionRing's tactile motion pattern.

5.4.2 Experimental procedure. The participant were asked to sit on a chair in front of a computer while wearing MotionRing and play three rounds of Football Dodging game with different feedback conditions. After each round ended, we asked the participants to rate the enjoyment, realism, and immersion regarding the football dodging experience on a 7-point Likert-scale questionnaire, as well as their ability to perceive the direction of object movement regardless of the visual. When all three conditions were completed, participants were asked to provide a preference ranking along with their reasons, and an overall qualitative feedback.

5.4.3 Results. Figure 4(b) shows the average Likert-scale ratings for football dodging with MotionRing, static vibration, and visual-only conditions. The statistical test are the same as the teleportation application section, and MotionRing still outperforms the visual-only condition regarding the four questions.

The participants reported significantly higher ratings for realizing the direction of the moving football with MotionRing than with static vibration ($p<0.05$). 75% of the participants preferred MotionRing's haptic feedback when dodging footballs.

Qualitative feedback. In terms of simulating objects flying by, participants have given some positive responses for the tactile motion feedback, such as "MotionRing simulates wind pressure in a very realistic way" (P4, P7) and "Motors vibrating from front to back really creates the sensation of ball passing by my side" (P6, P12). However, one participant commented that "The motion is too slow, resulting in unrealistic feedback. It is not bad that static vibration can indicate the side where the ball grazing the head" (P4).

6 DISCUSSION

6.1 Trade-off of Including More or Fewer LRAs

Reducing the number of LRAs reduces weight, physical wiring, system complexity, power consumption, and cost. Therefore, we focused on exploring the minimum number of LRAs necessary to achieve tactile motion on the head. We evaluated two such designs. With 12 and 16 LRAs, the spatial resolutions of the two designs are 30° and 22.5°, respectively.

To improve spatial localization, more LRAs can be added. Another approach is to use funneling illusion, which is the sensation of a single but phantom stimulus located between two actual stimulus locations. By controlling the amplitude of two actuators, stimuli of arbitrary locations in between can be simulated. Previous research [17] reported that over 50% of the participants perceived such an illusion when the distance between actuators was 5cm, and over 80% when 2.5cm. Given that the average head circumference of our study participants is 56.3cm, the 22.5° design (16-LRA) has an average distance of 3.52cm between actuators. This suggests that between 50%-80% of participants can perceive funneling illusion. By increasing the number of LRAs to 24, the distance would be reduced to <2.5cm and would have over 80% of participants perceiving funneling illusion.

6.2 Comparison with Similar Work on ATM for Different Body Parts

Similar research on ATM have been done on human back [11, 12] and forearm [11]. Compared to these work, MotionRing's headband

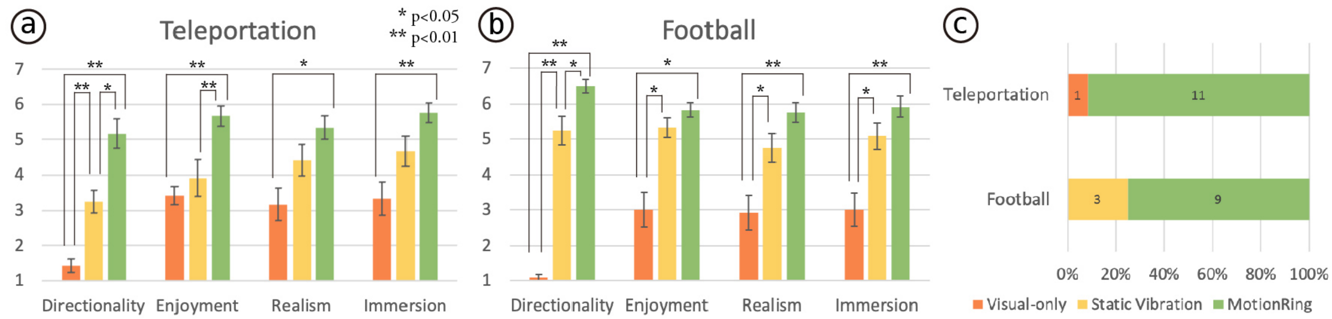

Figure 4: (a) (b) Average ratings of directionality, enjoyment, realism and immersion on a 7-point Likert scale for teleportation and football dodging with feedback conditions: 1) MotionRing, 2) static vibration, and 3) visual-only. (c) The most preferable feedback condition between MotionRing, static vibration and visual-only for teleportation and football dodging, showing that MotionRing is a highly desirable feedback condition.

design can be easily integrated into VR/AR head mounted displays. This improves usability and mobility as users do not need to put on an additional wearable device, such as a vest or a sleeve, nor be constrained to an external device, such as a chair. Also, our ring-shaped design enables 360° egocentric feedback with spatial resolution, compared to prior systems that provided non-egocentric feedback or smaller ranges of coverage.

In terms of perception models, there are three notable similarity and differences:

(1) For head, back, and forearm: as duration increases, ISOI values increase and the ranges of ISOI expand.
(2) Spacing is a factor for head and forearm, but not for the back [11].
(3) The average upper bound of ISOI can be larger than the durations of short stimulus, meaning that participants perceived tactile motion even when there are gaps between vibration (ie. none of the actuators are vibrating). This was observed for the head and back [12], with the max difference between ISOI and duration being smaller for the head (70 vs. 50ms) compared to the back (100 vs. 40ms). While [12] observed this effect for the back, [11] used a much longer short stimulus duration of 120ms, and did not observe this effect for the forearm and back.

6.3 Deploying MotionRing in More Events

Aside from symmetric and asymmetric tactile motion evaluated in our application study, there are some pattern design space not discussed yet. The ring-shaped device could also support circular, continuous, multi-point, and 360-degree patterns. Circular and continuous patterns may simulate the sensation of spiral winds such as hurricanes. Continuous and multi-point patterns may simulate air drag due to continued motion. 360-degree patterns can simulate effects such as objects passing by behind the user. These may be further explored in the future.

6.4 Effect of Vibration Noise

Upon operation of MotionRing, motors vibrate and induce noises right beside the user's head. Such noise get transmitted through both bone conduction and the air. This causes the noise to be hard to get fully eliminated with noise-cancelling headphones. However, in our user experience evaluation study, in which participants did not wear noise-cancelling headphones, few of them reported that the noise interfered their game experience. Therefore, we believe that the vibration noise is a minor problem in our case.

6.5 Time Mapping between Tactile Motion and Event

The asymmetric tactile motion pattern, designed for objects passing by, runs under the conditions that the vibration duration is 100 ms and ISOI is 20 ms. In the football dodging game, the time it takes for a football to pass by player's head is 250ms, while the total time to complete the tactile motion pattern is 240 ms. The real scale motion and haptic feedback take roughly the same amount of time.

The symmetric tactile motion pattern, designed for teleportation, runs under the conditions that the vibration duration ranges from 50 ms to 120 ms, and ISOI ranges from 12 ms to 30 ms. We collected in-game information to calculate the total time span of the teleportation event, and it costs 50 ms to 150 ms to complete single movement. However, MotionRing provides tactile motion feedback costing 134ms to 330ms, which are about 2 times longer then the actual teleportation duration. Despite the speed of motion in real scale does not completely match the speed of tactile motion, users still consider the experiences enjoyable.

7 CONCLUSION

We present MotionRing, a vibrotactile headband that creates tactile motion with angular speed 0.5-4.9 revolutions per second. We investigated the factors that affect the formation of apparent tactile motion and conducted perceptive studies to explore the upper/lower bounds of in ISOI which the apparent tactile motion could be formed within those ranges. In the user experience evaluation, MotionRing is the most preferred when comparing to static vibration feedback and visual-only experiences.

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