GuideBand: Intuitive 3D Multilevel Force Guidance on a Wristband in Virtual Reality

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ABSTRACT

For haptic guidance, vibrotactile feedback is a commonly-used mechanism, but requires users to interpret its complicated patterns especially in 3D guidance, which is not intuitive and increases their mental effort. Furthermore, for haptic guidance in virtual reality (VR), not only guidance performance but also realism should be considered. Since vibrotactile feedback interferes with and reduces VR realism, it may not be proper for VR haptic guidance. Therefore, we propose a wearable device, GuideBand, to provide intuitive 3D multilevel force guidance upon the forearm, which reproduces an effect that the forearm is pulled and guided by a virtual guider or telepresent person in VR. GuideBand uses three motors to pull a wristband at different force levels in 3D space. Such feedback usually requires much larger and heavier robotic arms or exoskeletons. We conducted a just-noticeable difference study to understand users' force level distinguishability. Based on the results, we performed a study to verify that compared with state-of-the-art vibrotactile guidance, GuideBand is more intuitive, needs a lower level of mental effort, and achieves similar guidance performance. We further conducted a VR experience study to observe how users combine and complement visual and force guidance, and prove that GuideBand enhances realism in VR guidance.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Haptic devices**.

KEYWORDS

Haptic feedback; force feedback; motion guidance; force guidance; virtual reality; wearable device.

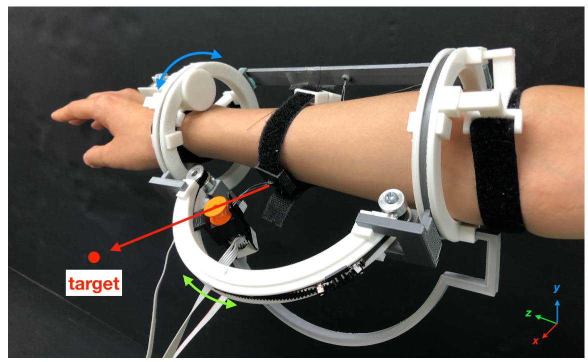

Figure 1: GuideBand provides intuitive 3D multilevel force guidance by pulling the wristband toward the target direction.

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1 INTRODUCTION

To guide users to see or move toward a target, *e.g.*, in navigation or remote assistance, there are many guidance methods in not only the real world but also virtual reality (VR). In addition to common visual guidance, haptic guidance allowing users to perceive guidance cues in an eyes-free manner, such as using vibration or skin stretch feedback, is also widely investigated. However, although intuitive guidance is important to reduce users' mental effort, it is still challenging for haptic guidance, which requires users to recognize patterns of haptic cues, especially in 3D space. Furthermore, how intuitive haptic guidance makes users feel realistically guided still waits to explore.

Previous studies leverage visual feedback for guidance or remote assistance [36, 40, 47, 48, 55], but the limited field of view (FoV), occlusion problem, or viewing angle limitation are the potential restrictions. For haptic guidance, several methods use vibrotactile

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actuators to generate vibrotactile patterns [4, 22, 29, 35, 62] or use motors to provide skin stretch cues [13, 14, 21, 30, 37] to guide users. However, vibrotactile guidance methods either only achieve discrete direction guidance or are difficult to be intuitive, since users have to learn, recognize and interpret the vibrotactile patterns, which increase their mental efforts. In this paper, discrete direction guidance means guidance for only separate direction cues, *e.g.*, up/down/left/right/forward/backward. Therefore, to guide a hand to the upper-right direction, the hand is guided rightward and then upward. This is different from the desired continuous direction or omnidirectional guidance, which is able to guide the hand toward any direction in 3D space, such as moving rightward and 70 degrees upward to the horizontal. For skin stretch methods, they either are discrete guidance or require handheld devices, which occupy the hand. For force guidance, previous works use motors to pull body parts, exoskeletons, robotic arms or electrical muscle stimulation (EMS) [7, 9, 12, 33, 39, 43, 44, 63] to render guidance cues. However, lightweight pulling motor and EMS methods provide limited guidance directions or overwrite users' motions. Although some exoskeletons and robotic arms indeed achieve 3D force guidance, they are generally either heavy or worn on two or more body parts, which restricts users' movements. Furthermore, none of these haptic guidance methods are used to enhance realism in VR guidance, as in other VR haptic research [10, 15, 26, 34, 57, 59].

We propose a lightweight wearable device, GuideBand, to provide intuitive omnidirectional 3D multilevel force guidance by pulling a wristband to indicate the target direction to enhance realism in VR guidance (Figure 1). As it is worn on a single forearm, this avoids excessive restriction of movement and keeps the hands free for other tasks. GuideBand consists of a wristband and three motors, which control the guidance force level, force direction in the xy-plane perpendicular to the forearm, and force direction along the z-axis parallel to the forearm, respectively. Therefore, users can perceive the forearm intuitively and realistically being pulled and guided by a virtual character or telepresent person in VR. Providing 3D force feedback achieves general guidance purposes, and rendering multilevel force feedback provides the user with a rough concept of the target distance. Such pulling guidance cues are intuitive and do not require users to interpret complicated patterns. We conducted a just-noticeable difference (JND) study to understand users' guidance force level distinguishability. Based on the results, we further performed a study to evaluate the guidance performance, and verify whether GuideBand is more intuitive and requires a lower level of mental effort and cognitive load than other methods. Finally, we conducted a VR experience study to observe how users combine and complement visual and force feedback guidance and verify that GuideBand enhances VR realism.

This paper presents the following contributions:

(1) Proposal of an elaborate wearable device to provide omnidirectional 3D multilevel force guidance, which is lightweight (225g), hands-free, and worn on a single body part.
(2) Rendering intuitive guidance, which requires a lower level of mental effort compared to state-of-the-art vibrotactile guidance, but achieves similar guidance performance.
(3) Exploration of users' guidance force level perception distinguishability on the forearm.
(4) Verification that GuideBand enhances realism in VR guidance and further exploration of how users combine and complement visual and force guidance.

2 RELATED WORK

2.1 Tactile Guidance

Tactile feedback for guidance is well discussed and implemented in previous works. To guide users to perform specific motions and postures, Ruffaldi *et al.* [42] use vibrotactile guidance to enhance users' error awareness and teach them to perform specific motions and postures for rowing training. Spelmezan *et al.* [49] use full-body vibrotactile patterns to provide haptic instructions for physical activities, such as snowboarding. Marquardt *et al.* [35] propose a vibrotactile glove to provide tactile patterns on the palm, back of hand and forearm for posture guidance.

For directional guidance, previous methods provide guidance cues in discrete or continuous directions. For discrete direction guidance, Shoe Me the Way [45] uses two vibrotactile actuators on two sides of a foot to deliver patterns for turning left/right and stepping forward/backward. Aggravi *et al.* [3] use four vibration motors on the arm to provide cues in six directions (*i.e.*, up /down/left/right/forward/backward). HapWRAP [5] uses pneumatic actuators worn at specific positions, so users could perceive cues in four directions (*i.e.*, up/down/left/right). Weber *et al.* [62] use six vibrotactile actuators on the wrist to provide guidance in four (*i.e.*, up/down/left/right) translation and two (*i.e.*, clockwise (CW) /counterclockwise (CCW)) rotation directions. FeelSpace NaviBelt [2] equips 16 vibration motors on a belt around the waist for 2D navigation. VT-WARE [28] contains six actuators, and four of them are around the wrist for guidance in four (*i.e.*, up/down/left/right) translation and two (*i.e.*, CW/CCW) rotation directions. The other two actuators are at the top of the wrist in line for forward/backward guidance. WAVES [16] uses voice coils to produce asymmetric vibrations on three fingers to deliver guidance cues in six translation and rotation directions, respectively. On the other hand, Chinello *et al.* [13, 14] use four servo motors around the forearm to render skin stretch cues to guide users' arm in four (*i.e.*, up/down/left/right) translation and two (*i.e.*, CW/CCW) rotation directions. Kayhan *et al.* [30] use two servo motors to pull two bracelets on the forearm, respectively, to provide skin stretch guidance for three degrees-of-freedom (3DoF) wrist rotation, including extension/flexion, radial/ulnar deviation, and pronation/supination. Guinan *et al.* [21] control two 2DOF skin stretch tactors grasped by the index finger and thumb to provide guidance in four (*i.e.*, up/down/forward/backward) translation and six rotation (*i.e.*, CW/CCW in roll/pitch/yaw) directions. Stanley and Kuchenbecker [51] present five wearable devices to provide tactile guidance cues for wrist rotation in two directions. These methods provide guidance in discrete directions, such as six separate translation and/or rotation direction cues, instead of omnidirectional or continuous direction guidance in 3D space. In discrete direction guidance, if the target direction is not aligned with the certain axes or directions of the device, *e.g.*, to exactly rightward, it needs to render a sequence of cues to guide the users' movement step by step.

For continuous direction or omnidirectional guidance, Hong *et al.* [27] use four vibration motors on a wristband to interpolate directions on a 2D surface. TactileGlove [22] uses nine vibration motors on the back of the hand and one on the palm to provide 3D guidance. Aggravi *et al.* [4] leverage four vibration motors on a wristband to guide users' forearm moving along a predefined path in 3D space. HapticHead [29] utilizes 22 vibrotactile actuators in three concentric ellipses around the head to interpolate 3D guidance directions. Furthermore, Norman *et al.* [37] propose a haptic device to stretch the skin on the index fingertip to provide 2D guidance. The device seems to provide continuous direction guidance in 2D, although only eight directions are used for guidance as mentioned in their paper. For continuous direction vibrotactile guidance, although these methods achieve 3D omnidirectional guidance, they generally require users to learn, recognize and interpret guidance patterns, which are not intuitive and increase users' mental efforts. Some vibration patterns made up of interpolation, funneling illusion or phantom sensation from a ring of actuators may be easier to recognize, but these are still not intuitive enough. Furthermore, several vibration motors arranged closely actuating simultaneously makes users numb and difficult to distinguish the vibrotacile cues. This makes the vibration patterns from several vibration motors or a ring of vibrotactile actuators even harder to recognize on body parts with small surface, such as a hand, wrist or forearm. For continuous direction skin stretch guidance, although no pattern is required, these devices provide feedback on the fingers or even are held by the hand, which occupies the hand preventing other tasks. Furthermore, since this paper aims for VR guidance, vibration feedback interfering with users' VR realism and immersion, as proven in [34, 58], is not a proper feedback approach.

2.2 Force Guidance

Grounded force feedback devices, such as Phantom, Novint Falcon and L-EXOS, are well-designed and commercialized for motion guidance and motor learning [8, 18, 20, 25]. However, such devices limit mobility. For ungrounded force devices, robotic arms [43, 44] and wearable exoskeletons [1, 19, 32, 38, 46] are able to achieve 3D force guidance. However, these devices are generally either heavy or worn on two or more body parts, such as a forearm, upper arm and shoulder, or several finger segments and a hand, which could restrict and interfere with users' movements. Since we intend to provide directional force guidance cues rather than restricting and changing a user's movements in this paper, instead of a powerful and heavy device, a lightweight force guidance device worn on a single body part is preferred.

For handheld devices, Buru-navi [6] moves a weight in asymmetric acceleration using a motor to produce a pulling sensation illusion for 1D translation (*i.e.*, forward/backward) guidance. iTorqU 2.0 [63] leverages gyroscopic effect by quickly spinning two flywheels to provide directional torques for rotational guidance. Weber *et al.* [60] propose a kinesthetic device which uses DC motors to provide four degrees-of-freedom (DoF) motion guidance cues on users' finger and wrist. Animotus [50] changes its shape to provide 2D guidance cues on the users' hand. Thor's Hammer [26] uses six motors and propellers to generate strong thrusts of air and provide omnidirectional force feedback on a controller in 3D space. Except for Thor's Hammer, previous methods do not achieve 3D translation force guidance. Although Thor's Hammer is the state-of-the-art ungrounded 3D force guidance device, it is a handheld device which prevents users from doing other tasks with their hands. To produce thrusts of air, it requires all six sides not to be blocked. Therefore, Thor's Hammer cannot be arbitrarily attached to body parts as a wearable device.

For wearable devices, ProximityHat [7] uses six pressure actuators around the head to deliver 2D spatial information. Motion guidance sleeve [12] uses two step motors connected with fishing lines to stretch the sleeve and provide 1D rotational guidance. CURF [9] and Pezent *et al.* [39] use two motors to control a band on a forearm to provide guidance in 1D rotation directions and compression. On the other hand, PossessedHand [53] uses electrical muscle stimulation (EMS) to stimulate users' fingers to learn instruments. Affordance++ [33] also uses EMS to guide users' arms, hands and fingers to properly operate devices with poor affordance. However, these methods generally provide limited or specific guidance directions. These methods may need sequential guidance cues with step-by-step movement to overcome the insufficient guidance range, similar to discrete direction guidance. To the best of our knowledge, a lightweight device worn on a forearm (single body part) to provide intuitive omnidirectional 3D force guidance is still challenging.

2.3 Haptic Guidance in Virtual Reality

For tactile guidance in VR, Zhao *et al.* [64] use tactile illusion on a cane controller to enable blind people navigation in VR. When users hit something in VR using the cane, the voice coil on the cane generates vibrotactile feedback to simulate the corresponding feeling or texture vibration from the real world. Masque [61] controls six tactors within an HMD to render skin stretch feedback for guidance in six translation directions. For VR force guidance, FacePush [10] leverages motors to press an HMD into a user's face to achieve 1D directional guidance in VR or 360 video. Although vibrotactile guidance cues are common as are quick hints and notifications [29], but such feedback reduces immersion and realism in VR, as mentioned in [34, 58]. For skin stretch and force guidance in VR, previous methods only use these feedback methods to notify users. How to use such guidance feedback to enhance realism in VR guidance is unexplored.

3 GUIDEBAND

We propose a wearable device, GuideBand, on the forearm to achieve intuitive 3D multilevel force guidance, and reproduce the effect of being pulled and guided by a virtual character or telepresent person in VR guidance.

3.1 Design Considerations

To achieve our goals, the following design considerations were needed to be taken into account.

- *Intuition.* To reduce mental effort from interpreting guidance cues, complicated vibrotactile patterns should be avoided. We choose intuitive pulling force as guidance cues, and the pulling directions represent the guidance directions.
- *Omnidirectional Guidance.* To achieve general-purpose haptic guidance in 3D space, guidance with only six directions

(*i.e.*, up/down/left/right/forward/backward) is insufficient. Therefore, omnidirectional guidance is our goal.
- *Multilevel Guidance Feedback.* In addition to directional information, having a sense of the distance to targets, even only a roughly concept, is also necessary. Therefore, we use multilevel force guidance feedback to represent this.
- *Mobility.* To ensure that users freely move and their hands are not occupied for operation during guidance, a wearable guidance device is required. To maintain mobility, guidance devices should not be too heavy to bother users' movement or cause fatigue.
- *Safety and Comfort.* For any haptic feedback device, users' safety and comfort are always the most necessary and basic premises. Therefore, the force feedback in the proposed method should not be too strong to make users feel uncomfortable or cause injury.

3.2 Hardware

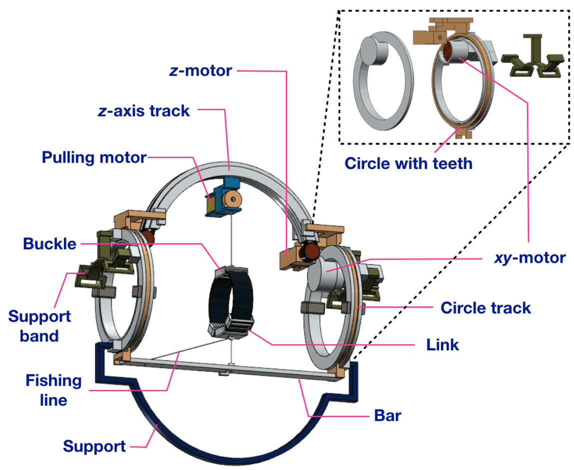

Figure 2: The hardware structure of the GuideBand prototype.

GuideBand is a wearable device worn on the user's forearm. We tried a simple preliminary approach using three motors to pull the wristband in three directions for 3D guidance. However, it renders feedback on certain positions on the forearm, which cannot simulate feedback as being pulled outward in omnidirectional around the forearm in VR. Therefore, we propose the current GuideBand prototype. It consists of a wristband and three motors. The motors control guidance force level, force direction on the xy-plane, which is perpendicular to the forearm, and force direction along the z-axis, which is parallel to the forearm, respectively, as shown in Figure 2. The coordinate system we use matches that of a Vive controller in Unity. The wristband is connected to a DC motor, called a *pulling motor* (Pololu Micro Metal Gearmotor with gear ratio 210:1), with a winding axle (radius: 6mm) and a rotary encoder (Pololu Magnetic Encoder 12 counts per revolution) by way of a fishing line. The pulling motor pulls the fishing line at different force levels to achieve multilevel force guidance. By pulling toward the target direction for guidance, such a mechanism achieves the intuition design consideration.

The pulling motor is placed into a motor case on a track that goes along the z-axis. When the motor moves along the track, a curved track provides a wider pulling direction range than a straight track of the same size. Therefore, using a timing belt connected to two sides of the pulling motor case, a motor with a gear, called a *z-motor* (gear ratio 298:1), moves the pulling motor along the curved z-axis track. Such a design provides the pulling direction range from ahead to behind the hand. It is worth noting that it is difficult to achieve fully horizontal forward and backward guidance since these require the pulling motor to pull from the fingertip or elbow, which is infeasible. The guidance direction range of GuideBand is approximately 55 degrees to the vertical, which is a bit different depending on users' arm size. This is the limitation of our design.

The two ends of the z-axis track are affixed on two circles, which are in their circular tracks, respectively. One circle has teeth facing inward, so a motor with a gear, called an *xy-motor* (gear ratio 210:1), can rotate the circles in the circle tracks and in turn rotate the whole z-axis track, including the pulling motor and z-motor, on an xy-plane. Combining the movement from the z-motor and xy-motor, the GuideBand achieves 3D omnidirectional pulling force guidance. The circle tracks are worn on the forearm near the wrist and elbow, respectively, via 3D printed supports and Velcro bands, called *support bands.* Different forearm sizes may need different support band sizes. When the motor pulls the wristband, reaction forces are inevitably applied to the forearm via the support bands, and the support bands press on the forearm. However, the support bands are far from the wristband, and the widths of these bands are all the same. Therefore, the reaction force is equally distributed to the support bands, and only half of the reaction force magnitude is applied to each support band, which reduces the perceptual interference.

Two wristband types, a rigid 3D printed circle and a soft Velcro band, were compared in a pilot study. Although users could perceive the normal force from the underside of both wristbands, they could perceive tangential or shear force along the sides of the wrist only from the Velcro band due to the band deformation. This is also an important cue for users to distinguish the force direction. Thus, the Velcro band (width 20mm) is used as the wristband in Guideband (Figure 4). We also observed that the band should be worn a bit loose and not be pulled too tight, since it should allow users to perceive the pulling force direction instead of merely nondirectional compression, and also allow the band to be smoothly rotated on the forearm on the xy-plane by the xy-motor.

We conducted another pilot study to observe how users perceived the direction of the pulling force when the wristband was pulled by three 3D printed buckles with different widths, 15mm, 20mm and 30mm, and a fishing line, as shown in Figure 3. These widths are similar to when the wristband is pulled by one or two fingers. We found that since the 15mm buckle and fishing line caused too much deformation on the wristband, it produced nondirectional compression. The 30mm buckle was too wide so the tangential force was not obviously perceived by the users. Therefore, the 20mm buckle is used on the wristband connected with the fishing line from the pulling motor. Furthermore, we also found that forward

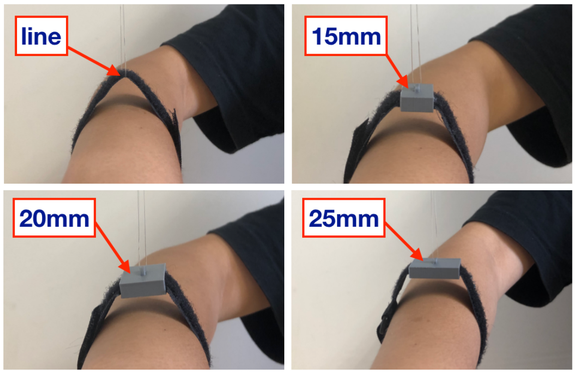

Figure 3: Different buckle sizes to enhance the pulling force guidance.

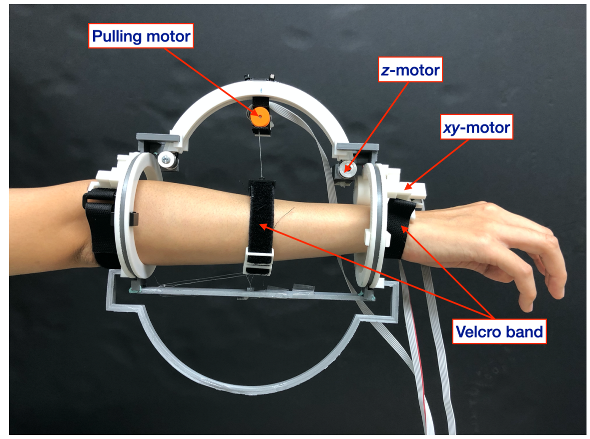

Figure 4: GuideBand prototype worn on a forearm.

and backward pulling force feedback were not easily distinguishable. However, such forces can still be clearly distinguished when wearing a metal watch band. This is because the links on a metal watch band tilt to press the forearm and provide clearer directional cues. Therefore, to reinforce the forward and backward force guidance for users, some 3D printed links are affixed on the underside of the wristband.

Due to the anatomy of a forearm, which is thinner closer to the wrist and thicker closer to the elbow, the wristband easily shifts out of place when it is pulled forward. Therefore, two designs are used to prevent this. Some grooves perpendicular to the forearm are 3D printed on the surfaces of the links of the wristband that come into contact with the forearm. The grooves increase friction only when the wristband moves forward and backward, but still allow the wristband to rotate on the xy-plane. In addition, a bar is affixed on the circles opposite to the z-track. Two fishing lines are connected to the bottom of the wristband and tied on the bar through the use of two small holes on the bar near the wristband and the elbow, respectively. Therefore, by adjusting the fishing lines to the proper length, these lines prevent the wristband from moving forward, and allow the wristband to rotate on the xy-plane smoothly. Another issue is that the two circle tracks are not connected to each other. Therefore, when the xy-motor rotates the circle with teeth, the other circle is further driven and rotated, which twists the forearm due to relative rotation between the circles. Although the bar affixed on the circles reduces the effect, this issue still may interfere with the users. We use another support affixed on two circle tracks to effectively mitigate this issue.

The three motors are connected with three Dual TB6612FNG motor drivers, respectively, and controlled by an Arduino Mega board. The signal wires of the three rotary encoders are connected with six interrupt pins on the board to maintain the rotation precision. 12V external power is provided for the DC motors. The total weight of the GuideBand prototype is 225g. GuideBand is lightweight and worn on a single body part (*i.e.*, a forearm) to avoid restricting the users' movement and keep the hands free for other tasks, which achieve the mobility design consideration.

3.3 Software

At initialization, the support bands are tied firmly to the forearm, and the wristband is worn slightly loose. The z-axis track rotates to 0 degrees on the xy-plane, which is directly above the forearm on the vertical (y-axis). Furthermore, the pulling motor is at the center of the z-axis track and right above the wristband. To adjust for different forearms, the pulling motor gradually pulls the wristband. When users perceive just a bit of pulling force, the motor loosens the wristband a little, which is referred to as *critical state*. In the critical state, the fishing line is usually taut but not tensioned. Any further pulling force applying to the wristband can be perceived by the users. The pulling motor loosens the fishing line in a half revolution from the *critical state* and induces the *initial state*, wherein the wristband is slightly loose. The two fishing lines attached to the bottom of the wristband are tied on the bar at the length not interfering with pulling force feedback.

At the beginning of the guidance, with the hand and target positions, the vector and distance from the hand or forearm to the targets are computed. The angles for the z-motor and xy-motor are obtained by computing the projection vectors on the yz-plane and xy-plane, and further computing their respective angles from the y-axis. These motors sequentially move the pulling motor to the target position on the tracks. The pulling motor then pulls the wristband at different force levels based on the target distance, and then releases it. To prevent the pulling motor from overheat or damage since it is quickly and consecutively actuated in both directions, all pulling force levels have the same period with a delay between motor pulling and releasing. To allow users to distinguish the target distance based on the force levels, the farther the target, the stronger the pulling guidance force, and vice versa. Therefore, the weakest force level means the hand very close to the target. When users reach the target, the force guidance feedback stops and the guidance is completed. Notably, we found that keeping pulling the wristband for guidance makes users numb and reduces the distinguishability of force direction and level. Therefore, instead of such continuous force stimuli, we choose discrete force stimuli (pulling and releasing) with distinguishable force levels for GuideBand. Although it provides discrete force stimuli, it still renders continuous direction guidance.

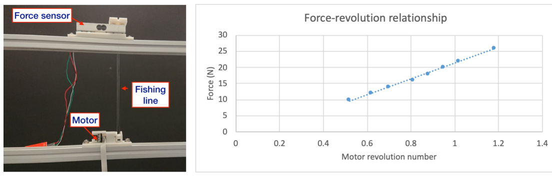

Figure 5: Pulling force stimuli measured by a force sensor.

Despite 55 degrees to the vertical being the range for most users as mentioned prior, to ensure that all users have the same guidance range, the maximum angle is set at 50 degrees. Although we intended to use pulling force to achieve motion guidance without any learning of patterns, to tackle the horizontal direction guidance limitation in GuideBand, a simple pattern is used. A 500ms delay is added during motor pulling, which indicates to users that the direction of forward or backward guidance is more than 50 degrees to the vertical. This pattern was clearly distinguished by users in a pilot study. Therefore, when the guidance direction is forward, backward or over 50 degrees to the vertical, the pulling motor is moved to 50 or -50 degrees by the z-motor, and pulls in accordance with the pattern. The average time for the pulling motor moving on xy-track is 1.4 seconds and on z-track is 1.2 seconds.

In the following sections, we performed three studies to observe users' force level distinguishability, evaluate the guidance performance of GuideBand and whether it requires less mental effort, and understand how users combine and complement visual and force guidance and whether GuideBand enhances realism in VR guidance.

4 JUST-NOTICEABLE DIFFERENCE STUDY

We performed a just-noticeable difference (JND) study to observe users' guidance force level distinguishability in regard to each axis, respectively. The results of distinguishable force levels are used to represent different target distances for the force guidance. Although the staircase design is a commonly used one in a JND studies, to prevent the participants from being fatigued, which may influence the JND results, we followed the study design in [23, 41] to perform this JND study.

4.1 Participants and Apparatus

The GuideBand device as mentioned prior was worn on the forearm. The bar between the two circles and the support between circle tracks were not equipped on the device in this study since directions of force stimuli were not changed for trials on each axis. An eye mask and earphones were worn to block visual and audio feedback generated by the GuideBand device. 12 right-handed participants (5 female) aged 22-33 (mean: 24.25) were recruited.

4.2 JND Stimuli

Before performing the JND study, we evaluated the JND force stimuli generated from the pulling motor. We built an aluminium extrusion frame and affixed the pulling motor and a force sensor (TAL220 with a HX711 amplifier) on different aluminum extrusion bars of the frame. A fishing line was connected between the winding axle of the pulling motor and the force sensor, as shown in Figure 5. At the

Up/down (y-axis)

Offset (N) \ Base (N)	11	12	14	18
0	0.08	0.00	0.13	0.17
2	0.38	0.58	0.71	0.38
4	1.00	1.00	0.96	0.63
8	0.96	1.00	1.00	0.96

Left/right (x-axis)

Offset (N) \ Base (N)	11	12	14	18
0	0.13	0.13	0.13	0.13
2	0.21	0.42	0.58	0.25
4	0.96	0.96	0.96	0.79
8	1.00	1.00	1.00	1.00

Forward/backward (z-axis)

Offset (N) \ Base (N)	11	12	14	18
0	0.04	0.29	0.08	0.04
2	0.29	0.33	0.71	0.38
4	1.00	0.88	0.96	0.75
8	1.00	1.00	1.00	1.00

Figure 6: Results of JND study. Fractions of responses that the pair of stimuli were supposed as unequal were shown. Upper: up/down (y-axis). Lower left: left/right (x-axis). Lower-right: forward/backward (z-axis).

beginning, we calibrated the fishing line to the critical state, which means that the line was taut but not tensioned, so no force was measured by the force sensor. We performed a pilot study to decide the JND stimuli range, and found that most users could clearly perceive the pulling force over 11N, and some of them felt uncomfortable when it was over 26N along all axes. Therefore, the JND stimuli levels examined in this study were between 11N and 26N to achieve safty and comfort. By repeatedly measuring the pulling force in different motor revolution numbers, we averaged and obtained the force stimuli, as shown in Figure5. The motor revolution numbers were 0.57 and 1.18 for 11N and 26N, respectively.

4.3 Task and Procedure

Participants wore GuideBand and perceived a pair of pulling force stimuli in a trial. They answered whether the levels of the stimuli were the same or not. If they were not sure about the answer, they could ask to play back the stimuli. Each pair of force stimuli were composed of a base and offset force level. There were four base (11N, 12N, 14N, 18N) and four offset force levels (0N, 2N, 4N, 8N), so 16 conditions were examined. The base and offset force levels increased exponentially, which complied with the JND standard [10, 23, 41, 56]. For 3D force guidance feedback, we examined the JND on each of the three axes, respectively. Due to symmetric perception on an axis, one of two force directions on an axis was randomly examined by the participants. For backward and forward force directions, the z-axis track was always above the the forearm, which means that it was upward, at zero degrees to the vertical. Furthermore, for stimuli in forward and backward, the pulling motor was moved to 50 and -50 degrees to the vertical, respectively. The stimuli order in each pair was randomized, and each condition was repeated once. Therefore, a total of 96 (= 3 (axes) × 16 (conditions) × 2(repetitions)) trials were examined for each participant. We asked them for feedback after the experiment. The study took about an hour.

4.4 Results and Discussion

The results of the JND study are shown in Figure 6. The aggregate fractions of responses that participants regarded the stimuli in pair as different force levels are shown. We observed that most participants could not distinguish the differences in the pairs with offset level 2N. For offset level 4N, most of the participants could discriminate the differences in the pairs including the base levels 11N, 12N and 14N. The exception is base level 18N. For offset level 8N, the pairs with all base levels are distinguishable. This is loosely consistent with Weber's law (constant = (offset stimulus intensity) / (base stimulus intensity)) that the pairs with the larger base force levels require the larger offset force levels to distinguish.

From post-study interviews, we oberved that some participants mentioned that when the force stimuli were very large, such as 26N, they could feel the reaction force from the circle tracks. However, they also supposed that this did not interfere with them distinguishing the stimuli. For force feedback on three axes, some participants mentioned that compared with the force stimuli for up/down and left/right, which were normal to the forearm, the force stimuli for backward/forward at 50 degrees to the vertical, which were composed of normal and tangential shear forces, seemed a bit more difficult to distinguish. However, based on the JND results, the participants had similar distinguishability for all three axes. To ensure the consistency among all three axes, the same base and offset levels commonly achieving high distinguishability are required. To avoid too strong of a pulling force to produce obvious reaction force, we choose base level 11N and offset level 4N for three-level force guidance. We fit a logarithmic function to the (Weber fraction = offset intensity/base intensity) versus the aggregated percentage of the data, and calculated the Weber fractions when 75% and 95% of participants can distinguish the difference and also the percentage of the chosen Weber fraction 0.36 (= 4/11) for each axis. For left/right (x-axis) (R^2 = 0.72), the Weber fractions with 75% and 95% JND are 0.29 and 0.46, and the fraction 0.36 with 85% JND. For up/down (y-axis) (R^2 = 0.70), the Weber fractions with 75% and 95% JND are 0.26 and 0.47, and the fraction 0.36 with 87% JND. For forward/backward (z-axis) (R^2 = 0.68), the Weber fractions with 75% and 95% JND are 0.28 and 0.47, and the fraction 0.36 with 85% JND. The chosen base and offset avoid obvious reaction force and maintain distinguishability (over 85% [10]). Therefore, levels (1, 2, 3) are (11N, 15N, 19N), respectively. Furthermore, the delays of levels (1, 2, 3) for the pulling motor procedure are (427ms, 489ms, 625ms), respectively, and for the whole pulling and releasing procedure are (1373ms, 1417ms, 1496ms), respectively.

5 GUIDANCE STUDY

We conducted this study to evaluate and compare the guidance performance between the state-of-the-art vibrotactile guidance method and GuideBand, and further verify whether GuideBand is more intuitive and requires less mental effort and cognitive load. We followed and modified the guidance concept for current vibrotactile guidance wristbands in [4] (Figure 7 (upper left)), which achieves 3D omnidirectional guidance on the forearm, for comparison.

5.1 Apparatus and Participants

A Vive Pro HMD was worn to display the VR scene with the guidance tasks and a Vive controller was held on the dominant hand. Earphones were worn and white noise was played to block the noise generated by the devices. 12 right-handed participants (6 female, 1 left-handed) aged 20-26 (mean: 23.67) were recruited. Although four of them had attended to the previous JND study, but more than one month had elapsed between the two studies. Four of the participants had not experienced VR before, while one had only a few experiences.

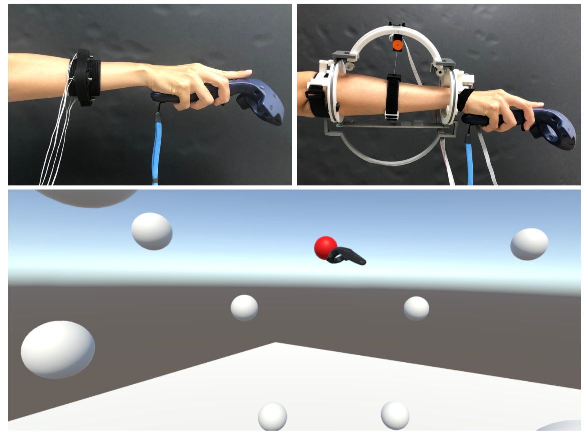

Figure 7: Vibrotactile (upper-left) and force (upper-right) guidance wristbands. Lower: The scene in the guidance study with twenty balls. A ball turns red when touched by the controller.

5.2 Guidance Methods

5.2.1 Vibrotactile Guidance. We implemented the vibrotactile guidance wristband based on the design in [4] using similar vibration actuators, which could provide the required patterns and frequencies. The wristband consists of four vibration motors (Precision Microdrives 310-002) at four positions, up (U), down (D), left (L), right (R), of the forearm. Vibrations from L and R guide users to move the hand toward left and right, respectively. The U and D vibration motors deliver upward/downward and forward/backward guidance, simultaneously. It leverages different U and D vibration intervals as guidance patterns to represent the directions on these two axes, respectively, at the same time. Furthermore, different vibration frequencies are used to represent distances toward a target. The farther distance to the target, the higher the frequencies are rendered. Four frequencies, 80Hz, 110Hz, 140Hz and 170 Hz, are presented in the ranges 0.1-0.15m, 0.15-0.25m, 0.25-0.4m and beyond 0.4m, respectively. If users move close to the target within 0.1m, the U and D vibration motors stop actuating.

5.2.2 Force Guidance. The GuideBand prototype was used and the guidance method is described in the previous section. For the target distance, similar to the vibrotactile guidance, the farther distance to the target, the stronger the pulling force is provided. Based on the JND study results, three instead of four levels 11N, 15N, and 19N, are presented in the ranges 0.1-0.15m, 0.15-0.25m and beyond 0.25m, respectively. When the distance between hand and target is less 0.1m, no pulling feedback is provided.

5.3 Task and Procedure

We conducted this study by following and modifying the study design in [29]. In a VR scene, 20 balls (radius: 0.1m) were distributed on 20 equidistant vortexes of a large invisible sphere (radius: 0.6m)

(Figure7 (lower)). In each task, participants were guided to select 10 random but not repeated target balls sequentially. When a ball was touched, it turned red. When it was selected as the target, the guidance cue of the next ball was rendered. There was no feedback to let the participants know whether the selected ball was correct. They were asked not to arbitrarily guess the target by touching every ball. A short audio clip was played after 10 balls were selected and the task was finished. They could take a break for up to 10 minutes to avoid any sense of fatigue.

In the beginning, the experimenter wore and calibrated the devices for each participant (Figure 7 (upper)). Furthermore, the invisible sphere with the 20 balls was adjusted to the proper height for each participant. The participants were introduced to the features and limitations of both devices. For the vibrotactile guidance, the vibration patterns were displayed. We illustrated the vibrotactile patterns with figures to help the participants to more easily understand and memorize the patterns. For GuideBand, force guidance cues in 12 directions (= 4 (directions on the xy-plane: 0°, 90°, 180°, 270°) × 3 (directions in z-axis: 50 °, 0 °, -50 °)) were rendered to the participants. The participants had a training session for 10 minutes, which was mainly used to provide more time for memorizing the vibrotactile patterns. They could ask to replay the cues in the introductions or practice in a training VR scene. In the training scene, there was only one red target ball. They held a Vive controller and moved their hand in different directions and distances to the ball to perceive the corresponding guidance cues. In the experiment, they pressed the trigger on the controller to select the targets.

A total of 60 (= 2 (guidance methods) × 10 (target balls) × 3 (repetitions)) trials were examined by each participant. The guidance methods were counterbalanced and target balls were randomized in each repetition. After finishing all tasks for one method, the participants wrote answers in response to a questionnaire to evaluate the experiences in terms of usability and satisfaction as in [11] (four items, such as "The process and experience of using this device are very good." Cronbach's alpha=.92), and cognitive load modified from NASA-TLX [24] (five items, such as "I made much effort to think, memorize and find during the task." Cronbach's alpha=.73). Responses were collected using a 7-point Likert scale. After finishing all tasks and questionnaires, participants were interviewed for some additional comments. The experiment took approximately 180 minutes including, the introduction, training sessions, breaks and interviews.

5.4 Results and Discussions

The quantitative data were analyzed using repeated measures ANOVA. The mean task completion time for the vibrotactile guidance is 686.8s (SD = 248.65), and for the force guidance is 589.79s (SD = 120.25) (Figure 8). No significant difference is found in task time ($F_{1,12} = 1.49, p = 0.25$). For accuracy, the vibrotactile guidance is 0.67 (SD = 0.15) and the force guidance is 0.84 (SD = 0.15). No significant difference is revealed ($F_{1,12} = 2.2, p = 0.16$). Therefore, compared with the state-of-the-art vibrotactile guidance, the force guidance from GuideBand has similar guidance performance in both task time and accuracy. In fact, GuideBand has even better performance but without significant difference.

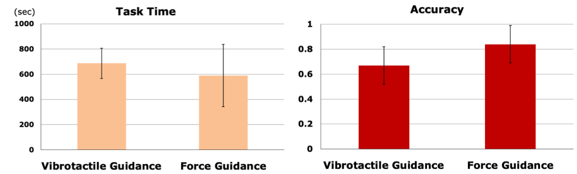

Figure 8: The results of task time and accuracy.

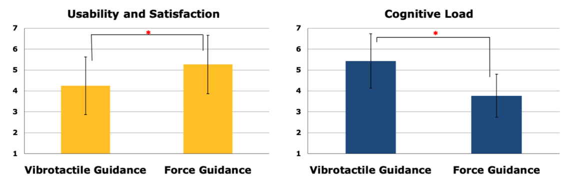

Figure 9: The results of usability and satisfaction, and cognitive load on a 7-point Likert scale.

For subjective evaluation in the 7-point Likert scale, the mean scores for usability and satisfaction are 4.25 points (SD = 1.4) and 5.27 points (SD = 1.38) in the vibrotactile and force guidance, respectively, (Figure 9). A significant difference is found in regard to usability and satisfaction ($F_{1,11} = 5.23, p < 0.05$). The mean scores for cognitive load are 5.43 points (SD = 1.03) and 3.77 points (SD = 1.3) for the vibrotactile and force guidance, respectively. A significant difference is found on cognitive load ($F_{1,11} = 27.39, p < 0.01$). Therefore, the force guidance from GuideBand is significantly easier to use, more satisfying and more intuitive than the vibrotactile guidance.

In our post-study interviews, we observed that since GuideBand delivered clearer directional information, especially in regard to the x and y axes, most participants preferred the guidance cues from GuideBand. They also mentioned that they did not have to pay much attention to learn the force guidance patterns. Some positive comments about GuideBand are as follows:
"The force guidance was more intuitive than the vibrotactile guidance with complicated patterns." (*P1*)
"I liked GuideBand more. I could easily feel the different pulling force levels and adjust the moving distance." (*P3*)
"I could feel the directional cues from GuideBand, and I could easily know where I should go in a moment." (*P4*).
"It was not necessary to learn how GuideBand worked, the direction cues were clear. It was intuitive to know the different force levels. When I felt stronger force, I moved further." (*P8*)

For the vibrotactile guidance, some of them agreed that guidance toward the left or right were clear enough and said that if they were given more time, they could learn the patterns better. In addition, the participants mentioned that using different vibration frequencies to notify the users of the target distances was helpful. Interestingly, some participants developed their own ways to complete the tasks without interpreting all patterns:
"Firstly, I distinguished which motor in left/right vibrated and decided the direction in left/right to move. Then I interpreted the vibration frequency (target distance cue) to test where I should move my hand.

(When moving toward the right direction, the vibration frequency reduced.) " (*P9*)
"I mostly relied on the vibration frequency to find my target. I tried to move to different directions and searched for the right one based on the vibration frequency."(*P10*)

Some participants felt confused when too many motors vibrated at the same time. Some of them mentioned that the motors vibrated over a wide range of their skin so they could not distinguish which motor vibrated. Others supposed that the different sides of their forearm had different sensitivity to vibrations, which might cause them to misunderstand the patterns. They described their confusions at feeling the vibration as follows:
"It was hard to know which motors vibrated. I was not sure whether the balls I selected were correct."(*P6*)
"If only one motor vibrated at once, I might be able to interpret it."(*P12*)

Based on these results, we understand that GuideBand provided clearer directional guidance cues to users, but did not achieve significant improvement in guidance task time as observed in this study. This may be due to the delay from the *xy*-motor and *z*-motor to move the pulling motor to the target position. We did mention the delay issue when introducting GuideBand to the participants. During the tasks, the participants needed to move slowly and wait for the updated force guidance cues. We also observed that in the comments of the participants as follows:
"The force guidance was easy to understand, but the latency was a little bit long." (*P2*)
"I needed to wait for the reaction from GuideBand to ensure where should I go next. I hoped that it could be faster."(*P3*)

However, some participants reported that they could learn how to coordinate with the latency properly. They correctly predicted when the delay occurred after they moved in order to follow the guidance cues from GuideBand smoothly:
"Because I knew that there was a delay for operation from GuideBand, it did not bother me during the task."(*P6*)
"It was confusing to get latency at the beginning, but it was not a problem later."(*P9*)

The advantage of the vibrotactile guidance is that it has less latency. Most participants said that the reaction of the vibrotactile guidance was immediate, and this matched their expectations. Although there is a large latency difference between the vibrotactile and force guidance, GuideBand was still rated as the more satisfying guidance method.

Although GuideBand is lightweight, but many participants mentioned that the size of the GuideBand prototype was a bit large. All participants agreed that the vibrotactile wristband was light and easy to wear and take off. However, considering the complicated patterns, GuideBand is still preferred.
"Even if raising my arm made me feel sore, it did not bother me to distinguish the directional information."(*P3*)
"GuideBand was heavier, but its advantage was that I could feel the directional cues during the whole task." (*P4*)
"I liked GuideBand more because it was more difficult to remember the vibration patterns."(*P6*)

Although the current GuideBand devices has several limitations such as latency and size, the intuitive designs for directional and distance guidance cues are appreciated and satisfying to most of users. The results show that GuideBand is more intuitive, requires a lower level of both mental effort and cognitive load, and achieves similar guidance performance to the vibrotactile guidance. This fulfills the intuition design considerations.

Figure 10: The VR scene includes the messy home office (upper), the *guidance hand* and the click board showing the Stroop test (lower).

6 VR EXPERIENCE STUDY

We performed a VR experience study to observe how the proposed force guidance enhances realism in VR guidance. Furthermore, we observed how users combined and complemented the visual and force guidance in the situations where visual guidance is temporarily unavailable [29], *e.g.*, visual attention is occupied by performing other tasks or the target is not in the FoV [22]. Since objective guidance performance was evaluated in the previous study, we focused on understanding users' VR experience and subjective opinions in this study.

6.1 Apparatus and Participants

In this study, the GuideBand device and the vibrotactile wristband in the previous study were used. Basically the apparatus was the same as in the previous study, except that music instead of white noise was played to block the audio feedback. 12 right-handed participants aged 22-27 (mean: 23.58) were recruited. Nine of them had participated in the previous study and were recruited again for reducing the training time regarding use of the two haptic guidance devices.

6.2 Task and procedure

Three guidance methods, including visual (V), vibrotactile (T) and force (F) guidance, were examined in this study. Visual guidance was displayed in all three methods, but the vibrotactile wristband and GuideBand device were only used in (T) and (F), respectively. To observe how users combined and complemented visual and haptic guidance, each task consisted of a main task and a sub-task. This simulated the situations that users paid most of visual attention to the main task and they performed a sub-task with guidance at the same time, *e.g.*, guiding users to find an electrical element while soldering, to fetch an object while driving, or to find a conversational target while doing telecollaborative work.

The sub-task required the participants to follow the guidance and fetch a target object in a messy home office in VR (Figure 10 (upper)). The home office size was $6m^2$ (2m × 3m) in the VR scene. The participants sit in front of a desk. There were two book shelves and one wall shelf around them. Many objects spread on the desk and in the book shelves. Based on the position of the Vive controller held by the participants, a virtual hand with a wristband was rendered. The wristband was further gripped by a translucent *guidance hand*. The guidance hand repeatedly pulled and released the wristband, guiding it toward a target object, which was glowing constantly (Figure 10 (lower)). The longer pulling distance was performed by the guidance hand, the farther target distance was indicated by the visual guidance. They needed to fetch six different target objects in each task. Three objects were placed 70cm away from the participants and the other three were 1m away, which could be easily reached if they stretched their arms. The objects' sizes and positions were different but similar among the three feedback methods to prevent learning effect.

The main task was a modified Stroop test [52]. A color name with a random font color was shown on a clipboard in the middle of the desk (*e.g.*, the word "yellow" with font color blue). The color name and font color were rendered randomly from a pool with five candidates, including purple, brown, red, blue and green, and updated every 2.5 seconds, respectively. The participants were required to count how many names of color matched the font colors.

During each task, the participants were asked to perform the main task and maintain an accuracy of above 75%. At the same time, they needed to follow the guidance to grab the target object by pressing and holding the trigger of the controller, and then placing it on a board near the clipboard by releasing the trigger. If the target object was grabbed, when the trigger was pressed, the guidance stopped and a short audio clip was played. When the target object was placed on the board, it disappeared, and the next guidance cue was rendered. Otherwise, the guidance cue to the same target object kept being provided. The order of the three guidance methods was counterbalanced. After experiencing each guidance method, the participants were asked to fill out a questionnaire modified from [31] to rate their experiences. Responses were collected using a 7-point Likert scale. After the entire experiment, the participants were interviewed regarding the process and acceptance about the features of the three guidance methods. The study took approximately 40 minutes.

6.3 Results and Discussions

The data collected from the post-study questionnaires were analyzed using repeated measures ANOVA. Significant main effects are

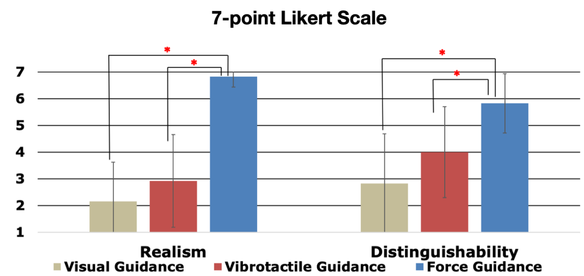

Figure 11: The results of realism and distinguishability in VR study.

found in regard to realism ($F_{2,13} = 40.17, p < 0.01$) and distinguishability ($F_{2,13} = 14.69, p < 0.01$). Post-hoc tests using Turkey HSD show that the mean score of 6.83 points (SD = 0.39) in force guidance was significantly higher than the mean score of 2.16 points (SD = 1.47) in visual guidance and the mean score of 2.92 points (SD = 1.73) in vibrotactile guidance in regard to realism (Figure 11). For distinguishability of target distances, post-hoc tests reveal that the mean score of 5.83 points (SD = 1.11) in force guidance was significantly higher than the mean score of 2.83 points (SD = 1.85) for visual guidance and the mean score of 4 points (SD = 1.7) for vibrotactile guidance.

For visual guidance, the participants said that they used their peripheral vision to search for the target objects. Some participants (*P1*, *P7* and *P8*) mentioned that it was very challenging and difficult to perform the main task with visual guidance. *P1* further said that s/he felt under pressure.

For force guidance, all participants expressed that GuideBand was their favorite. Some participants (*P4*, *P5*, *P6*, *P7* and *P8*) said that they totally relied on the force guidance from GuideBand instead of their own peripheral vision to search for the targets. When the force level became low, they glimpsed their hand position to ensure that they grabbed the correct object, since they knew that the target was nearby.

Participants described their process for performing the tasks as follows:

"When I wanted to get an object in the sub-task, I relied on force guidance for 80% of the time since it was clear. I only glanced at the target because I knew my target was there." (*P5*)

"I let GuideBand guide me so it was not necessary to keep searching for the targets. I only needed to see the target in a short time when my hand was about to get it." (*P8*)

For vibrotactile guidance, participants said that it was easy to distinguish the target on their left or right at the beginning. Some participants also used different vibration frequencies to know the target distance. However, they said that they could not interpret the patterns from up and down vibration motors, especially when they had to perform the main tasks. As a result, the participants still used their peripheral vision to search for the target, or very quickly switched their focus between searching for targets and the main tasks. The participants made some additional comments as follows:

"It was difficult for me to focus on the main task when interpreting the

patterns. Vibrotactile guidance cues for left and right directions were indeed helpful, but the other patterns were disturbance. Therefore, I searched for the target objects using visual guidance." (*P9*)

"I could only perceive vibrations from the left and right motors. For up or down directions, I relied on the guidance hand visual feedback. I might spend more time on these tasks without visual guidance." (*P10*)

"I only could know the directions to the left or right. I outstretched my arm to test where would reduce the vibration frequencies. That might be closer to the targets." (*P12*)

The participants reported that they felt it most realistic when experiencing force guidance among the three methods. *P10* said that *"There were several moments that I really felt that someone was pulling my hand. It was easy to map the animation of the guidance hand to the force feedback."* Some participants mentioned that the vibrotactile guidance interfered with their immersion and realism in VR. Therefore, five participants ranked vibrotactile guidance with the least realism although the results show that there is no significant difference between the visual and vibrotactile guidance. They even commented that the vibration bothered them when performing the main tasks.

"The vibration made my hands (forearms) uncomfortable and disturbed me a lot. I would rather choose the visual guidance." (*P8*)

Most participants mentioned that they enjoyed the experiences of the tasks. Half of them would like to try again. The participants also offered suggestions regarding some possible applications for GuideBand (*P3* and *P12*). They thought that GuideBand could provide clear guidance but not as strong as visual hints. Therefore, it could be used in room escape games for providing immersive aiding as from a real person. Based on the results and interviews, we realize how users combine and complement visual and force guidance, and did verify that force guidance from GuideBand enhances realism in VR guidance.

7 LIMITATIONS AND FUTURE WORK

Although GuideBand obtained quite positive comments in these studies, there are still some limitations. The size of the GuideBand device is a bit large and the latency is not ignorable. Although the current size is a defect, but it is still suitable for the interactions not close to the body or desk, like VR guidance for fetching objects, drawing, or posture correction for Tai Chi or rehabilitation, which is usually achieved by larger and heavier exoskeletons. Furthermore, since the GuideBand size is relative to users' arm size, it is feasible to use a smaller GuideBand device to provide the same force guidance for users with thinner arms. In this paper, we propose a proof-of-concept device and focus on exploring the proposed guidance interactions. We leave the downsize issue to future work, or even envision alternative methods, *e.g.*, tiny on-body robots [17], could achieve the same interactions. In addition, due to the support bar and wires, the z-axis track cannot rotate more than 180 degrees but needs to rotate reversely to the target positions. An improved hardware design might solve this problem. Since GuideBand delivers clear directional cues, it could solve the issues that users experienced presenting ambiguities when expressing 3D directional information in collaborations [36, 54]. We would like to explore how force guidance supports remote collaborations and communications in the future.

8 CONCLUSION

In this paper, we propose a wearable device, GuideBand, to provide intuitive 3D multilevel force guidance in VR. By pulling the wristband toward the target direction at the force level corresponding to the target distance, GuideBand achieves intuitive 3D force guidance with a relatively lightweight device when compared with exoskeletons or robotic arms. We conducted a JND study to understand that users can distinguish three pulling force levels (11N, 15N, 19N). Based on the results, we performed a 3D guidance study to prove that GuideBand is more intuitive, requires less mental effort and achieves similar or even better guidance performance compared with the state-of-the-art vibrotactile guidance. We further performed a VR experience study to explore how users combine and complement visual and force guidance, and verify that the force guidance from GuideBand enhances realism in VR guidance.

9 ACKNOWLEDGEMENTS

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