Pull Outperforms Push as Vibrotactile Wristband Feedback for Mid-Air Gesture Guidance

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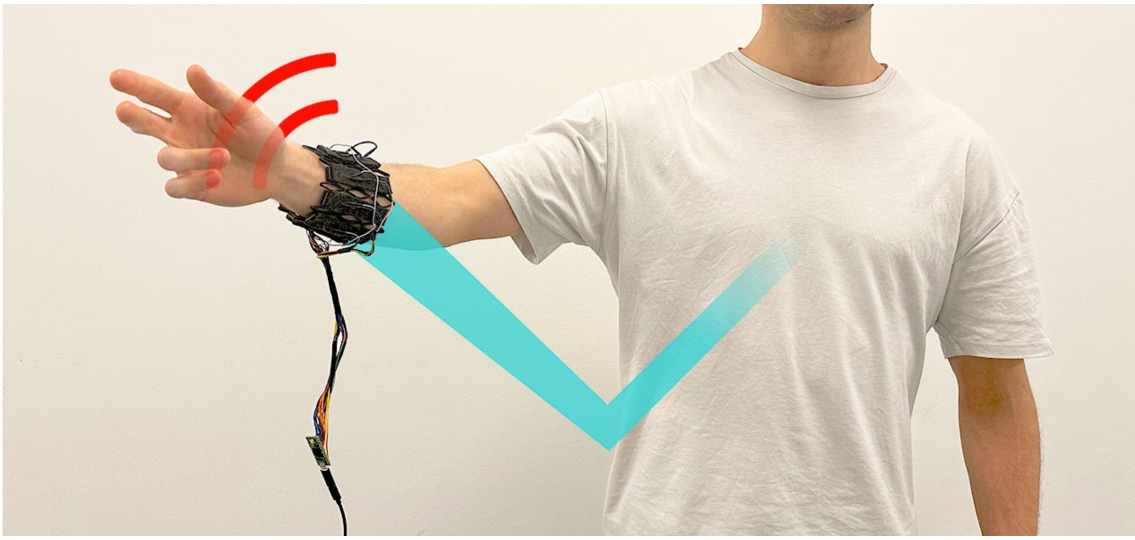

Fig. 1. Using a vibrotactile wristband for teaching gestures, it was investigated whether participants either want to be guided by a pull or a push metaphor. The pull metaphor would apply attractive stimuli in the direction where the user's hand should move. The push metaphor would apply repulsive stimuli on the opposite side, thereby pushing the user's hand towards their goal. This image visualizes the pull metaphor (red: origin of the vibration, cyan: gesture path so far).

The use of mid-air gestures to control interactive systems is becoming increasingly important, particularly in mixed reality scenarios. However, these gestures are not always intuitive and can be challenging to learn as they lack visual guidance. Therefore, it is crucial to explore strategies to improve the learnability of these gestures. In this work, it is investigated how a vibration stimulus can be applied at the forearm to guide a person in performing a gesture. Utilizing a prototypical wristband with 24 vibrotactile actuators, the metaphors pull and push, representing attractive and repulsive feedback, were compared against each other. Results of a controlled user study show that participants perform significantly better with the pull metaphor, completing gestures faster, and make fewer errors. In line with this, the majority stated a subjective preference towards pull after experiencing both metaphors.

CCS Concepts: • **Human-centered computing → Empirical studies in interaction design**; **Haptic devices**; *Gestural input*.

Additional Key Words and Phrases: Mid-Air Gestures, Guidance, Wristband, Haptic Feedback, Vibrotactile, Attractive and Repulsive Feedback

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1 INTRODUCTION

Gestures grow more and more in importance, as new technologies tend to break away from traditional button-based periphery devices, such as keyboard, mouse, and controllers. Especially, the rise of mobile and immersive technologies increased their prominence. One exemplary platform is the smartphone, that utilizes few but relevant gestures, especially swipe and pinch. A variant of gestures is the mid-air gesture, that is performed in three-dimensional space without a screen or similar as reference surface. Mid-air gestures are often utilized in immersive technologies such as Augmented and Virtual Reality. For example, the first generation HoloLens[1] Augmented Reality (AR) headset makes use of pinch gestures to select items and a bloom gesture to open up a menu.

When using gestures, there usually are no indicators that point at the existence or execution of a gesture. Therefore, users are required to keep the available gestures in mind. When gestures increase in complexity or deviate from common ones, it also becomes necessary for users to learn a gesture in the first place before they can perform it reliably. This process requires some form of guidance or tutorial, so that the user has an idea of how to move [17].

The common approach to providing guidance for mid-air gestures is through visual cues. These are for example used on external smartphones to explain commonly used gestures, but also more complex gestures can also be visualized [3, 7, 9]. This approach has the drawback of binding the users' attention to visual instructions and therefore potentially distracting them from the actual task. It is also possible to implement these visualizations using AR systems so that the user is less distracted by a remote screen. However, this approach has its limitations. For example, it typically involves a head-mounted display, but the weight and limited battery life of such devices currently pose a challenge for prolonged use. Although projectors can be used, their output often suffers from poor visibility in daylight conditions. Alternatively, audio cues can guide the user by describing the actions that need to be taken [29], this however can be annoying, difficult to incorporate in multitasking situations, and unsuitable for scenarios such as noisy locations. Lastly, users could be guided by haptic impulses that are placed directly on the body part that should be used for performing the gesture [1, 8, 10, 29]. Mid-air gestures that involve hand or arm movements can benefit from gesture tracking and guidance hardware that can be conveniently integrated into a wristband [1, 10, 13, 23, 25, 29]. In addition, haptic wristbands offer a practical solution for enabling gesture guidance in a variety of contexts, particularly as fitness wristbands and smartwatches continue to gain widespread adoption. Therefore, it is of importance to study how to best apply vibrotactile feedback on the wrist area.

In the case of applying vibrotactile feedback to the wrist and forearm of a user, the question remains as to how best to translate the guidance of a gesture into haptic impulses. One fundamental decision has to be made about the metaphor the guidance builds on. In this work, we investigate whether the signal should *pull* or *push* the user towards their goal. In the case of *pull*, the haptic stimuli are created on the side of the forearm that is also the direction the user should move, meaning it is attractive feedback. The inverse metaphor is *push*, which applies haptic stimuli at the opposite side, thereby shoving the user's arm away from the vibration towards the wanted direction, corresponding to repulsive feedback.

[1] https://www.microsoft.com/en-us/hololens

These fundamentally different approaches can be compared to scrolling with the mouse on Windows and macOS systems. In one system, moving the wheel down results in moving the view down, while in the other one, the same action results in the view moving up. In the case of this example, both metaphors can be justified, as these systems coexist with users on both ends, that can also relatively easy switch from one system to another. It remains to be researched if this is the case for vibrotactile feedback applied to the wrist and forearm for guidance, or if one metaphor outperforms the other.

Close to our work, Günther et al. conducted a comparison of *push* and *pull* metaphors using a vibrotactile glove, in which the attractive *pull* outperformed the repulsive *push* for basic hand movements in 3D space [8]. Since gloves tend to interfere with the hand's ability to touch, feel, and manipulate real-world objects, it makes even more sense to explore alternative body locations, such as the wrist and forearm, to provide guidance for mid-air gestures through tactile stimulation. People generally tend to have thicker wrists and forearms compared to their hands, therefore, this may also reduce a proximity problem that came up due to the anatomical characteristics of the human hand [8]. Further, other works suggest that preferences for attractive or repulsive feedback can be different depending on the body parts targeted. For example, in the cases of Tannert et al. and Lee et al. *push* was preferred when applied to the upper body [14, 27].

In this work, we conducted a controlled user study to compare the *pull* and *push* metaphors when applied to the wrist and forearm via a vibrotactile wristband during gesture execution. Our results show that participants who did not have a distinct predetermined preference for a particular metaphor prior to the study developed a clear *Subjective Preference* for the *pull* metaphor during guided gesture execution. This preference is supported by both quantitative and qualitative data showing that the *pull* metaphor is significantly more effective than the *push* metaphor across the metrics *Success Rate*, *Task Completion Time*, *System Usability*, and *Subjective Mental Load*. From these results, recommendations for designers and researchers are derived. Lastly, our results underline that preferences in vibrotactile feedback vary based on the body part that is targeted.

2 RELATED WORK

We discuss here three research directions that are related to this work. First, guidance systems are reviewed that use visual cues to guide the user. Afterward, works closer to our approach, using wristbands and haptic stimulation, are presented. This is followed by research focusing on the differences between attractive and repulsive feedback, as we do with the metaphors *pull* and *push*. Finally, related work is summarized and put in perspective to our work.

2.1 Visual Gesture Guidance

OctoPocus is a dynamic gesture guide developed by Bau and Mackay, helping to learn, execute and remember gesture sets [3]. It was originally applied to desktop computer systems. If a user holds the mouse button for a certain time, a map consisting of paths representing possible gestures is displayed on a screen. The user can then follow the gesture path with the cursor. Meanwhile, less likely gesture guide paths become thinner and finally disappear. OctoPocus was evaluated as advantageous compared to a classic marking menu.

Lucchese et al. proposed GestureCommander as a visual aid when performing gestures on a touchscreen [16]. While drawing the gesture on the screen, already drawn parts were corrected and the most likely gesture was feedbacked as a text in the screen corner. Similarly to OctoPocus, the possible outcomes in form of the text feedback were visible to the user while they were performing the gesture.

Henderson et al. investigated how mid-air gestures could be taught by transferring knowledge about gestures learned on a touchscreen to mid-air interactions [9]. Therefore, participants trained a gesture on a smartphone touchscreen and afterward performed the gestures in mid-air while holding the smartphone as a motion-gesture device. This procedure was compared to learning and performing gestures directly in mid-air. The authors claimed that the knowledge transfer works well, as results showed minimal difference between the approaches.

Rovelo et al. proposed an intelligent gesture guidance system to support mid-air gestures targeted at walk-up displays [20]. The available gestures were shown subdivided in posture sequences from which one leads to another, while showing the users' current pose and the step previously performed. Their approach was found to be more effective than providing a printed graphical guide to the full set of gestures. Again, similarly to OctoPocus [3] and GestureCommander [16], the benefit lies in the prediction of possible and exclusion of no longer possible gestures on the fly.

The OctoPocus system by Bau and Mackays [3] was adapted in 2021 by Fennedy et al. for 3D mid-air gestures in Virtual Reality (VR) [7]. In an evaluation, it was compared to a static crib-sheet of the available gestures presented in VR. The VR OctoPocus enabled participants to execute gestures faster and with more accuracy [7].

By providing visual cues to the user, all of these approaches attempt to make gestures easier to perform, easier to remember, or easier to represent the available gesture set. As visual cues can be distracting or – due to missing displays – unavailable in some situations, we try to utilize vibrotactile cues instead. Since our goal is to support mid-air gestures, the use of wristband is an interesting approach that has been researched in multiple variants in the past.

2.2 Haptic Guidance

Hong et al. researched haptic guidance via a wristband on a 2D touchscreen, addressing vision impaired users [10]. Therefore, the authors investigated how to set up such a wristband, comparing different conditions, like using 4 or 8 motors, activating a single actuator or interpolating between two actuators to communicate a direction. In a first study, single-actuator feedback and interpolated feedback were tested against each other. The single actuator turned out to be faster and more accurate. In the follow-up study, the single-actuator feedback with four actuators was faster, more accurate, and most preferred compared to the similar feedback provided by eight motors. As a tablet was used as a reference plane, participants were limited in the dimensions to move, compared to mid-air gestures.

Sergi et al. investigated guidance of the forearm with a vibrotactile bracelet, but in combination with visual cues [23]. They compared visually-guided trajectories to visuotactile-guided trajectories while using VR to represent a virtual arm and the direction of the target. Visuotactile guidance achieved better accuracy, while analysis suggested that increasing the number of stimulators could improve the communicated directionality. However, as the elbow was fixed on a table, only two degrees of freedom were available.

Stanley and Kuchenbecker compared different feedback techniques for turning a handle left or right [25]. Vibrating, dragging, squeezing, tapping, and twisting were tested as techniques. In addition, each feedback was presented in a steady and a pulsing variant. The authors concluded that the best combination for actuator and drive algorithm being dependent on the movement the user shall perform. However, the best overall performance was achieved by tapper actuators that were pulsing. In their outlook to applications such as sports and dance training, future research should examine tactile motion guidance in multiple-degree-of-freedom tasks – as we intend to do with this work. Instead of rotations, we focus on mid-air arm translations, therefore utilizing more degrees of freedom in comparison to the single one in the publication of Stanley and Kuchenbecker.

Using a wristband with four actuators placed around the wrist, Kronester et al. used vibrotactile feedback to enhance the perception of virtual objects during mid-air gestures [13]. Thereby, undetectable properties such as electricity, weight, and tension were incorporated in the haptic experience. Different vibration patterns were evaluated in a user study, indicating that especially the constant vibration condition was found to perform best.

In their work from 2016, Aggravi et al. studied collaboration in human-robot teams using haptic wrist guidance for urban search and rescue scenarios [1]. A robot guides the hand of the operator that is equipped with four vibration motors. The hand can either be guided along a predefined path or to a specific location. Especially the first task is similar to tasks used in this work. However, we are interested in exploring fundamentals of haptic guidance, in this case, what kind of metaphor is better suited to guide the user's hand.

Close to our work is the publication of Weber et al. from 2011, using the VibroTac wristband [22] to spatially guide a user's arm in the indicated directions [29]. The VibroTac wristband consists of six actuators equally distributed around the participant's wrist. In the study, participants should move the arm to the indicated place and rotate their arm afterward to a certain angle. As a guidance metaphor, the *pull* metaphor was used, providing feedback at the side of the arm where it should move towards. As it was not researched whether a *push* metaphor would have been a suitable alternative, we investigate the potential differences between the two in this work. Further, we research a different task scenario by omitting the final rotation but instead using more complex gestures consisting of two steps, thereby including a transition with direction change.

Alternatively to vibrotactile feedback, ultrasound [24] and pneumatics can be used [19] to guide mid-air gestures, each bringing their own benefits and drawbacks. The prototype developed by Tsai et al. generates the actual pulling force on the forearm by pulling the wristband in the desired directions using attached motors and strings, providing 3D multi-level force guidance [28]. However, these approaches are usually more costly and complex, while being less established than the use of vibrotactile actuators that are already existent in off-the-shelf devices such as smartwatches.

As presented, multiple researchers addressed the topic of haptic guidance through a wristband. Besides prototypical devices, there have also been developments of wristbands, which lean more towards products that can be used by other researchers or developers. Examples are VibroTac [22, 29], Myo [6], and Tasbi [18].

2.3 Attractive versus Repulsive Feedback

Besides the use of haptic feedback in general, research has been done on the mental model users have when being guided by haptic feedback. Therefore, multiple publications looked into the use of attractive feedback – pulling towards a goal – and repulsive feedback – pushing towards a goal.

Günther et al. embedded actuators in a glove for providing spatial guidance in 3D space [8]. They compared different amounts of actuators and especially investigated which metaphor is preferred by users. The task was for participants to move their hand towards an assigned area in front of them. Similar to our work, they compared attractive and repulsive feedback as the metaphors *pull* and *push* against each other. *Pull* performed better than *push* in almost every case. It was also found that a higher number of actuators can be beneficial, resulting in faster completion times. In line with the work by Günther et al., we compare the metaphors *pull* and *push*, but by using a wristband, which allows the hand of the user to be free, capable of touching, feeling, and exploring other objects.

Bark et al. guide user arm movements by providing vibration feedback at wrist and elbow in addition to visual cues [2]. In a study, participants had to align their arm position to movements shown as visual cues or visual combined with vibrotactile feedback. While participants preferred the additional modality, tracking results showed that it did not improve their performance. Further, attractive and repulsive tactile feedback were evaluated, but no strong preferences or performance differences could be found [2].

In their publication from 2021, Tannet et al. investigated how postural control can be guided by providing vibrotactile feedback [27]. Therefore, participants with closed eyes were confronted with attractive or repulsive feedback on their upper torso to adjust their body pose. Repulsive cues, that indicate an obstacle avoidance, appeared to be slightly superior compared to attractive stimuli in terms of sway parameters. This was also reflected in subjective feedback [27]. Similarly, Lee et al. explored how to emulate a remote expert guiding a local person's movement for motion instructions, for example in a therapeutic scenario [14]. Actuators were placed on the upper body, near the navel and the spine. They compared repulsive and attractive instructional cues, with repulsive resulting in the greatest correlation between expert and subject motion, the least amount of time delay, and the least amount of average tilt error. Subjective preference depended on the order in which the participants were confronted with a type of feedback, always preferring the latest one. Lastly, learning effects indicate that longer periods of using the system would lead to a better performance [14]. While the use case and is different from ours, the conclusion of repulsive feedback being perceived better than attractive feedback indicates that preferences differ depending on the body part the feedback is applied to. Therefore, it is of interest which metaphor is preferred when feedback is applied on wrist and forearm.

2.4 Summary and Delimitation

By reviewing related works, it can be stated that there exist multiple approaches for guiding gestures. While visual assistance systems [2, 3, 7, 9, 16, 20] help to remember, select, and execute gestures, they occupy the attention of the user, which might not be possible or wanted in all situations. Numerous works attempted at haptic guidance of gestures [1, 2, 8, 10, 13, 23, 25, 29] by applying vibrotactile cues at the arm, hand, and elbow. The degrees of freedom differ between works, ranging from one dimensions to completely free mid-air gestures. In many publications, there was a presumption of how the guidance should work, usually using attractive feedback in the form of a *pull*-like metaphor to convey information [29]. Some works, however, studied the differences between attractive and repulsive feedback [2, 8, 14, 27], concluding with different preferences depending on the scenario and body part. Closest to our approach is the work of Günther et al., using a glove device where *pull* outperformed *push*. To our knowledge, there has been no specific evaluation of guidance metaphors using vibrotactile wristbands that are placed on wrist and forearm. To examine the potential differences between metaphors more thoroughly, we compare mid-air gestures that do not consist of a single movement toward a point in space [1, 23, 25, 29], but of two movements with a change of direction as transition in between.

3 EVALUATION

A controlled lab study was conducted to determine what guidance metaphor better fits the task of performing mid-air gestures. For that case, a vibrotactile wristband provided attractive or repulsive feedback according to the both compared metaphors: *push* and *pull*.

3.1 Study Design

The evaluation followed a within-subject design. The independent variable is *Metaphor*. The variable *Metaphor* came with the types *Pull* and *Push*. *Pull* represents the application of stimuli at the area closest to the goal, thereby being pulled towards the correct direction as attractive feedback. *Push* describes the idea of the arm getting pushed towards the goal, by applying a stimulus on the area which is furthest away from the goal as repulsive feedback. Different *Gestures* were performed wearing the wristband. For *Gesture*, a path similar to a checkmark was used, consisting of two steps of different directions that must be performed subsequently and transitioned in between. It was transformed into

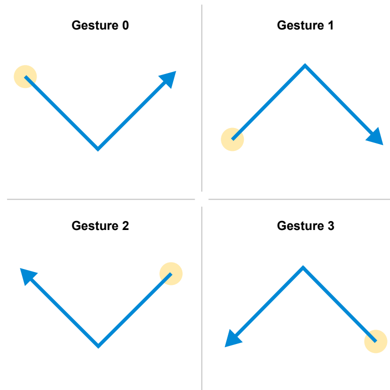

Fig. 2. The four variations of the gesture are derived from a basic check-mark inspired gesture.

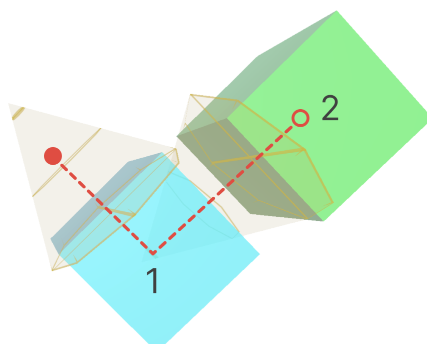

Fig. 3. Concept of the checkmark gesture in Unity (Gesture 0 in the left image). The red dashed line represents the ideal gesture path. 1 is the first checkpoint to be reached, 2 is the final checkpoint. The beige cones represent the allowed areas that still count as correctly performed gestures. They move with the user in the targeted direction. Leaving these areas will result in the execution being counted as not successful.

four variants by flipping it on different axes (vertical, horizontal, and diagonal), as shown in Figure 2. The resulting gestures resembled arrowheads pointing down (the classic checkmark), to the right, to the left, and up.

3.2 Measurements

As dependent variables, we measured both, quantitative and qualitative data. Participants were asked at the beginning of the evaluation about their expected *preference* or their expectation on how such a haptic guidance system would work. This question was repeated at the end of the study to determine if opinions had changed and to allow participants to state their *preference* after experiencing both metaphors.

The effectiveness of a *Metaphor* was measured as *Success Rate (SR)*, describing if a gesture was completed within tolerable boundaries (described in section 3.4). Moreover, for task efficiency, the *Task Completion Time (TCT)* was logged. *System Usability (SU)* was measured with the System Usability Scale (SUS) questionnaire [4]. In addition, we measured

Subjective Mental Load (SML) of participants using the Subjective Mental Effort Questionnaire (SMEQ) [30], as it was shown that it can be a suitable addition to usability questionnaires [21].

For qualitative results, participants had the opportunity to provide feedback on what they liked and disliked after completing all tasks for one guidance metaphor. Both guidance metaphors could be commented on. However, this kind of feedback was optional.

3.3 Apparatus

The setup consisted of a wristband connected by cable to a computer running a Unity application that managed tracking, calculated gesture completion, and organized task conditions. A visualization of the apparatus in action is shown in Figure 1.

3.3.1 Wristband. The wristband used in the study is depicted in Figure 4, which shows the physical setup and its virtual representation. It consisted of 24 actuators[2] that were arranged in a 3x8 pattern around the forearm. Actuators were in direct contact with the participant's skin. The horizontal housings held 8 actuators each and were 3D printed with flexible connectors between each actuator element. This allowed the wristband to be flexible for different arm circumferences. The three segments were arranged one behind the other and connected with felt to dampen the vibrations emanating from an actuator and prevent them from being transmitted to the entire wristband. The felt further partly covered and protected the wiring.

The actuators were controlled by a Teensy 4.0 microcontroller[3] and could be driven independently with PWM signals. The microcontroller could be connected to a computer over micro-USB and programmed with Arduino code. Outside the Arduino environment, the wristband could receive data as JSON to access actuators.

3.3.2 Tracking and Software. Tracking of the physical wristband was solved with external lighthouse tracking, normally used for VR scenarios. The full setup is displayed in Figure 4. A VIVE tracker[4] was mounted on top of the wristband to find its location in three-dimensional space. The tracking system was tested in a pre-study and supervised during the actual study. It did not show any signs of malfunction or deviations. Further, an additional VIVE controller was provided, so that the participant could start the gesture guidance with the main trigger.

To control and utilize the wristband, we implemented an application in Unity[5]. With the start of gesture guidance, a prefab consisting of checkpoint and boundary cone, representing the direction and allowed area in which the first part of the gesture shall be performed, was instantiated, see Figure 3. The segment of the wristband closest towards the checkpoint center provided haptic impulses (inverse in the case of *push*). For that purpose, all three actuators of the segment were activated at full power. Different methods for interpolation between two segments were tested, with the goal that the directional instructions feel seamless and point towards areas in between segments. Interpolation use was tested in an informal pre-study by multiple researchers. While the feedback felt smoother, it was uncertain if there was an actual benefit for more precise guidance. In contrary, it appeared that the increased vibration area led to imprecision. Therefore, we did follow the guidelines of Stanley and Kuchenbecker to omit any kind of interpolation [25]. By using 8 segments, which each occupy 45 degree of the total 360 degree, the maximum guidance error that could occur without interpolation would be a misdirection of 22.5 degree.

[2]ERM coin vibration motors by Garosa (rated voltage: 3.0V DC, rated rotational speed: 11000 ± 2500 rpm, rated current: 80mA max, diameter: 10mm)
[3]https://www.pjrc.com/teensy/
[4]https://www.vive.com/accessory/tracker3/
[5]https://unity.com/ (version: 2021.3.6f1)

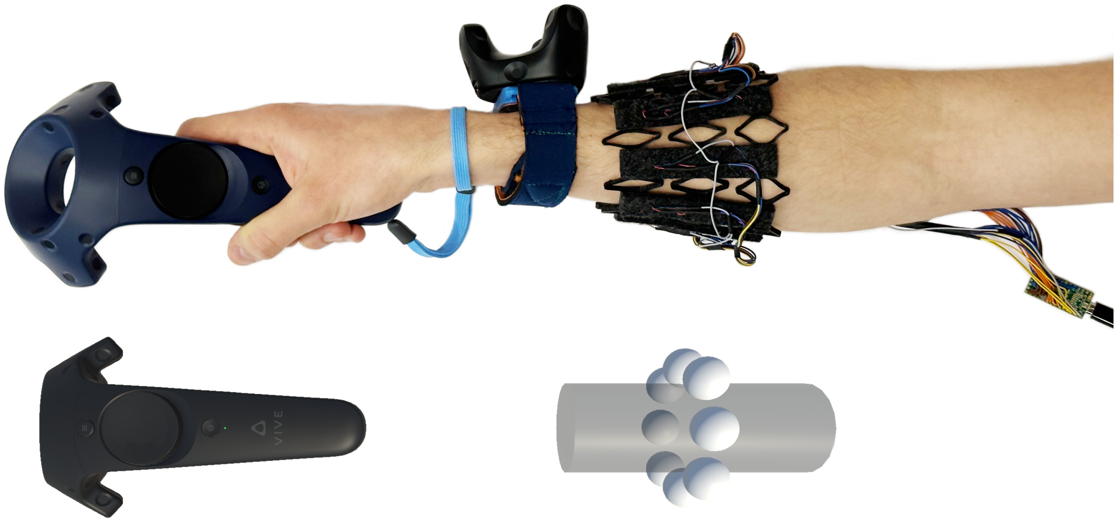

Fig. 4. Tracking setup at the participant's arm. *From left to right:* The participant holds a VIVE controller in their hand to trigger the gesture (below, virtual twin in scene). Near their wrist, a VIVE tracker is mounted, which allows to track the wristband position. The vibrotactile wristband is placed in the center of their forearm (below, virtual twin in scene with spheres representing each segment). The wires lead from the individual actuators to the Teensy controller operating the wristband actuators.

Upon reaching the first checkpoint, a second checkpoint was created, along with a boundary cone. Subsequently, the wristband guidance reoriented itself towards the new goal. The newly created checkpoint and its cone are in motion for the first moments after the participant reached the first checkpoint. This brief period of motion can be attributed to the participant needing time to interpret the new direction after the switch in haptic guidance. The movement of the second checkpoint stopped as soon as the participant made a 45-degree turn in the new direction. Given that the checkmark-like gesture was inspired by its two-dimensional representation, it was understood as a 2D gesture in 3D space. Consequently, the checkpoints and cones aligned themselves on a virtual plane that was established in front of the participant as soon as the gesture was initiated. A visualization of this complete conceptual gesture representation is depicted in Figure 3.

3.4 Task

Participants were instructed to perform a gesture with their right arm while standing. The checkmark gesture was chosen because it is commonly used and can be performed as a mid-air gesture. To avoid unwanted learning effects, the gesture was transformed into four variants by flipping it on different axes, as shown in Figure 2.

To perform a task, participants needed to press the main trigger on the VR controller to start the haptic guidance. The goal was to complete the felt gesture as precise as possible while staying in the boundaries. No visual clues were given, only haptic guidance was provided. If the task was completed successfully, a confirmation sound was played and the vibration stopped. A task was logged as successful, if it was performed inside boundaries with a deviation radius of 35 cm to the ideal line and has not taken longer than 10 seconds per segment (counting the transition time between the first part of the gesture and the second part as its own segment - making 3 segments total).

3.5 Participants

We recruited 20 participants (11 male, 9 female) aged between 20 and 26 years (M = 22.6, SD = 1.46) for the study. All participants reported being right-handed, and none of them reported any perceptual impairments or physical disabilities that could potentially affect their performance in the study.

3.6 Procedure

The study began with participants providing informed consent and completing a demographic questionnaire. Afterward, participants were asked to indicate their expected preference for either the *pull* or *push* metaphor. The wristband was placed in the middle of each participant's forearm, along the area between the elbow and the wrist. The VIVE tracker was placed directly in front of it, as shown in Figure 4. For adjustment, the upper segment vibration was activated, and the participant was asked if it felt like applying feedback to the upward side of the forearm. One of the metaphors was chosen to be used as the first technique in a counterbalanced order to ensure that both metaphors were used an equal number of times as the first and second techniques. For each metaphor, the participant received a tutorial in which a static stimulus was applied to the forearm at the top, left, right, or bottom. In accordance with the guidance metaphor employed at the beginning, participants were required to interpret the direction of movement required.

Once the participant confirmed that they understood the input, they were given the following instructions for the task: They should hold their arm casually in front, without stretching it completely straight or angling it by 90 degrees. The gesture should be performed as if they would draw a 2D gesture in mid-air on an imaginary canvas in front of them. Lastly, the rotation of the arm, hand, or wrist should be avoided as much as possible.

Afterward, the actual tasks began with one metaphor and were repeated for the other. The participant had to execute the gesture variations based on the vibrotactile guidance by using the selected metaphor. Each variant was tested exactly 3 times per metaphor, resulting in a total of 12 gestures to be performed per metaphor. To further reduce any unwanted learning effects, the order of these 12 gestures was randomized. In total, each participant performed 24 gestures over the course of the study.

After the completion of a guidance metaphor, the participant was asked to fill in a SUS questionnaire and draw a mark on the SMEQ form. Further, qualitative measures were derived in the form of a semi-structured interview. In the final part of the study, participants were prompted again about their preferences of guidance metaphor.

4 RESULTS

The present study yielded both quantitative results, obtained from measurements of participants' gestures and evaluations of questionnaires, and qualitative results, based on their feedback to questions about the tested metaphors. In the following, these results will be presented and examined in detail.

4.1 Quantitative Results

In this subsection, we present the numerical results obtained from our study. These results are divided into further subsections based on the different aspects of our study, including Preference, Success Rate (SR), Task Completion Time (TCT), System Usability (SU), and Subjective Mental Load (SML).

4.1.1 Preference. Before participants conducted any task, the preferences and expected preferences for a metaphor were perfectly balanced, with 8 participants leaning toward *pull*, 8 participants leaning toward *push*, and 4 participants indicating they had no preference. At the conclusion of the study, 18 participants expressed a preference for the *pull*

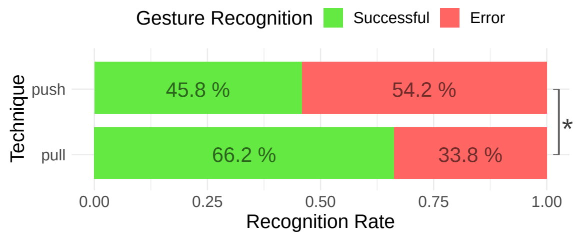

Fig. 5. Success rate of gesture recognition for push and pull. Gestures performed while being guided by pull result in significantly more successful trials.

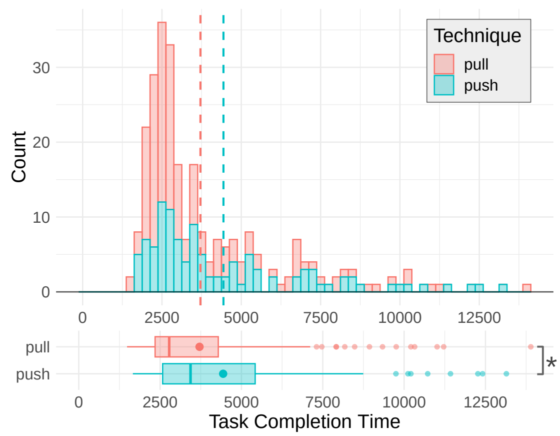

Fig. 6. Time in milliseconds required for successfully recognized gestures between the two tested metaphors (*top*: histogram with stacked bars and dashed lines for means; *bottom*: corresponding boxplot).

metaphor, while only 2 participants preferred the *push* metaphor. Notably, participants who changed their preference during the study only shifted towards the *pull* metaphor. The remaining 2 participants who still preferred the *push* metaphor at the end of the study had also preferred it at the beginning. A neutral response was not allowed in the final assessment.

4.1.2 Success Rate. To examine the effectiveness of the two guidance metaphors, we looked at gesture recognition success rates. In the *pull* guidance metaphor condition, the system correctly recognized 159 out of 240 gestures with 81 errors, resulting in a SR of 66.2%. In contrast, the system correctly recognized 110 out of 240 gestures and rated 130 gestures as errors when participants were given the *push* guidance metaphor, resulting in a SR of 45.8%. To compare the effectiveness of the two guidance metaphors on gesture recognition success, we performed an exact McNemar's test. The results indicated a significant difference between the two guidance metaphors ($p < .001$), see Figure 5.

4.1.3 Task Completion Time. To investigate the completion time of our task, we first conducted Wilcoxon signed-rank tests to compare the time taken for successfully recognized gestures between the two tested metaphors. The analysis revealed a significant difference ($z = -2.776$, $p = .006$) in the completion time for successful gestures between the *push* and *pull* metaphors. Specifically, the completion time for successful gestures was significantly shorter when the *pull*

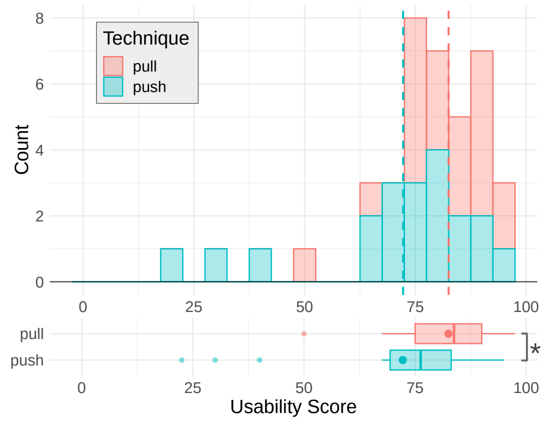

Fig. 7. Distribution of SUS scores for the perceived level of usability experienced by the participants while using each metaphor (*top*: histogram with stacked bars and dashed lines for means; *bottom*: corresponding boxplot).

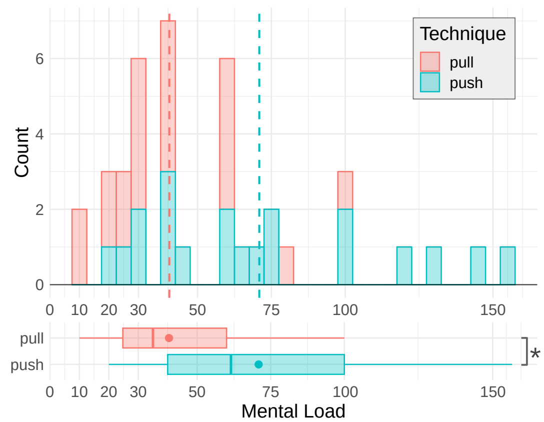

Fig. 8. Distribution of SMEQ scores for the level of mental load experienced by the participants while using each metaphor (*top*: histogram with stacked bars and dashed lines for means; *bottom*: corresponding boxplot).

metaphor (M = 3712 ms, SD = 2234) was used than when the *push* metaphor (M = 4438 ms, SD = 2644) was used, see Figure 6.

4.1.4 Usability. To compare the two guidance metaphors in terms of usability, all participants completed the SUS questionnaire for each metaphor. Participants rated the *pull* metaphor with a higher median SUS score of 83.8 (range: 50 – 97.5) compared to the *push* metaphor with a median SUS score of 76.2 (range: 72.5 – 95). The mean SUS score for the *pull* metaphor with 82.5 (SD = 11.3) was also higher than the mean SUS score for the *push* metaphor with 72.2 (SD = 19.8). Figure 7 shows the distribution of SUS scores for both guidance metaphors. The difference in mean SUS scores between the two systems was statistically significant ($t(19) = 3.4269$, $p = .003$), indicating that *pull* was perceived to be more usable than *push*. The effect size of the difference in SUS scores between *pull* and *push* was 10.26 ($d = .766$). According to Cohen, this difference is considered medium [5].

4.1.5 Mental Load. The mental load of participants using the *pull* and *push* metaphors was compared by analyzing the SMEQ scores. The mean SMEQ score for the *pull* metaphor was 40.4 (SD = 23.3), while the mean SMEQ score for the *push* metaphor was 70.9 (SD = 41.3). A paired t-test was conducted to compare the SMEQ scores between *pull* and *push*. The results showed that the mean SMEQ score for *pull* was significantly lower than the mean SMEQ score for *push* ($t(19) = -4.780$, $p < .001$). Figure 8 shows the distribution of SMEQ scores for both *pull* and *push*. The effect size of the difference in SMEQ scores between *pull* and *push* was -30.45 (d = 1.069). This difference is large, according to Cohen [5].

4.2 Qualitative Results

Since feedback on the guidance metaphor was optional and respondents were allowed to respond twice per metaphor, a total of 78 comments were collected (out of 80 possible comments). Of these, 4 were removed due to not being a valid answer to the asked question, leaving a total of 74 valid responses. The obtained data was coded using Grounded Theory [26]. We used axial and selective coding, starting with categories structured according to the questions about what participants liked and what they disliked.

The coding was done individually by two researchers. In a subsequent discussion, they consented to a unified code book, which was then used to again individually re-code all statements. Lastly, differently coded answers were discussed and agreed upon. The qualitative results are presented in the following, structured by the questions asked. The codes created during the coding phase are highlighted in *italic*.

We first report the qualitative result for the *pull* metaphor, which outperformed the *push* metaphor in the quantitative analyses for Preference, Success Rate, Task Completion Time, System Usability, and Subjective Mental Load, followed by the results for the *push* metaphor.

4.2.1 Positive feedback to Pull. The majority of participants (n = 15) appreciated the clear *guidance* provided by the system when using the pull technique ("It taught me well the gestures or the direction of the gestures to make.", P11; "It supported me well, I could just follow the vibration.", P20). Some participants (n = 3) also appreciated the *intuitiveness* of performing gestures using the pull technique ("It felt more natural to push in the direction of the vibration. Very intuitive use", P10; "I was able to perform movements by feel and intuitively", P21). Participants further reported experiencing *learning effects* (n = 2) or being able to adapt (*adjustment*, n = 1) quickly to the pull technique ("At first it was a little strange, but after 2 or 3 gestures you could get used to it and let yourself be guided by the vibrations.", P7). This feedback was mixed with a slight criticism regarding *uncertainty* (n = 1) ("Has helped quite well, only sometimes still confusing with the exact direction. Takes a little getting used to, but then very good.", P5). Using the field to provide critical feedback, seven participants indicated that they did not perceive any noticeable obstruction (*no obstruction*, n = 7) from the pull technique ("Has not obstructed me.", P8; "Not at all, pull was rather helpful.", P3).

4.2.2 Criticism on Pull. The majority of negative comments were related to *uncertainty* (n = 5) or *inaccuracy* (n = 3), especially in *localization* of the vibration origin (n = 4) ("At first, I was not one hundred percent sure whether the vertical or the horizontal was vibrating.", P5; "It was difficult to feel the exact location of the vibration.", P6). Three participants reported learning effects (n = 3), one of which was directly related to gesture guidance (n = 1) ("The diagonals are somewhat confusing, but can be quickly understood.", P12; "It takes a few unsuccessful attempts for the gesture guidance to be understood.", P2). In addition, a few participants reported difficulties related to physical load (n = 1) and spatial constraints (n = 1) ("The arm feels strange because of the constant vibration.", P1; "A lack of awareness of just how big the 3D space really is.", P19). There was also one participant who made a criticism that is interpreted as a recommendation (n = 1) for further improvement of the system ("The vibrations changed direction quickly.", P0).

4.2.3 *Positive feedback on Push.*

Just over half of the participants (n = 12) appreciated the clear instructions provided by the system when using the push technique ("Guided me in the execution of the gesture.", P12; "Vibration feedback sent clear directional signals.", P17). Participants reported experiencing *learning effects* (n = 2) or being able to adapt (*adjustment*, n = 1) quickly to the push technique ("Once the system was explained, it was very clear how to use it. It has guided the directions through push.", P11; "It was different from the pull version because you had to rethink and were tempted to go with the vibration. But it got easier from gesture to gesture.", P7). Regarding *localization* (n = 2) of vibrations, there were two comments made by the participants ("The vibration was clear.", P14; "Vibration was more noticeable.", P19). A comment from one of the participants can be attributed as both *recommendation* (n = 1) and *intuitiveness* (n = 1) ("With shorter and longer, lighter and stronger feedback, you could estimate relatively accurately which direction to move the controller.", P10).

4.2.4 *Criticism on Push.*

Participants provided negative feedback about the push technique, with *uncertainty* (n = 7) being the category that received the most negative comments ("It is sometimes confusing when you are sure and end up being wrong.", P5; "The change in direction was a little confusing.", P3). Some participants reported that they had difficulty *adjusting* (n = 5) to this metaphor ("It was harder to adjust my thinking and I wanted to move more toward vibration.", P21; "I was confused by the change in thinking that I now had to counteract.", P7). In addition, participants reported difficulties with the *localization* (n = 5) of the vibration position during the use of the push technique ("Sometimes I am not sure which direction the vibration indicates.", P0; "It was difficult to determine exactly where it was vibrating.", P6). Some participants also criticized the *intuitiveness* (n = 3) of the metaphor ("[...] In general, this seems a little more counter-intuitive than the other experiment.", P17; "Pushing was not very intuitive without explanation. [...].", P11). There were also reports of *spatial constraints* (n = 3) from some participants ("Obstructed in the sense of an invisible wall.", P18; "Sometimes it felt like short bursts were coming from two different directions, and it can be difficult to move on the plane without moving the body when you want to move to the non-operating arm.", P10). Additionally, one comment was categorized as *inaccuracy* (n = 1), another comment was categorized as *physical load* (n = 1), and a third comment was categorized as *guidance* (n = 1) ("Inaccurate where the vibration originated.", P1; "Was a little heavy on the arm in the long run, [...].", P14; "I always felt that I was following the vibration, but the gesture was considered wrong.", P20). A response made by one of the participants can be interpreted as a *recommendation* (n = 1) ("The vibration intensity is always the same. If it decreases the closer you get to the object, it would be more intuitive to use.", P2). Only two participants reported experiencing *no obstruction* (n = 2) for this metaphor. Using the answer field for positive feedback, a few participants (n = 3) also mentioned the *uncertainty* of performing gestures with the pull technique ("It left me a little confused, but mostly supportive.", P15; "Again, not sure in which direction.", P5).

4.2.5 *Summary.*

Our quantitative results show that the *pull* metaphor significantly outperformed the *push* metaphor. These results are consistent with the overall preference of participants for the *pull* metaphor after the conclusion of the study. Our qualitative results confirm the quantitative results and contribute to a better understanding of them.

5 DISCUSSION

In this study, we investigated two guidance metaphors, *pull* and *push*, for guiding mid-air gestures using vibrotactile feedback on the forearm via a wristband. Our quantitative and qualitative results resented in section 4 are interpreted and discussed in the following.

5.1 Pull is Preferred and Perceived as Less Confusing

The *pull* metaphor clearly outperforms the *push* metaphor in every measurement taken in this user study (success rate, mental load, usability, task completion time). These results are supported by the qualitative feedback. When asked what aspects of the guidance hindered the performance of the gesture, 35% (7 out of 20) of participants reported no obstruction when using the *pull* metaphor, whereas only 10% (2 out of 20) had no criticism when using the *push* metaphor. Furthermore, when looking at the combined questions regarding the *push* metaphor, 45% (9 out of 20) of the participants made a total of 11 comments about uncertainty caused by confusion. On the other hand, only 24% (5 out of 20) of the participants mentioned uncertainty for the *pull* metaphor in 6 comments. These may have contributed to the higher mental load and lower usability ratings for *push*. It can be concluded that *pull* appears to be less confusing since it does not require reinterpretation of feedback and is closer to the expectations and mental models of users how a vibrotactile guidance at the wrist could work.

In addition to the quantitative analysis and qualitative responses, the vast majority of participants (90%, 18 out of 20) indicated a preference for the *pull* metaphor after completing the study. This is particularly striking given that prior to participating in the study, participants were split between the two options, with some indicating that they were unable to decide which they expected to prefer. It's worth noting that participants were first asked about their preference before testing out the wristband. This may have influenced their initial preferences and expectations, since participants could have imagined the vibrotactile feedback differently than it actually felt.

Despite the clear advantages of *pull* that the quantitative data showed, it should be regarded that there remain personal preferences that deviate from the majority. After the study concluded, two participants (out of 20, 10%) named *push* as their preferred option. There is a chance that, just like the example of the scrolling metaphor in Windows versus macOS introduced in section 1, *pull* should not be omitted and can be an alternative for some users.

5.2 Results are valid for Vibrotactile Feedback at the Wrist

These results and the interpretation of such are in line with the study conducted by Günther et al. [8] on vibrotactile gloves. We extend the previous research by combining arm movements with a change of direction as a transition in between, which better represents common mid-air gestures such as drawing a checkmark sign. By targeting the wrist and forearm, this allows the hand, which is one of the most important tools in everyday life, to be free from obstructions such as a glove.

One motivation for this work was the existence of different preferences for attractive or repulsive feedback depending on the body part that was targeted. While Günther et al. state similar findings as we do, works in which actuators were attached to the upper body showed preferences for repulsive feedback [14, 27]. One explanation for this could be that the mental models are different based on the scenario. In pointing and guidance tasks in which the hand, wrist, or arm are targeted, users expect attractive feedback as the goal position pulling the limb. In contrary, when applying feedback on the torso, users rather associate another person assisting and adjusting their posture, thereby expecting the repulsive guidance of a gentle push towards another state. In the work of Bark et al. feedback was applied at the wrist and the elbow, resulting in no noticeable preferences nor measurable differences between the two types of feedback [2]. This possibly hints at applying feedback to wrist and elbow being closer to the scenario of a person holding and moving the arm at the elbow towards a goal.

5.3 Recommendation

Based on the results of the study, we strongly recommend the *pull* metaphor as the default technique for vibrotactile feedback at the forearm in the context of guiding mid-air gestures. However, it should be kept in mind that personal preferences could vary.

6 LIMITATIONS & FUTURE WORK

This work had several limitations and opportunities for further research that are described in the following. The user study investigated arm movements by tracking the forearm near the wrist. However, people naturally tend to perform gestures with their hands utilizing the flexible wrist joint, as it is the most versatile [15]. Known mid-air gestures, such as the pinch gesture on the HoloLens device family, work as hand gestures instead of sweeping arm gestures. This case could not be studied in the evaluation, as the wristband only supports whole arm movements and accordingly participants needed to perform gestures this way.

Tracking of wristband position was solved with external lighthouse tracking because of its high accuracy. Further, the wristband was connected by cable to a laptop. These limitations resulted in the setup not being self-contained and therefore not suitable for actual use in the real world.

The investigated gestures only consisted of two individual movements. While this is a higher complexity than only moving to a certain point in space, often used in related work [1, 23, 25, 29], this still represents a limited complexity. The gestures were performed in mid-air, but were designed to be aligned with imaginary planes in front of the participants. The mapping of gestures onto a curved plane in front of the user, the use of the third dimension in z-direction (depth), and the gesture-dependent rotation of the participant's wrist have not yet been investigated.

Since the focus was on the guidance metaphors *pull* and *push*, only continuous feedback was prototyped. Alternative patterns could further improve the overall guidance experience. For actual use of the wristband for gesture training, the speed of gesture completion and the accuracy of the gesture path may be an aspect worth investigating.

The majority of limitations can be directly translated into research tasks for future work. For example, further engineering is required to transfer the static study setup to a self-contained wristband that tracks its rotation and position itself. While interpolation techniques were experimented with, a comprehensive study of their use, benefits, and drawbacks could be of interest. Another study related example would be the addition of a third dimension, and the guidance towards different rotation positions in combination with the so far investigated position guidance in two dimensions. Lastly, future research could be done on dual wielding wristbands for guiding mid-air gestures performed with multiple arms.

The insights gained in this work can also be applied to other application areas than gesture guidance. The aspect of collaboration was studied in related work [1, 11, 12]. It remains to be investigated how to utilize a vibrotactile wristband in unidirectional and bidirectional collaboration scenarios.

7 CONCLUSION

A user study was conducted in a controlled lab environment to investigate whether users rather prefer to be guided by a vibrotactile wristband using a *pull* or a *push* metaphor, representing attractive and repulsive feedback. The evaluation was done by participants performing checkmark-inspired mid-air gestures with their arm. Quantitative results indicate that the difference between metaphors was significant for Subjective Preference, Success Rate, Task Completion Time, System Usability, and Subjective Mental Load in favor of *pull*. While the expected preferences of the participants were split prior to the study, the vast majority of participants expressed a preference for *pull* after the study. We are therefore confident in recommending the use of the *pull* metaphor as the default technique for vibrotactile wristbands to provide guidance for mid-air gestures.

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