Evaluating Wrist-Based Haptic Feedback for Non-Visual Target Finding and Path Tracing on a 2D Surface

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ABSTRACT

Precisely guiding a blind person's hand can be useful for a range of applications from tracing printed text to learning and understanding shapes and gestures. In this paper, we evaluate wrist-worn haptics as a directional hand guide. We implemented and evaluated the following haptic wristband variations: (1) *four* versus *eight* vibromotor designs; (2) vibration from only a *single* motor at a time versus from two adjacent motors using *interpolation*. To evaluate our designs, we conducted two studies: Study 1 (*N*=13, 2 blind) showed that participants could non-visually find targets and trace paths more quickly and accurately with single-motor feedback than with interpolated feedback, particularly when only four motors were used. Study 2 (*N*=14 blind or visually impaired participants) found that single-motor feedback with four motors was faster, more accurate, and most preferred compared to similar feedback with eight motors. We derive implications for the design of wrist-worn directional haptic feedback and discuss future work.

CCS Concepts

Human-centered computing→Accessibility→Empirical Studies in Accessibility

Keywords

Haptic feedback; haptic wristband; blind user; wearable computing; accessibility.

1. INTRODUCTION

Directional hand guidance can be useful for a range of everyday activities for people who are blind and visually impaired (VI), such as physically tracing printed text to hear text-to-speech output [36, 37], learning handwriting [4] and touchscreen gestures [26], and understanding shapes [13]. To provide this guidance, researchers have explored both audio feedback, such as sonification and verbal guidance [26], as well as haptics, such as finger-mounted vibromotors [36, 37] or force feedback [13].

Smartwatches present new opportunities for directional hand guidance that is proximal to the hand yet embedded unobtrusively into an existing general-purpose device. For example, haptic motors around the wrist, as shown in Figure 1, may be useful for guiding a blind user's hand on a 2D surface. However, how to design this guidance is an open question. While placing a larger number of haptic actuators around the wrist may offer more precise feedback, it also increases the physical weight and complexity of the device. At the same time, fewer motors may still be useful, particularly if it is possible to create *phantom sensations*, where two closely-placed motors vibrating at once create the perception of a single vibration located between the two [2].

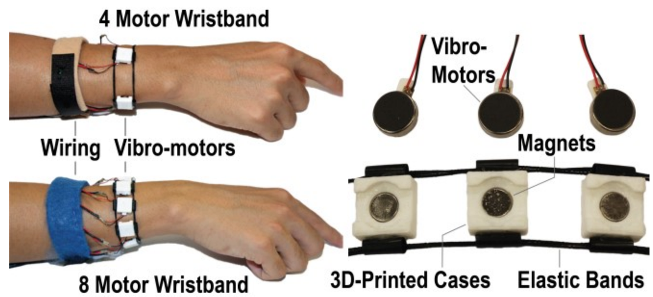

Figure 1. Wristbands with four and eight motors. Image adapted from our prior work [18], which used the same hardware and wristband configuration.

Wrist-worn haptic feedback has been primarily studied with sighted users and, even then, in the context of notifications such as the user's ability to recognize different pulse patterns (*e.g.*, [29]). For blind users, one [7, 8, 20] or four vibromotors [27] have been used on the wrist to support navigation (*i.e.*, directing the user's whole body) but not for precise hand guidance, which is our focus. A small number of studies with sighted users have focused on wrist-worn haptics for directional hand guidance [1, 35, 40]; however, [1, 35] did not compare multiple haptic designs so conclusions about efficacy cannot be drawn. Two exceptions come from Weber *et al.* [40] and Hong *et al.* [18]. Weber *et al.* [40] compared wristbands with four or six haptic motors to verbal instructions (up/left/right/down) to guide sighted users in moving and rotating their arm. However, they did not find statistically significant differences between the haptic designs, and their focus was on guiding hand movement in free space rather than on a 2D surface. Hong *et al.* [18] showed that an 8-motor wristband resulted in small accuracy benefits over a 4-motor design but their experimental task was relatively simple (making a directional swipe) and their study did not include blind users, who may perform differently due to differences in tactile perception (*e.g.*, [16]).

To study directional wrist-worn haptic feedback for blind users and to compare the effectiveness of different feedback designs, we implemented and evaluated the following haptic wristband variations: (1) *four* versus *eight* vibromotor designs; (2) vibration from only a *single* motor at a time versus from two adjacent motors, with the intention of creating an *interpolated*, more precise phantom sensation (vibration) between the two. In theory, eight vibromotors and the use of phantom sensations should provide more precise feedback than the other options but requires more hardware and could also be more cognitively or physically taxing. We conducted two controlled lab experiments: the first study included 11 sighted and 2 blind participants and was aimed at paring down the number of experimental conditions before conducting a second study with 14 blind and VI participants.

Study 1 showed that participants could non-visually find targets and trace paths more quickly and accurately with single-motor feedback than with interpolated feedback, particularly when only four motors were used. Study 2 (with blind participants) eliminated the interpolated feedback conditions and found that single-motor feedback with four motors was faster, more accurate, and most preferred compared to similar feedback with eight motors. In summary, this paper contributes empirical evidence that wrist-worn haptic feedback with a single motor vibrating at once performs better than interpolated feedback, and that embedding four motors in the wristband performs better than eight motors. We also provide design implications for non-visual wrist-worn haptic guidance. Our results have implications for future smartwatch haptic wristband designs.

2. RELATED WORK

We highlight assistive uses of haptic feedback as well as wrist and hand-worn haptic feedback devices.

2.1 Haptic Feedback for Assistive Applications

Haptic feedback has been used for a range of assistive applications for users with visual impairments. Most effort has focused on sensory substitution of visual information (*e.g.*, [31]) and on navigation (*e.g.*, [15]) but other areas have also been investigated, such as hand-worn dynamic braille for deaf-blind users [3, 17]. Sensory substitution maps visual information to alternative channels such as audio or haptics. A well-known example is *BrainPort*, which translates images from a glasses-worn camera into electrical stimulations on the tongue [31]. Another example is *Optacon*, which translates black and white areas on a printed page to dynamic tactile output for the user to touch [33]. Haptic wristbands and gloves have also been used to convey the color of objects under the finger [9, 34].

In this paper, we explore the use of haptics for directional guidance. Here, most work has focused on whole-body navigational support. An early example comes from Ertan *et al.* [15], who employed a 4x4 grid of vibrotactile actuators on the back of a vest to indicate turn information. Similarly, Scheggi *et al.* [32] used wrist-worn devices with two haptic actuators that were controlled by a remote observer to help blind users avoid obstacles while walking. Mann *et al.* [24] employed a haptic helmet combined with a depth camera to help blind users avoid collisions, although no user evaluation was reported. Cosgun *et al.* [12] evaluated a haptic belt with eight motors to provide directional guidance in discrete, 45° increments. They showed that users could recognize which of the eight motors was vibrating with 55-97% accuracy, depending on the motor. Though these studies showed that haptic feedback devices in different form factors are feasible to use for whole-body navigation, the design of wrist-worn haptic feedback for precise hand guidance has not been investigated with blind users.

2.2 Non-visual Directional Hand Guidance

For non-visual directional hand guidance specifically, prior work has explored both audio and haptic channels. For example, Oh *et al.* [26] used verbal feedback and sonification to teach blind users how to make touchscreen gestures. Audio feedback has also been used to help users reach targets in their peripersonal space [28, 41]. Directional audio guidance, however, has the drawback of interfering with other uses of the audio channel, such as screenreader or text-to-speech output [37]. Haptic feedback addresses this issue. Kim *et al.* [21] used four vibromotors mounted on a handheld smartphone to guide users with visual impairments to find targets on a large display. A user study showed that speech plus haptic feedback was faster than speech alone in helping users find targets. Shilkrot *et al.* [36] and Stearns *et al.* [37] both employed haptic actuators mounted on the finger and audio feedback to provide up/down (1D) finger guidance for a blind user tracing along a line of printed text. The latter conducted a controlled experiment with 19 blind participants to compare haptic and audio feedback for this reading task, finding that there were tradeoffs in accuracy and user preference between the two [37]. In contrast to these studies, our paper focuses on using haptic feedback around the wrist for precise 2D directional guidance for blind users.

Wrist-worn directional haptic guidance has been investigated to a greater extent with sighted users. In addition to the Weber *et al.* [40] example mentioned in the introduction, another study that is closely related to ours evaluated the accuracy with which users can perceive four or eight vibromotors placed around the wrist and move their hand in response [18]. In a user study, they vibrated one or two motors at a time to create a phantom sensation that conveyed direction more precisely than the 90° or 45° angular intervals between the four or eight motors. Users were asked users to move their finger in the direction they perceived. The wristband with eight motors was more accurate than the wristband with four motors, though the angular error in movement ranged from ~23–25° for both wristbands. In comparison to that study, our paper focuses on more complex and realistic tasks (target finding and path tracing), includes blind and visually impaired users, and explores a wider range of haptic feedback designs.

Other haptic studies with sighted users have investigated using a grid of motors on one side of the wrist to convey direction instead of placing motors around a band. For example, Lee *et al.* showed that the accuracy of perceiving direction with the grid of motors on the back of a smartwatch is more accurate with sensory saltation (an illusion of stimulus movement) than without it [22]. Another study empirically showed that the accuracy of localizing a vibration within a 3x3 grid layout was ~22–76% depending on the motor [10]. Finally, Matscheko *et al.* [25] compared a grid layout to a wristband layout for directional guidance while users are engaged in tasks that occupy the visual and audio sensory channels. They found the band layout to be more accurate, which supports our decision to use a design with motors around the band rather than in a grid.

3. DESIGN OF HAPTIC GUIDANCE

To evaluate the performance of different haptic feedback designs on 2D hand movement, we implemented two haptic wristbands: one with four motors and the other with eight motors. They employ the same hardware design as in [18] but with different software.

3.1 Hardware

The wristbands, shown in Figures 1 and 2, are identical except for the number of motors. We use eccentric rotating mass (ERM) disc vibromotors 10mm in diameter. [1] ERMs are inexpensive and ubiquitous, their flat design can be easily integrated into a wristband, and they have been used to create phantom sensations [30]. Additionally, ERMs performed better for our user tasks when compared to a similar wristband design with linear resonant

[1] https://www.adafruit.com/product/1201

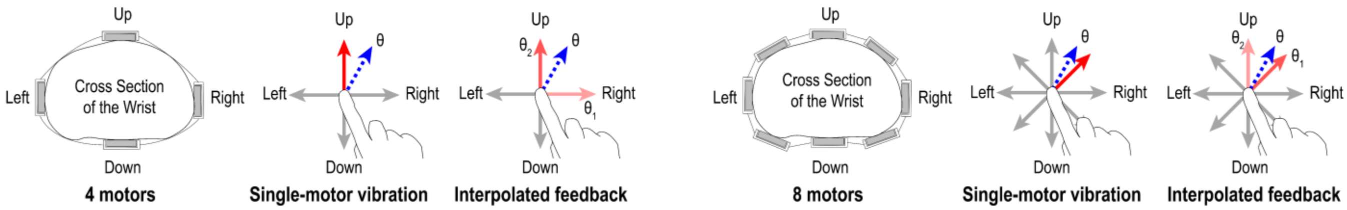

Figure 2. The position of motors around the wrist and an example of haptic feedback of 4 or 8 motors with single motor vibration or interpolation. In this figure, θ is the prompted direction (blue dotted arrow) and red and light red arrows are directions of vibration.

actuators (LRAs) when tested with three internal pilot participants. When mounted on the wristband and worn by a user, we measured the amplitude of the ERMs at 0-1.2g and the frequency at 0-162Hz; Figure 3 shows the measured frequency and amplitude in response to applied voltage. The response time to drive the motor to full vibration from the complete idle state was 100ms.

As shown in Figure 1, our custom wristband design addresses three issues: vibration transfer along the band, variation in wrist size, and the non-uniform shape of a wrist. To isolate the motors and limit vibration transfer, we mounted the motors on a band separate from the wiring and housed them magnetically in 3D-printed cases connected only by thin elastic thread. The band with the wiring connected to an Arduino Mega for communication and power. Because the wrist is not a uniform oval, placing the motors equidistantly around the band (as in [40]) means that the motors are not necessarily at the position the user expects—for example, the right-most location on the wrist may not be midway between the up and down positions. To address variation in wrist sizes and shapes, our prototype is adjustable. The band with the motors is threaded through the motor cases rather than affixed, which allows the cases to slide (with effort) along the band, and allows the band to be tightened or loosened (based on [19]). The experimenter could thus adjust the band per user. The Arduino Mega was in turn connected to a Samsung Galaxy Tab 4 tablet via an on-the-go (OTG) cable. The tablet communicated serially with the Arduino Mega, sending a signal at a frequency of 92 Hz to update the vibration.

3.2 Feedback

We implemented two different vibration types: *single-motor* vibration, which is simpler and thus may be easier to perceive, and *interpolated* vibration, which should offer more precise directional information. To mitigate desensitization that can occur when haptic feedback is continuously applied at a single location [5], our feedback designs provide only *corrective* guidance. That is, when the user's finger moves off course, vibration guides them back to the intended direction (corrects the finger movement). When the finger movement is on course, no vibration occurs. This design was selected among several options based on extensive piloting within our research lab, including options that provided continuous vibration such as dropping to low intensity rather than no vibration.

3.2.1 Single Motor Vibration

For this feedback type, only one motor vibrates at a time, and the location of that motor maps to a direction on a 2D plane (Figure 2). Directions are in 90° increments for the 4-motor wristband and 45° increments for the 8-motor wristband. For example, vibrating the leftmost motor on the wrist indicates that the finger should move to the left on the 2D surface. To convey directions *between* two motors, the single closest motor vibrates (*e.g.*, for a prompted direction of 15°, the rightmost motor, at 0°, vibrates).

To provide corrective guidance, no vibration occurs if the difference between the finger's trajectory and the intended direction is less than 22.5°; 22.5° was selected based on prior work

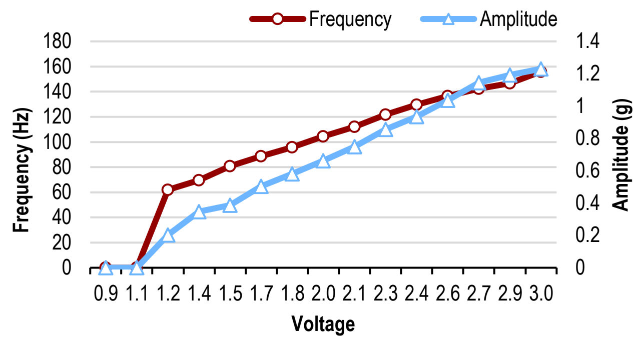

Figure 3. Measured frequency and amplitude of an ERM vibro-motor mounted on a user's wrist as applied voltage changes. Graph adapted from our prior work [18].

showing the minimum angular accuracy in moving the hand based on vibration around the wrist is at least 23° [18]. As the finger's trajectory diverges from the intended direction, vibration intensity increases: the applied voltage increases linearly from 1V when the user's hand movement trajectory is 22.5° away from the intended direction to 3V (maximum intensity) when the user's trajectory is 90° or farther from the intended direction.

3.2.2 Interpolated Vibration

With the second feedback design, one or two motors vibrate at a time to allow the user to interpolate a more precise direction. Vibrating two adjacent motors should theoretically create an illusory single 'phantom sensation' between the two [2]; varying the amplitude and frequency of each motor impacts the specific location of the phantom sensation. Following [2], we logarithmically adjust the amplitude and frequency based on the precise angle we wish to indicate between the motors. To indicate an angle θ between two motors, we calculate:

$$V_1 = V_{max} \times \frac{log(\theta_2 - \theta + 1)}{log(\theta_2 - \theta_1 + 1)}$$

$$V_2 = V_{max} \times \frac{log(\theta - \theta_1 + 1)}{log(\theta_2 - \theta_1 + 1)}$$

where V_1 and V_2 are the voltages on the two adjacent motors and θ_1 and θ_2 are the angles of directions mapped to the two motors as shown in the Figure 2. As with the single motor vibration design, V_{max} was controlled to avoid continuous vibration on the wrist. V_{max} was set to 3V if the difference between the intended direction and the finger movement was greater than 90°. If the difference was less than 22.5°, V_{max} was 0V. If the difference was in the 22.5–90° range, V_{max} linearly ranged from 1V–3V.

4. STUDY 1: INTERPOLATION AND NUMBER OF MOTORS

To gather preliminary data before running a full study with blind and visually impaired participants, we first conducted an initial study with 11 sighted and 2 blind participants. This study included

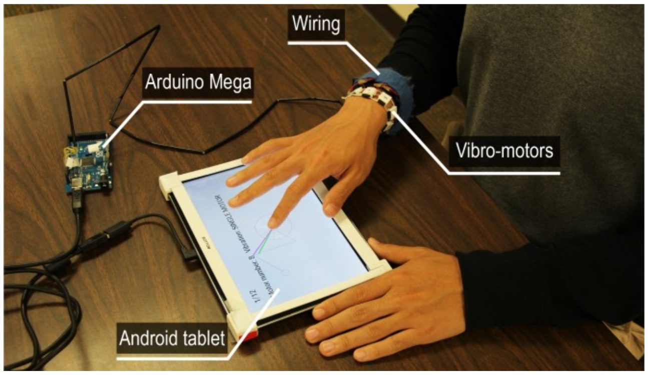

Figure 4. The experimental setup for both studies. Visuals on the screen were for the experimenter and were not visible to sighted participants nor perceptible to blind participants.

both the 4-motor and 8-motor wristbands as well as the single-motor and interpolated feedback. It was not meant to substitute for evaluation with blind and visually impaired participants but instead allowed us to identify the most promising feedback designs to evaluate later with our VI participants—thus allowing for a simplified and more statistically powerful experimental design.

4.1 Method

4.1.1 Participants

We recruited 11 sighted participants (6 female, 5 male) and two blind participants.[2] The sighted participants were recruited through campus email lists and ranged in age from 19 to 34 ($M = 25.3$, $SD = 4.5$); all were right-handed. The blind participants were recruited through a list of potential participants maintained by our research lab. One was 53 years old, male, and right-handed, while the second was 63 years old, female, and left-handed.

4.1.2 Procedure

The study session took up to two hours. We first collected demographic information and touchscreen device experience. The tablet device, which had non-slip feet attached, was placed flat on a table in front the participant, as shown in the Figure 4. The four conditions were presented in counterbalanced order with a five-minute break offered between each one. Sighted participants were blindfolded during the tasks to isolate the effects of the haptic feedback and to provide a better indication of which conditions we should evaluate in the follow-up study with VI participants. The procedure for each condition consisted of the following four steps.

Step 1: Wristband placement and introduction. The experimenter placed the wristband on the participant's wrist and adjusted the position of the motors while the participant held their hand on the tablet screen. To confirm that the motors were perceptually at the correct positions (Figure 2), the experimenter vibrated each one in turn and adjusted its position if the participant reported that it felt off. Participants were then given a brief introduction to the wristband (~5 minutes) that consisted of 16 trials: a motor vibrated, the participant attempted to move their finger in the direction of the vibration, and the system provided feedback about how close the movement was to the presented angle of movement (perfect: ≤ 5.625° from presented angle, close: > 5.625° and ≤ 22.5°, and incorrect: > 22.5°). If the movement was incorrect, the direction was repeated until the participant moved correctly, with the experimenter giving verbal instructions after two incorrect

[2] An additional five sighted participants completed the study but their data was not usable due to a technical problem with Bluetooth where the Arduino and tablet disconnected repeatedly. In Study 2, we resolved this problem by using a wired connection.

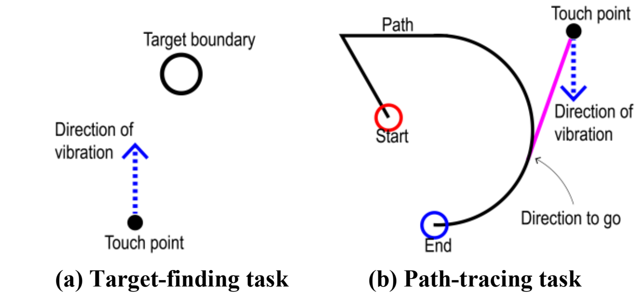

Figure 5. Single-motor haptic feedback for example target-finding and path-tracing trials. The motor closest to the ideal angle of movement is vibrating. For the path-tracing task, the ideal angle of movement is computed using a tangent line drawn from the touch point to the curve.

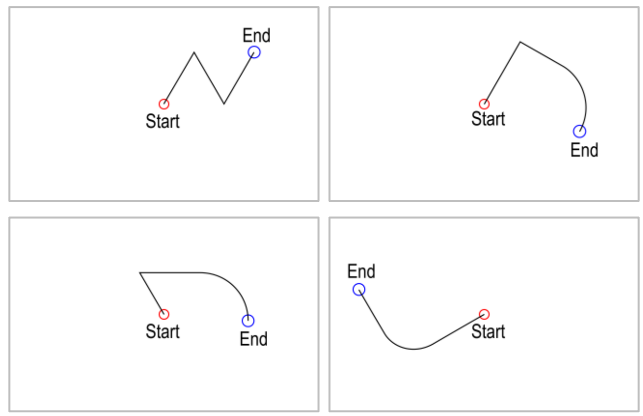

Figure 6. Sample paths used in the path-tracing task. All paths started at the center of the screen.

attempts. For the single-motor feedback conditions, the 16 trials consisted of 4 or 2 trials per motor for the 4-motor and 8-motor wristbands, respectively. For the interpolated feedback conditions, 16 target directions were evenly distributed at 22.5° intervals for both wristbands, with one trial in each direction.

Step 2: Target-finding task (Figure 5a). For the target-finding task, each trial consisted of moving from the center of the touchscreen to a randomly placed circular target (15mm in diameter) with at least 7.5mm buffer (a target radius distance) between the edge of the target and the edge of the screen. A sticker at the center of the tablet provided a tactile indicator of the start location. To begin a trial, the participant placed their finger on the sticker for one second, after which a sound played and wristband vibration indicated the trial had begun. Upon entering the target bounds, an end sound also played. Participants completed 5 training trials and 30 test trials for this task, where the training trials included decreasing levels of experimenter guidance, from physically guiding the participant's finger to having the participant do the trial fully independently. Participants were asked to complete the test trials as quickly and accurately as possible.

Step 3: Path-tracing task (Figures 5b and 6). Following the target-finding task, participants were asked to trace paths (as if they were following a route on a map). We programmatically generated a set of 18 paths based on route features from a real university campus map, including the relative length of segments, the angles between segments, and the ratio of straight to curved segments. Each path consisted of three straight or curved segments, with the constraint that not all three could be curved. The distance between the start and end points of each path was at least 30 mm. The average path length was 140 mm (*SD*=26.4).

During this portion of the study, each participant completed 5 path-tracing training trials presented in the same order followed by 10 test trial paths presented in random order. As with target finding, the experimenter provided decreasing levels of guidance during the training trials. Again, a trial started by placing the finger on the start sticker until a sound played and vibration started. The system then guided the user to trace each segment in turn. For straight segments, the system guided the user to the segment end point in the same manner as guiding to a target in the target-finding task. For curved segments, the system guided the user to the tangent point of a line drawn from the curve to the finger, the location of which was continuously updated as the finger moved (Figure 6). For both straight and curved segments, reaching the "end of the segment" was defined as being within 7.5 mm of the exact end point (*i.e.,* within the radius of a target in the target-finding task). A beep indicated the end of each segment and a chime sound indicated the end of the trial. Again, participants were asked to complete the test trials as quickly and accurately as possible.

Step 4: Subjective feedback. After each condition (*e.g.,* single *vs.* interpolated with 4 *vs.* 8 motors), we asked participants to rate overall experience, ease, accuracy, and speed on 7-point Likert scales, and solicited open-ended feedback. When all conditions were done, we asked participants to select the easiest, fastest, most accurate, most preferred, and least preferred conditions and to provide overall feedback about their experience.

4.1.3 Study Design
The study used a within-subjects design with two factors: *Number of Motors* (4-motor *vs.* 8-motor) and *Vibration Type* (single motor *vs.* interpolation). The order of presentation for the four conditions was counterbalanced using a balanced Latin square and participants were randomly assigned to orders.

4.1.4 Measures and Data Analysis
The main measures were trial completion time and movement error. Trial completion time was computed from the time the vibration started until their finger entered the target bounds for target-finding trials or reached the end of the last segment for path-tracing trials. For target-finding trials, movement error was computed as the ratio of: the actual distance the finger moved during the trial to the Euclidian distance between the start location and the closest point on the target (lower values are better):

$$movement\ error = \frac{finger\ movement\ distance}{shortest\ possible\ distance}$$

For path-tracing trials, movement error was computed by first uniformly resampling the user's actual trace to have one point every 1 mm, then matching the points from the resampled path to the presented path using dynamic time warping (DTW) [6], which measures the distance between two temporal sequences of points. The average of the distances between matched points was then computed as the movement error; lower numbers are better.

For each participant, outlier trials were defined based on trial completion time as being more than 3*IQR (interquartile range) above the upper quartile or less than 3*IQR below the lower quartile within a given experimental condition [39]. In total, 1.6% of trials were excluded from analysis. The trial completion times and movement errors for both tasks violated the normality assumption (Shapiro-Wilk tests, $p < .05$). Therefore, we ran

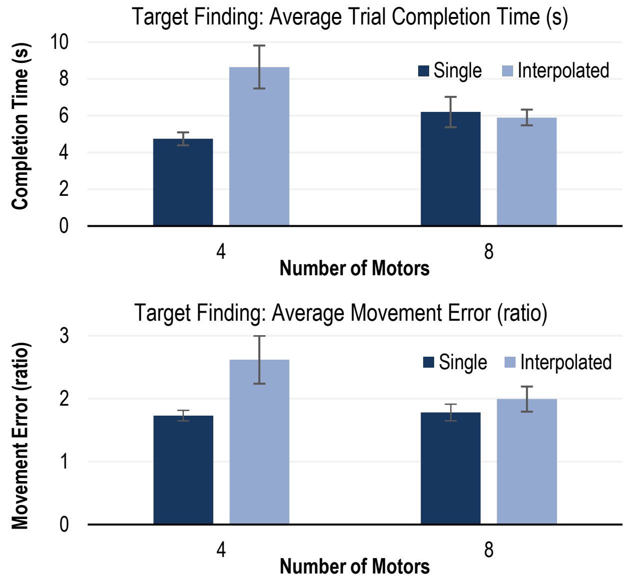

Figure 7. Average trial completion time and movement error for the target-finding task in Study 1, showing interpolated feedback is less accurate than single-motor feedback. Error bars show standard standard error. (*N* = 13)

nonparametric analyses using 2-way ANOVA with aligned rank transform (ART) [42]. Bonferroni corrections were used for all posthoc pairwise comparisons.

4.2 Results
We present speed and accuracy for both the target finding and path-tracing tasks, followed by subjective feedback.

4.2.1 Target Finding
Figure 7 (top) shows the average trial completion times for the target-finding task. Overall, the interpolated feedback was slower than the single-motor feedback, at 7.3s per trial on average (*SD* = 3.4) compared to 5.4s (*SD* = 2.3). This difference was significant, as shown by a main effect of *Vibration Type* ($F_{1,36} = 8.83$, $p = .005$, $\eta^2 = 0.21$). While there was no significant effect of *Number of Motors* ($F_{1,36} = 0.53$, $p = .470$, $\eta^2 = 0.04$), there was a significant interaction effect between *Number of Motors* and *Vibration Type*, showing that efficacy of the vibration type depended on how many motors there were ($F_{1,36} = 8.91$, $p = .005$, $\eta^2 = 0.13$). Pairwise comparisons showed that interpolated feedback was slower than single-motor feedback with the 4-motor wristband, at 8.6s per trial on average (*SD* = 4.2) compared to only 4.7s per trial (*SD* = 1.3); this difference was significant with a Wilcoxon signed rank test ($W = 3$, $Z = -2.97$, $p = .001$, $r = 0.58$). In contrast, no difference was found between the two vibration types for the 8-motor wristband with 6.2s per trial (*SD*=3.1) for single motor and 5.9s (*SD*=1.5) for interpolated ($W = 42$, $Z = -0.24$, $p = .839$, $r = 0.05$).

In terms of accuracy (Figure 7, bottom), interpolated feedback also resulted in higher error than single-motor feedback, with a movement error of 2.3 on average (*SD* = 1.1) compared to 1.8 (*SD* = 0.4); this difference was significant, as shown by a main effect of *Vibration Type* ($F_{1,36} = 5.67$, $p = .023$, $\eta^2 = 0.14$). The main effect of *Number of Motors* ($F_{1,36} = 1.71$, $p = .200$, $\eta^2 < 0.01$) and the interaction between *Number of Motors* and *Vibration Type* ($F_{1,36} = 1.62$, $p = .212$, $\eta^2 = 0.04$) were not significant.

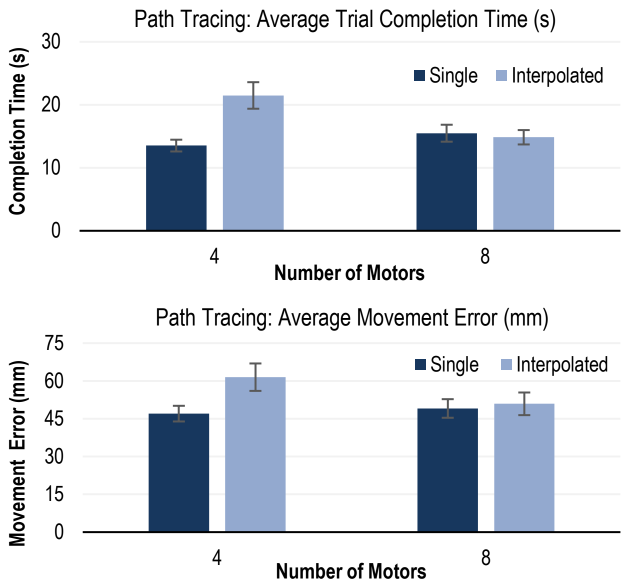

Figure 8. Average trial completion time and movement error for the path-tracing task in Study 1, showing interpolated feedback is slower and less accurate than single-motor feedback. The error bars are standard error. (N = 13)

4.2.2 Path Tracing

This pattern of findings was similar for the path-tracing task, with interpolated feedback not faring well, particularly with the 4-motor wristband design. Figure 8 (top) shows the average trial completion times. Interpolated feedback was significantly slower than single-motor feedback with average trial times of 18.1s (SD = 6.9) compared to 14.5s (SD = 4.2); main effect of *Vibration Type* ($F_{1, 36}$ = 8.27, p = .007, η^2 = 0.24). The number of motors did not have a significant effect on the trial completion time ($F_{1, 36}$ = 4.93, p = .057, η^2 = 0.14); however, there was a significant interaction effect between the *Number of Motors* and the *Vibration Type* ($F_{1, 36}$ = 12.5, p = .001, η^2 = 0.15). As with the target-finding task, pairwise comparisons showed that this latter result was due to interpolated feedback slowing participants down only with the 4-motor wristband. Here, trials took on average 21.5s (SD = 7.6) with interpolated feedback and 13.5s (SD = 3.4) with single-motor feedback, which was a significant difference (W = 90, Z = 3.11, p < .001, r = 0.61). There was no such difference for the 8-motor wristband.

Movement error (Figure 8, bottom) was also significantly higher with interpolated feedback than with single-motor feedback, at 9.5mm on average (SD = 3.1) compared to 8.2mm (SD = 2.1); main effect of *Vibration Type* ($F_{1, 36}$ = 4.66, p = .038, η^2 = 0.11). While the main effect of *Number of Motors* was not significant ($F_{1, 36}$ = 2.2, p = .147, η^2 = 0.11), the interaction effect between *Number of Motors* and *Vibration Type* was significant ($F_{1, 36}$ = 4.17, p = .048, η^2 = 0.04). As with earlier results, interpolated feedback resulted in higher movement error than single-motor feedback for the 4-motor wristband, at 10.6mm (SD = 3.3) versus 8mm (SD = 1.9); the difference was significant (W =80, Z = 2.41, p = .013, r = 0.47).

4.2.3 Subjective Responses

Subjective responses reflected the performance results, as shown in Figure 9. Participants consistently rated the 4-motor wristband with interpolation worse than the other three conditions in terms of ease, speed, and accuracy. Table 1 shows vote tallies for easiest, fastest, most accurate, and most/least preferred of the four conditions. The

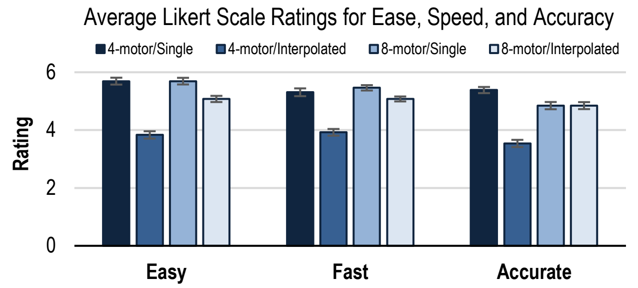

Figure 9. Study 1 subjective ratings on 7-point Likert scales for ease, speed, and accuracy, where 1=*strongly disagree* and 7=*strongly agree.* The single motor condition received higher ratings than interpolated feedback. Error bars are standard error. (N = 13)

	4-motors		8-motors	
	Single	Interpolated	Single	Interpolated
Easiest	7	1	4	1
Fastest	6	1	4	2
Most accurate	9	1	3	0
Most preferred	6	2	4	1
Least preferred	0	9	1	3

Table 1. Subjective vote tallies in Study 1, showing 4-motors with interpolation was the least preferred condition. (N = 13)

single-motor feedback options received more positive votes compared to interpolated feedback options.

4.3 Summary and Discussion

Interpolated feedback was slower and less accurate in both tasks, but was particularly problematic with the 4-motor wristband. Subjective feedback matched this performance data. One limitation of this study is that the sighted participants' performance may not be representative of blind users. However, performance from the two blind participants matched the overall trends comparing single-motor *vs.* interpolated feedback: both blind participants were faster with single-motor feedback for both tasks, while single-motor feedback was more accurate for path tracing for both participants and resulted in mixed accuracy for target finding (one participant was more accurate, one was less accurate). Based on these results, we focused only on single-motor feedback in Study 2 with blind and VI participants.

5. STUDY 2: EVALUATION WITH BLIND AND VISUALLY IMPAIRED USERS

Based on the findings from Study 1, we eliminated the interpolated feedback conditions and conducted a follow-up study with 14 blind and visually impaired participants to compare single-motor feedback with the 4-motor and 8-motor wristbands.

5.1 Method

The study method is largely the same as for the pilot study with a few key changes highlighted below.

5.1.1 Participants

We recruited 14 (8 female, 6 male) visually impaired participants through an existing participant pool and local organizations working with people with visual impairments. Participants were on average 44.8 years old (SD=13.9; range 22–64). Seven participants were totally blind, two were blind with light perception, and five were legally blind. All 14 used a screen reader on their computer and/or smartphone. Twelve participants were right handed, one was left handed, and one reported using her left hand for writing tasks and right hand for touchscreen devices (she used her right hand for study tasks). All but one participant owned a touchscreen device. Of the 13 touchscreen device owners, 11 participants reported daily use and 2 participants reported use every few days.

5.1.2 Procedure

The study procedure lasted up to 90 minutes. As we removed the interpolated feedback conditions, we had only two experimental conditions: single-motor feedback with four or eight motors. The conditions were fully counterbalanced and participants completed the same set of tasks with each condition as in Study 1. Due to a steep learning curve that we saw persist into the test trials during Study 1, we also provided more training and increased the number of test trials as follows: (1) After first putting on the wristband, participants completed the same 16 *familiarization* trials as in Study 1; however, an additional trial was appended every time a participant made two consecutive incorrect attempts in a specific direction, up to a maximum of four or eight additional trials depending on the number of motors on the wristband. (2) For the *target-finding* task, participants completed at least 12 training trials including an initial two guided by the experimenter. Additional training trials were added up to a maximum of 20 if the movement error (ratio) was greater than 3.0 in two or more of the most recent five training trials. The number of test trials for target finding also increased from 30 in Study 1 to 36 here. (3) For the *path-tracing* task, participants completed 7 training trials and 12 test trials (up from 5 and 10, respectively in Study 1). (4) Finally, because of comments from some Study 1 participants about desensitization to the haptic vibration, we imposed an eight-minute break between conditions.

5.1.3 Study Design, Measures and Data Analysis

Study 2 included a single experimental factor of *Number of Motors* (4 or 8). This was a within-subjects factor and was fully counterbalanced, with participants randomly assigned to orders. However, to capture possible learning effects, we split the 36 trials in the target-finding task into two blocks of 18 trials each and included *Block* as an additional factor in the analysis of that task. We did not do so for the path-tracing task because of the smaller number of trials and the increased likelihood of any individual trial unduly affecting the average within a block of only nine trials.

As with Study 1, the main measures were *trial completion time* and *movement error*. Outlier trials were detected within each condition per participant using the IQR method as in Study 1. Out of 1,344 test trials in total across the 14 participants, 31 outlier trials (2%) were excluded from data analysis.

Shapiro-Wilk tests showed that trial completion times and movement error violated the normality assumption of parametric tests for both tasks ($p < .05$). Thus, for the target-finding task, a 2-way repeated measures ANOVA (*Number of Motors* x *Block*) with ART was used to anlayze the trial completion time and movement error. We used Wilcoxon signed rank tests to analyze the trial completion time and movement error for the path-tracing task, as well as for subjective ratings.

5.2 Results

We present performance analyses followed by subjective ratings and an analysis of open-ended comments from participants.

5.2.1 Target Finding

As shown in Figure 10 (top), similar to Study 1, participants were again faster with the 4-motor wristband than the 8-motor one, at 7.3s per trial on average ($SD = 4.8$) compared to 9.8ms ($SD = 4.9$). This difference was significant (main effect of *Number of Motors*: $F_{1,39} = 14.51$, $p < .001$, $\eta^2 = 0.05$). The main effect of *Block* was not statistically significant ($F_{1,39} = 2.54$, $p = .119$, $\eta^2 < 0.01$) nor was the interaction between the two factors ($F_{1,39} = 1.45$, $p = .235$, $\eta^2 < 0.01$).

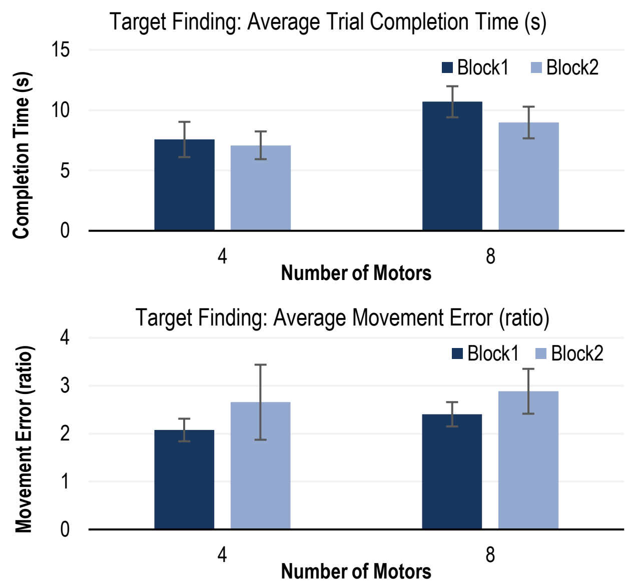

Figure 10. Trial completion time and movement error for the target-finding task in Study 2. The 4-motor wristband was faster and more accurate than the 8-motor wristband. Error bars are standard error. (*N* = 14)

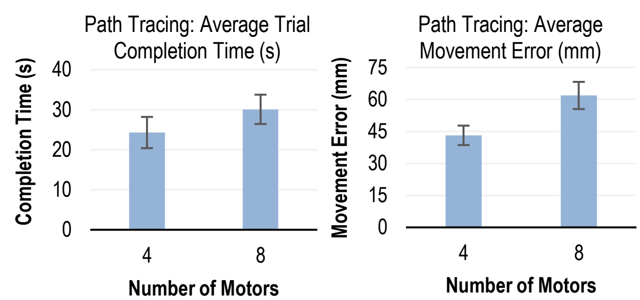

Figure 11. Trial completion time and movement error for the path-tracing task in Study 2. The 4-motor wristband was more accurate than the 8-motor wristband. Error bars are standard error. (*N* = 14)

Participants were also more accurate with the 4-motor wristband than the 8-motor one (Figure 10, bottom). The movement error ratio was on average 2.4 with four motors ($SD = 2.1$) compared to 2.6 with eight motors ($SD = 1.4$), a significant difference (main effect of *Number of Motors*: $F_{1,39} = 5.14$, $p = .029$, $\eta^2 < 0.01$). As with completion time, the main effect of *Block* was not statistically significant ($F_{1,39} = 0.34$, $p = .560$, $\eta^2 = 0.01$) nor was the interaction between the two factors ($F_{1,39} < 0.01$, $p = .947$, $\eta^2 < 0.01$).

5.2.2 Path Tracing

Performance for the path-tracing task is shown in Figure 11. The results partially mirror the target-finding results: participants were not faster with either wristband ($W = 25$, $Z = 1.73$, $p = .091$, $r = 0.33$) but were significantly more accurate with the 4-motor wristband ($W = 12$, $Z = -2.54$, $p = .009$, $r = 0.48$). Trials took on average 24.3s with four motors ($SD = 14.6$) and 30.1s with eight motors ($SD = 13.7$). The movement error was 7.4 mm ($SD = 2.9$) with four motors and 10.6 mm ($SD = 4.1$) with eight motors on average.

	4-motor *M(SD)*	8-motor *M(SD)*	Wilcoxon signed rank test result
Ease of understanding*	6.4 (0.7)	5.2 (1.6)	W=36, z = -2.54, p = .008, r=0.48
Speed	6.1 (0.8)	5.1 (1.2)	W = 61, z = -1.75, p = .085, r = 0.33
Accuracy*	5.9 (1.0)	4.8 (1.1)	W = 59, z = -2.36, p = .021, r = 0.45

Table 2. Subjective ratings on 7-point Likert scales, were 7 indicated strong positive agreement. Measures with statistically significant differences are shown with '*'.

5.2.3 Subjective Feedback

Table 2 shows subjective Likert scale ratings collected at the end of each condition, which largely reflect the performance results. Participants perceived the 4-motor wristband to be significantly easier to understand and more accurate than the 8-motor wristband. No differences were found in perceptions of speed.

When asked about overall preference at the end of the study, participants were split: eight participants preferred the 4-motor feedback while six participants preferred the 8-motor feedback. The most common reason cited for preferring 4-motor feedback was that it was easier to understand (6 participants). For example, P9 said: "*[4-motors] was easier to use and I felt less frustrated. I felt like I did better. I was more sure of [...] which one was vibrating."* For the 4-motor wristband, some participants mentioned the ease of mapping the vibrations to the four cardinal directions on the tablet screen (one person mentioned this for 8-motor feedback too). One participant also mentioned that with four motors it felt like there was less vibration, whereas with eight motors it felt like the entire hand was vibrating. Finally, one participant appreciated the spacing between motors with the 4-motor option because she had a small wrist.

Reasons for preferring 8-motor feedback included higher perceived accuracy and increased precision. For example, P8 said, "*The feedback is more fine-grained and I like that [...] Instead of a general direction I like precision."* P3 also mentioned:

> *"...this would be good for [...] not just maps but statistics, because [...] when you put the numbers on a graph, you know, you have more, more to figure out where everything is for charting the graph."* (P3)

At the same time P11 noted the additional information with the 8-motor feedback had some drawbacks, saying: "*I could adjust better [with 8-motor], but I did think that it slowed me down more."*

Some participants mentioned applications for which they thought the wrist-worn haptic feedback could be useful, including: drawing, navigating maps, plotting graphs, and operating touchscreen devices. At the same time, issues of learning and fatigue arose, suggesting that the haptic designs could be further refined to limit vibration. Eight participants commented that they would have performed better with more practice. For example. P15 mentioned for 8-motor feedback: *"I feel it, I understand. [The] more I was practicing, [the] more I was getting it."* Four participants mentioned that after a while their wrist got tired, and as a result, they had more trouble identifying which motor was vibrating. For example, P07 mentioned for 8-motor feedback: *"After a while [...] the way it jumps [from one direction to another], if there is no constant stopping of vibrations, it kind of starts blending into each other."* We return to this issue in the Discussion section.

5.3 Summary

Study 2 largely reaffirms our Study 1 findings. Participants completed the target-finding task faster and more accurately with the 4-motor wristband than the 8-motor wristband. In the path-tracing task, participants were significantly more accurate when they used 4-motor wristband than 8-motor wristband. The subjective evaluation supported the performance results with positive feedback about the 4-motor wristband.

6. DISCUSSION

Across the two experiments, our findings showed that the fastest, most accurate, and most preferred design was the four-motor wristband with a single-motor vibration. This conclusion is counter to our expectations: we had expected that having more vibromotors (8 *vs.* 4) and attempting to induce precise phantom sensations between adjacent motors would lead to more accurate performance. We discuss this and other issues relevant to future wrist-worn haptic feedback designs below.

6.1 Why Does 4-motor Outperform 8-motor?

We were surprised that doubling the number of haptic actuators around the wrist did not result in performance benefits: the 8-motor design was slower and less accurate than the 4-motor design in both studies. While further work is necessary to uncover why this might be, some possible reasons include vibration transfer, higher cognitive load, and perceptual limitations. Vibration transfer occurs when the actuation of one motor causes one or more adjacent motors to also vibrate. The transfer is a function of the intensity of the actuated motor, the distance and physical connection between the motors, and the wrist itself (*e.g.,* the skin, bone structure). While our elastic band was designed to mitigate vibration transfer, it was not completely suppressed. In particular, because the inter-motor distance was lower with the 8-motor design, transfer would theoretically be higher. The interpolated conditions also used higher combined intensity vibrations than the single-motor conditions, which may have exacerbated transfer problems and created inadvertent phantom sensations or other perceptual issues. In practice, embedding the motors in a solid smartwatch strap or wristband robust enough for daily use will likely result in greater vibration transfer than our elastic design, magnifying the benefits of the 4-motor design over the 8-motor design.

6.2 Designing Wristband Haptics

Creating wrist-worn directional hand guidance systems requires exploring a large design space. In this paper, we built and investigated only a few possible designs. Important design considerations, include: cognitive factors (*e.g.,* understandability, learnability), perceptual factors (*e.g.,* desensitization, phantom sensations), as well as the design of the wristband, haptic hardware, and underlying software algorithms to actuate those haptics.

Early in our design process, we examined a range of haptic hardware, including muscle wire (shape memory Nitinol), tactors, piezoelectrics, and vibromotors. We settled vibromotors based on our internal experiments and results from prior work (*e.g.,* [18]). In the haptics literature, two vibromotor designs are common: ERM and LRA. We initially built and examined prototypes for both. While LRAs are attractive because they offer faster response times than ERMs and allow for independent control of amplitude and frequency, our internal tests showed that our ERM design performed better. For example, in a small pilot test with three participants, all participants performed faster and more accurately with the ERM prototype than the LRA prototype. Consequently, we refined and used the ERM prototype in this paper.

As with the haptic hardware, designing an appropriate haptic feedback signal is a difficult design problem. One needs to consider the hardware response time, the intensity and frequency of the vibration, and the vibro-modulation pattern. To help inform the approach used in this paper, we designed four guidance methods. Three of the four methods used *corrective guidance*—that is, the vibromotors were actuated only when the user's finger trajectory and the intended direction differed by at least 22.5°. Of these corrective guidance approaches, one vibrated at maximum intensity regardless of the magnitude of the difference, one increased linearly as the angular difference increased, and the third increased in a small number of discrete steps as the angular difference increased. A fourth option was to use a pulse vibration (100ms on / 100ms off) to indicate intended direction, regardless of the difference between the actual and intended direction. Among the four methods, the corrective guidance with linear change in vibration was fastest and most accurate in our pilot tests, so it was selected for our studies. However, further work may yield improved haptic feedback designs (*e.g.,* more perceptible feedback patterns).

6.3 Effect of Age and Technology Experience

Before refining our prototypes and approach for Study 2, we attempted to replicate Study 1 with 22 blind participants (*M*=54.3 years old; *SD*=10). In contrast to our Study 1 and Study 2 experiences, only 10 of the 22 participants in this interim study could complete the experiment within the allotted time; the other 12 dropped out early or were unable to complete all tasks. This experience partly motivated us to increase the number of training and test trials in Study 2. At the same time, participant age and overall familiarity with technology may have played a role in the low success rates in this interim study. The interim study participants were older than in Studies 1 and 2: on average 54.3 years old (compared to 28.3 in Study 1 and 44.8 in Study 2). Age is an important variable given that older persons have lower sensitivity for perceiving vibration stimulus on the skin [11]. The interim participants also had less experience with touchscreen technology, with only 14 of the 22 owning a touchscreen device, compared to almost all participants in Studies 1 and 2.

6.4 Limitations and Future Work

The results and limitations of our studies reveal several directions for future work. First, some participants mentioned fatigue from using the haptic feedback, which may be partly due to desensitization. While we attempted to mitigate desensitization by providing corrective guidance rather than continuous vibration (Section 3.2), it could have impacted some feedback designs more than others (*e.g.*, interpolated *vs.* simple); for example, desensitization occurs more quickly at higher intensity levels [5] and with more sustained activation [23]. We also included 5-8 minute breaks between conditions, but recovery time between vibration stimuli is still an active area of research (most work suggests 30 secs to 3 mins, *e.g.*, [5, 14, 23]). Ultimately, to limit fatigue, wrist-based haptic feedback may be most applicable to short tasks (*e.g.*, learning a new route, exploring a drawing, reading a flyer) rather than in-depth tasks (*e.g.*, reading a book line-by-line). It is also possible that fatigue lessens as participants gain experience. Future work should explore these concerns further.

Second, some participants indicated needing more time to learn and effectively use our wristband prototypes. While we examined learnability by splitting Study 2 into blocks, we found no clear learning effect during the duration of the target-finding task. Future work should examine how performance changes with time by using a more longitudinal study design.

Third, while our study tasks were developed to model two common real-world tasks, finding a target and tracing a route, more work is necessary to understand whether the observed performance numbers are accurate enough to provide value in practice (*e.g.*, did participants have a strong conceptual understanding of the paths that they tried?). It will also be important to explore other applications, such as drawing, plotting graphs, and operating touchscreen devices in general, as suggested by participants.

Fourth, our focus was on isolating the effects of specific wrist-based haptic designs but non-haptic and hybrid approaches should also be considered (*e.g.*, sonification or vocal directions like "move up"). Note, however, that the audio channel is often overloaded in assistive applications and audio directional guidance can interfere with speech output (*e.g.*, screenreaders) [38].

7. CONCLUSION

In this paper, we report on the design and evaluation of two haptic wristbands, 4-motor *vs.* 8-motor, and two actuation approaches, simple (single motor) *vs.* interpolated (two motor). Our Study 1 findings showed that participants could non-visually find targets and trace paths more quickly and accurately with single-motor feedback than with interpolated feedback, particularly with the 4-motor design. In Study 2, we eliminated the interpolated feedback conditions and found that single-motor feedback with four motors was faster, more accurate, and most preferred by blind participants compared to similar feedback with eight motors. Our results help establish important benchmarks for future work and contribute to the growing body of hand guidance research.

8. ACKNOWLEDGMENTS

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