Evaluating Angular Accuracy of Wrist-based Haptic Directional Guidance for Hand Movement

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ABSTRACT

Haptic guidance for the hand can offer an alternative to visual or audio feedback when those information channels are overloaded or inaccessible due to environmental factors, vision impairments, or hearing loss. We report on a controlled lab experiment to evaluate the impact of directional wrist-based vibro-motor feedback on hand movement, comparing lower-fidelity (4-motor) and higher-fidelity (8-motor) wristbands. Twenty blindfolded participants completed a series of trials, which consisted of interpreting a haptic stimulus and executing a 2D directional movement on a touchscreen. We compare the two conditions in terms of movement error and trial speed, but also analyze the impact of specific directions on performance. Our results show that doubling the number of haptic motors reduces directional movement error but not to the extent expected. We also empirically derive an apparent lower bound in accuracy of ~25° in interpreting and executing on the directional haptic signal.

Keywords: Wearables, haptics, non-visual directional guidance.

Index Terms: H.5.m. Information interfaces and presentation (*e.g.*, HCI)

1 INTRODUCTION

Haptic guidance for the hand can be useful for a range of applications, including virtual reality [26, 33], teaching new motor skills [11, 20], and accessibility for blind users [13, 30]. Such guidance can offer an alternative to visual or audio feedback when those information channels are overloaded or inaccessible due to environmental factors, vision impairments, or hearing loss. For example, a driver may need to interact non-visually with their car's console [4], a firefighter may require fine-grained guidance in a smoky room with no visibility [9], or a blind user may want to accurately trace a line of printed text with a wearable system while listening to text-to-speech output of that text [13, 30].

While researchers have looked at both finger-worn [13, 30] and wrist-worn haptic directional guidance [11, 26, 28, 33], the wrist offers a balance of proximity to the finger, sensitivity [7], surface area, and social acceptability. The larger surface area, for example, allows for a greater number of vibration sources than is possible on the finger. Moreover, emerging smartwatches offer a compelling and timely opportunity to embed haptic feedback in the watchband itself to support a range of non-visual interactions.

Wrist-based haptic feedback, however, has primarily been studied for notifications, such as providing pulse patterns with a single motor (*e.g.*, [24]) or localizing one motor in a grid of motors (*e.g.*, [5, 22]). Fine-grained directional guidance for the hand has received less attention. Weber *et al*. [33] and Sergi *et al*. [28], for example, studied wrist-based haptic guidance for 3D hand movements and a relatively small set of target directions (4 or 6). However, the accuracy with which users can interpret an arbitrary target direction (*e.g.*, our study evaluates 32 directions) and execute a corresponding movement is not yet known—basic information that would impact the design of a range of interactions, from quickly finding a target to tracing a path.

In this paper, we report on a controlled lab experiment to evaluate the impact of wrist-based vibro-motor feedback on hand movement, comparing lower-fidelity (4-motor) and higher-fidelity (8-motor) wristbands. Twenty participants completed a series of trials consisting of interpreting a haptic stimuli and executing a 2D directional movement on a touchscreen. For the results to apply to non-visual interaction scenarios such as situational impairments, participants were blindfolded. We assess movement error and trial speed, but also analyze the impact of specific directions on performance. The contributions include: (i) empirical evidence that doubling the number of haptic motors reduces directional movement error, and that movement error is greater to the upper-left than in other directions; (ii) identification of an empirically derived maximum threshold of ~25° accuracy using our approach; (iii) design considerations for incorporating directional haptic guidance into a smartwatch band—in particular, for most applications, a four-motor wristband may be sufficient.

2 RELATED WORK

Designing effective haptic feedback requires a consideration of factors such as human perception thresholds and the ability to discriminate different haptic patterns; see [6] for a survey. While our focus is on fine-grained directional guidance for hand movements, many projects have looked at directional feedback for directing the user's whole body (*e.g.*, for navigation). These include a few examples with wrist-worn devices with one [2, 3, 18] or four [23] vibro-motors, but more commonly other parts of the body are used, such as the waist or back [8, 17]. In terms of general feedback on the wrist or forearm, Cholewiak *et al*. [7] showed that localization is most precise when the stimulus is close to an anatomical point of reference (*e.g.*, wrist or elbow).

Most closely related to our study is work on haptic directional guidance for the hand or arm. Schätzle *et al*. [26] studied different fidelities of wrist-based translation and rotation feedback, but the study had critical validity issues including no counterbalancing. In follow-up work, Weber *et al*. [33] compared wristband conditions with four or six motors, assessing the user's ability to perceive a signal and rotate or move their arm in one of four or six directions. Providing a verbal direction ("up", "down", "left", or "right") resulted in better performance than the haptic feedback for this relatively simple task. In contrast, we evaluate movement in 32 directions, for which discrete verbal feedback would not be feasible. Sergi *et al*. [28] compared the impact of visual and haptic feedback on reaching accuracy in a virtual reality (visual) environment with a small set of targets. Stanley and

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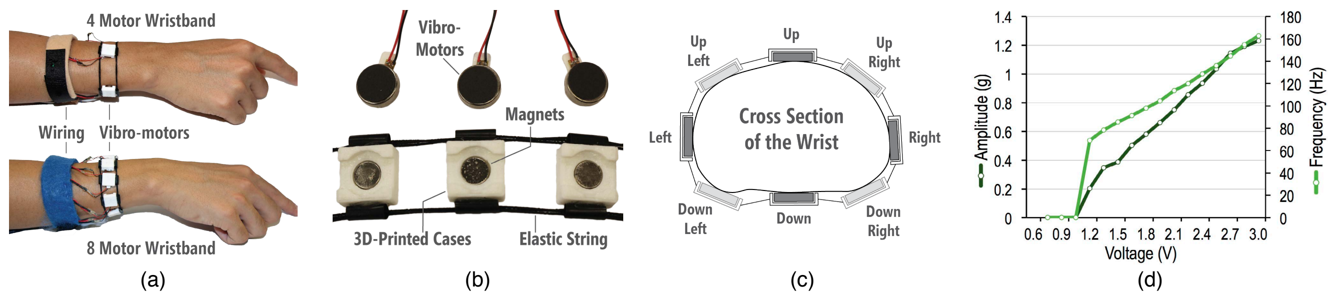


Figure 1: (a) The four- and eight-motor haptic wristband prototypes. **(b)** A close-up of our haptic design; motors were placed in the 3D-printed cases using magnetic attachments, and the wristband faced downward so that the motors directly contacted the skin. **(c)** Motor placement on the right-hand wrist, from wearer's perspective. Our custom-designed wristband could accommodate wrists of various shapes and sizes. Motor placement was adjusted per participant to match this figure. **(d)** Graph of effective voltage *vs.* vibration frequency and amplitude using a wrist-worn motor measured with an oscilloscope and an accelerometer respectively. The x-axis is the analog voltage output on the Arduino Mega, which simulates analog output using PWM. Results were used to verify a linear relationship of voltage input with amplitude and frequency and to empirically determine minimum voltage (1.2V).

Kuchenbecker [29] examined bi-directional rotation guidance on the wrist (guidance to rotate the wrist left or right) by manipulating intensity to indicate the degree of rotation required. Their approach thus provides 1D feedback in contrast to our 2D guidance.

As opposed to these wristband designs, another approach is to arrange motors in a grid or on the back of a watch face rather than along the band. For example, Chen *et al*. [5] compared 3×3 grids of motors on the dorsal and volar sides of the wrist, concluding that only two motors could be reliably distinguished. To indicate cardinal directions (among other information), Yatani and Truong [34] used a cross-layout of five actuators on the back of a phone, while Lee *et al*. [19] used sensory saltation with a 3×3 grid on the back of a smartwatch display. Our prototypes use motors along a wristband, although grids could be explored in the future. Matscheko *et al*. [21] compared the user's ability to discriminate motors placed on the back of a watch face versus on the band, finding higher perception with the band.

Our design relies on a phenomenon called *phantom sensation*, where two vibrotactile actuators placed closely together on the skin create the illusion of a single vibration between the two actuators [1]. In early work, Alles [1] showed that the location of a phantom sensation can be changed by varying the amplitude of the two motors (amplitude inhibition) or offsetting the time at which each motor vibrates (temporal inhibition), but concluded that amplitude variation was most effective. While Alles originally suggested theoretically that it would be better to vary amplitude logarithmically rather than linearly, there is some debate (*e.g*., [16]), and Seo and Choi [27] recently showed that users were better able to localize the phantom sensation with linear interpolation. For our work, we use linear interpolation.

3 METHOD

To compare directional guidance with four or eight wrist-mounted vibration motors, we conducted a controlled lab experiment assessing participants' ability to move their finger in a prompted direction. Participants were blindfolded to help simulate a non-visual context and limit distraction. The main hypotheses were that the two wristband conditions would impact accuracy and trial completion time differently, with the eight-motor wristband being particularly accurate.

3.1 Participants

We recruited 20 participants (10 male) aged 19-58 years old (M = 29.7, SD = 10.6) through campus email lists. All but two participants reported daily use of a touchscreen device, and all participants had experience with vibration feedback from a smartphone, video game controller, or other device. Participants were volunteers and compensated $10.

3.2 Apparatus

The custom experimental system consisted of a vibrotactile wristband connected to an Arduino Mega microcontroller, and an Android application running on a Samsung Galaxy Tab 4 (10.1-inch screen, 1280 × 800 resolution). The experimental tasks were presented on the tablet, which communicated with the Arduino via Bluetooth. For each trial, the participant interpreted a vibration and moved their finger correspondingly on the tablet. The touchscreen allowed us to capture precise finger traces in reaction to the stimuli. During the study, the tablet was affixed in a landscape position on a table in front of the participant.

3.2.1 Physical prototype design

The two wristbands, shown in Figure 1a, were identical except for the number of motors (four or eight). We used circular eccentric rotating mass (ERM) disc vibro-motors 10 mm in diameter, with maximum voltage of 5V, maximum frequency of 183Hz, and response time of 100ms.[1] This type of motor has been effectively used to create phantom sensations [25], is inexpensive and ubiquitous, and the flat design means it can be easily integrated into a wristband.

Our custom design addresses three issues: vibration transfer along the band, variation in wrist size, and the non-uniform shape of a wrist. To effectively isolate the motors and limit vibration transfer—an issue in our early designs—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 (Figure 1b). The band with the wiring connected to the Arduino for communication and power. Because the wrist is not a uniform oval (Figure 1c), placing the motors equidistantly around the band (as in [26, 33]) 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 [14]). The experimenter could thus adjust the band per user.

[1] Adafruit motor disc: http://www.adafruit.com/product/1201

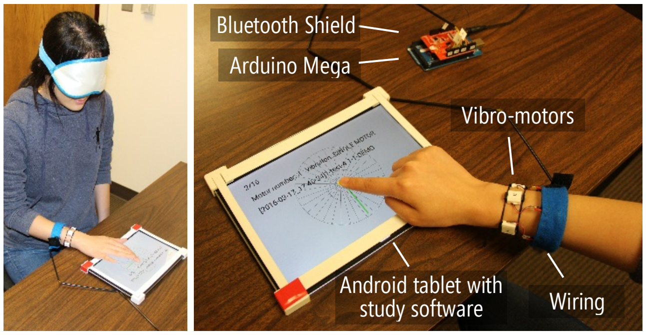


Figure 2: The experimental setup showing the Android tablet, 4-motor wristband, and the Arduino Mega with Bluetooth Shield.

3.2.2 Haptic feedback

Vibration amplitude and frequency were controlled by the Arduino's analogWrite() function, which controls output voltage using pulse-width-modulation (PWM). A higher voltage corresponded to higher vibration amplitude and higher frequency in the ERMs (Figure 1d). ERMs do not provide independent control of amplitude and frequency, but frequency is not a significant factor in accurately locating a phantom vibration [7].

The amplitude range used for the experiment was 0.2–1.2g, while the corresponding frequency range was 69–162 Hz. These ranges were determined through two mechanisms. First, to empirically investigate the physical performance of our ERMs, we used an accelerometer to measure amplitude and frequency at different voltages with an ERM worn on the wrist. As shown in Figure 1d, the relationship was roughly linear above 1.2V for both amplitude and frequency, up to a maximum amplitude of 1.2g and frequency of 162Hz at 3V. Second, to ensure that the full vibro-range used in the experiment would be perceptible by users, we conducted a simple perception test with six participants from our lab. We increased the voltage continuously from 0V and noted the threshold at which the participant first reported feeling a light vibration, then decreased it from 3V until no vibration was felt (again, marking the voltage threshold). To be conservative, we selected the maximum value among all reported thresholds (corresponding to 0.2g and 69Hz) as a perceptible lower bound on our vibration range.

To indicate a target direction, one or two motors vibrated. If the target direction exactly matched a motor's location on the band, the maximum voltage was applied (3.0V) to that single motor. For directions between two motors, voltage was linearly interpolated to produce correspondingly linearly interpolated amplitudes and frequencies within the ranges given above. For example, 45° is exactly between two motors on the 4-motor wristband, so both motors vibrated at the midpoint of the amplitude and frequency ranges, while for 70°, one motor vibrated at higher amplitude and frequency than the other. More formally:

$$V_1 = (\theta_2 - \theta - \theta_{start}) \frac{V_{max} - V_{min}}{\theta_2 - \theta_1 - \theta_{start}} + V_{min},$$

$$V_2 = (\theta - \theta_1 - \theta_{start}) * \frac{V_{max} - V_{min}}{\theta_2 - \theta_1 - \theta_{start}} + V_{min}$$

where V_1 and V_2 are the voltages applied to the two neighboring motors, $V_{max} = 3.0$, $V_{min} = 1.2$, θ_1 and θ_2 indicate the motor placements, and θ is the target direction ($\theta_2 > \theta > \theta_1$). To support 32 discrete directions for our experimental task (11.25° intervals; Section 3.3), interpolation only occurred if θ is >= 11.25° from any motor; θ_{start} is thus a constant equal to 11.25°.

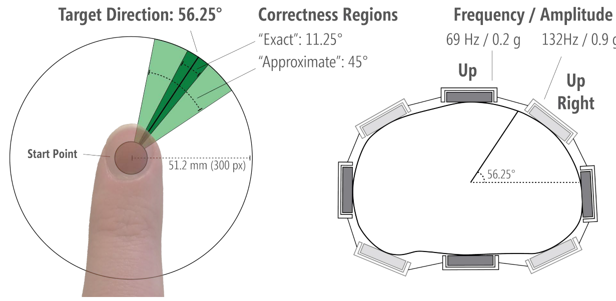


Figure 3: Example trial with target angle of 56.25°, showing start location, "exact" and "approximate" correctness regions, and relative frequency and amplitude of the two neighboring motors used to interpolate the target angle.

3.3 Procedure

The study began with a background survey. The two experimental conditions (4-motors or 8-motors) were then presented in counterbalanced order. For each, the experimenter placed the wristband on the participant, adjusted the size to be tight yet comfortable, positioned the vibration motors as shown in Figure 1c, and moved the tablet perpendicular to the participant's arm. We did not directly control the participant's arm placement, but asked them to use the same posture throughout. Participants were then blindfolded to ensure non-visual interaction. See Figure 2 for pictures of the experimental setup.

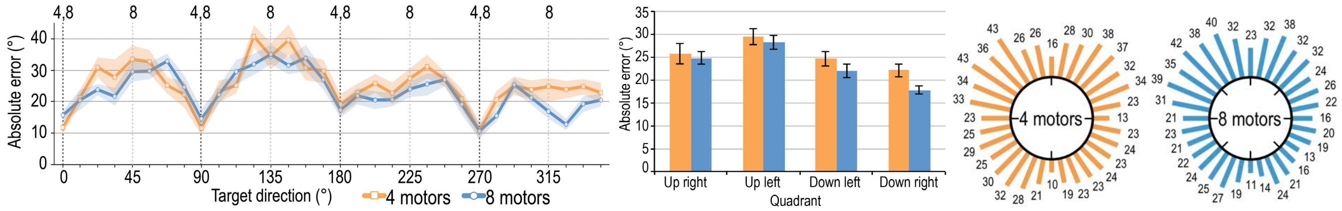
The task included 32 uniformly distributed target directions (11.25° intervals). The number of directions (32) was chosen both because it is divisible by 8—thus covering all cardinal and intercardinal directions—and because it offers greater precision than experienced members of our research team could achieve when using the wristbands—thus likely allowing us to identify an upper bound on human performance with this task.

For each trial, the participant placed their finger on a tactile marker (a small, thin sticker) in the middle of the screen. After one second, a chime played and the wristband began vibrating in a target direction. The participant moved their finger in that direction until the vibration stopped and audio feedback played, which happened when the finger was more than 51.2 mm (300 px) from the start. The vibration stimulus was thus applied for the full duration of the trial, which was about two seconds in our study. As shown in Figure 3, we provided two levels of success feedback so that participants could aim for precision but not be discouraged: "exact" success was within an 11.25° interval centered at the target angle (a chime followed by the word 'Perfect!"), while "approximate" success was within a 45° interval (only the chime). Otherwise, the trial was an error (beep sound).

Participants completed 16 practice trials: eight directions at 45° counterclockwise intervals, and eight more directions randomly selected from the full 32 (but the same for all participants). During practice, participants could repeat error trials once. The test task consisted of 96 trials: three repetitions of each of the 32 directions presented in randomized order per participant. Participants were asked to complete the task quickly and accurately. Afterward, participants compared the two conditions (4-motors and 8-motors) on ease of use, accuracy, and preference.

3.4 Experiment Design and Hypotheses

We used a within-subjects design with a single factor of *number of motors*: four or eight motors. Order of presentation was fully counterbalanced and participants were randomly assigned to orders. Our hypotheses were:



(a) (b) (c)

Figure 4: (a) Average absolute error per direction, showing lower error in cardinal directions but a less clear trend for intercardinal ones, even for the 8-motor wristband. The numbers at the top of the graph (4, 8) indicate directions corresponding to physical motor placement (4- or 8-motor bands).Shading indicates standard error. **(b)** Absolute error by quadrant. Error bars indicate standard error. **(c)** Average absolute error by angle, showing highest errors in top-left quadrant. *N* = 18 for all three figures (two participants were extreme outliers and not included).

- *H1: The 8-motor condition will result in lower absolute error than the 4-motor condition*. Because eight motors provide twice the fidelity, participants should be able to more precisely interpret the vibration than with four motors.
- *H2: The 8-motor and 4-motor conditions will impact trial completion time differently*. For this measure, which encompasses both the time to perceive the stimulus and execute a motion, we did not have a directional hypothesis. Conceivably, the 4-motor condition could be faster because it is simpler and should be perceptually easier for at least the cardinal directions, or the 8-motor condition could be faster because of the additional intercardinal information.

3.5 Data and Analysis

All touchscreen interactions during the trials were logged. The primary measures were *absolute error*, defined as the absolute angular difference between the target angle and movement angle, and *trial completion time*, defined as the time per trial measured from the start of directional vibration. We also examined *signed error* as a secondary measure to assess any systematic clockwise or counterclockwise bias to the movements.

In total, participants completed 1920 trials: 20 participants × 96 trials. Two participants were extreme outliers on the primary measure of absolute error for at least one condition using the inter-quartile range method [32]; they are thus excluded from analysis. One of these participants was the oldest of the set, while the second encountered substantial confusion in recognizing vibrations on the top of his wrist during the first condition. In general, we used parametric tests when the data met applicable assumptions, and non-parametric tests otherwise. For our primary measures specifically, the absolute error measure did not violate the normality assumption (*i.e.*, Shapiro-Wilk tests for the 4-motor and 8-motor conditions were not significant). Thus, since hypothesis H1 was directional, we used a one-tailed paired t-test for this measure (the only one-tailed test used in the entire analysis). Trial completion time (speed) did violate normality in the 4-motor condition (Shapiro-Wilk test: $W = 0.88$, $p = .029$), so we used a Wilcoxon signed rank test in this case.

4 Results

We compare the two conditions in terms of error and speed, and provide secondary, more in-depth directional analyses.

4.1 Movement Error and Trial Success Rates

For both conditions the absolute error was about twice the interval between the target directions. As expected, participants were more accurate with the 8-motor condition than with the 4-motor condition, with an average absolute movement error of 23.2° (*SD* = 3.47) compared to 25.4° (*SD* = 4.6). This difference

Threshold	Exact	Approximate
4 motors	15.9% (*SD*=5.2%)	54.3% (*SD*=8.2%)
8 motors	16.3% (*SD*=2.9%)	56.4% (*SD*=6.5%)

Table 1: Average number of exactly or approximately correct trials. A movement within an 11.25° interval of the prompted direction was considered *exactly* correct, while movement with a 45° interval was considered *approximately* correct.

was statistically significant with a small-to-medium effect size, supporting hypothesis H1 (t_{17}=−1.95, p = .034, d = 0.46). This difference in absolute error, however, did not translate to significant differences in task success. In both conditions, participants had difficulty completing trials exactly correct (*i.e.*, within the 11.25° interval). As shown in Table 1, roughly 16% of trials were completed exactly correct regardless of condition, while just over half were completed approximately correct.

Finally, to understand whether there was a systematic bias in the direction of movement error either clockwise (+) or counterclockwise (-), we analyzed signed error. The average signed error was close to zero for both conditions: −1.3° (*SD* = 7.6) with four motors and 0.8° (*SD* = 7.9) with eight motors. This suggests that error in either direction (clockwise or counterclockwise) tended to cancel out on average. A paired t-test comparing the two conditions was not significant.

4.2 Trial Completion Time

The average completion time per trial was roughly two seconds: 2268.5 ms (*SD* = 767.2) with four motors and 2058.2 ms (*SD* = 664.6) with eight motors. The difference in average completion times between conditions was not significant with a Wilcoxon signed ranks test ($Z = -.89$, $p = .372$). The majority of this time consisted of perceiving the stimulus and planning the motor movement—the start of finger movement only began on average after 1707.8 ms (*SD* = 506.5) with 4 motors and 1557.9 ms (*SD* = 466.9) with 8 motors. Hypothesis H2, that there would be a speed difference between the two conditions, is not supported.

4.3 Detailed Directional Analysis

As a secondary analysis, we explored the extent to which the target angle impacted performance; Figure 4. We expected that the 8-motor condition would outperform the 4-motor condition for intercardinal directions (45°, 135°, 225°, and 315°), but as shown in Figure 4a, this pattern was not as clear as predicted. The average absolute error for these directions was 30.0° (*SD* = 8.7) with four motors versus 26.4° (*SD* = 7.0) with eight motors. This difference was only a trend-level result, suggesting that a larger sample size may be needed (paired t-test: t_{17} = -1.87, p = .08). Absolute error was lower with the cardinal directions, at 13.3° (*SD* = 6.0) for four motors and 14.6° (*SD* = 5.1) for eight motors, but the difference between the two wristband conditions was not significant (paired t-test: $t_{17} = 0.67$, $p = .510$).

More interesting is a breakdown of error by quadrant. As Figures 4b and 4c show, error tended to be higher in the top-left quadrant than in other directions. A two-way repeated measures ANOVA (number of motors × quadrant) was conducted for absolute error.[2] A significant main effect showed that the quadrants impacted the error ($F_{2.0,41.1} = 10.38$, $p < .001$, $\eta^2 = .38$). Posthoc comparisons with a Bonferroni adjustment showed that the upper-left quadrant was significantly worse than the two downward quadrants (at $p < .05$). The main effect of number of motors was only a trend ($F_{1,41.1} = 3.81$, $p = .068$, $\eta^2 = .18$), and the interaction effect was not significant.

4.4 Subjective Response

While no open-ended comments were collected, participants selected their preferred wristband in terms of ease of use, accuracy and overall preference. For accuracy, 13 participants chose the 8-motor wristband, suggesting they perceived value in the extra information it provided over the 4-motor wristband. Participants were divided, however, in terms of overall preference (9 *vs*. 9) and ease of use (10 votes for the 4-motor wristband *vs*. 8 votes for the 8-motor one).

5 Discussion and Conclusion

Our results confirm one of our two hypotheses, showing that doubling the number of haptic motors from four to eight increases accuracy of wrist-based directional guidance of the hand; however, speed was not impacted either way. Practically speaking, whether to include four or more motors for directional guidance will depend on the accuracy needed for the task. For example, tracing a shape or route would require higher accuracy than simply finding an object with the hand; the latter task could even be completed successfully even if the hand only moved in cardinal or intercardinal directions. Thus, the added cost and weight of doubling the number of motors may not be worth what was only an extra two degrees of accuracy in our study. Thus, we recommend that in most cases only four motors be used.

We also empirically identified a potential upper bound on accuracy with our approach, about ~23-25°. This accuracy is high enough to show that the frequency interpolation between adjacent motors was effective at least in the 4-motor condition. But, it also suggests that other human perceptual or motor factors are at play. While our study purposely did not isolate these two factors—we were interested in holistically evaluating the impact of haptic guidance on hand movement—it is an important area for future work. For example, a future study could present a visual array of 32 uniformly distributed target directions (at 11.25° intervals) and ask participants to select the target corresponding to the perceived vibro-stimulus; this would limit the impact of human motor factors.

Detailed analyses of the impact of target direction on error also showed that movements in the upper-left quadrant were less accurate than other quadrants, particularly the bottom quadrants. This pattern may be due to all participants completing the task with their right hand, and the upper-left quadrant requires more gross motor movement than the bottom quadrants. It is also possible that there is lower acuity at that location on the wrist due to factors such as bone structure or nerve density. Further work, including with left-handed users, is needed.

Our design included ERM vibro-motors embedded in a wristband, with the motivation that such a solution could be incorporated at low cost into a smartwatch. Other vibro-motor types, however, offer different characteristics that may be worth considering. For example, while the response time of our motors (~100ms) was much less than the overall time before participants initiated movement (> 1.5s), a design similar to ours but with linear resonant actuators (LRAs) could be useful to explore. LRAs offer shorter response time and allow for independent control of amplitude and frequency. Also, we applied linear interpolation to manipulate the perceived location of vibration, but since there is some debate about whether linear or logarithmic interpolation is better [1, 16], future work should compare the two. Another alternative is to use a grid of actuators perhaps placed on the back of a watch face to indicate at least coarse-grained direction (*e.g.*, [15, 19, 22]); such an approach could be compared to our band design. In addition, while we used a two-band design to reduce vibration transfer and adjust the motors per participant, we envision watchband designs with embedded motors and wiring. More work is needed to investigate vibration transfer using other form factors and band materials.

Future work should also investigate how our identified accuracy limit affects performance for more realistic tasks with continuously updated directional guidance (*e.g.*, finding a target, or tracing a path). While our current study did not include blind users, one long-term goal of our work is to extend these findings to include users with visual impairments and to investigate the use of haptic feedback for tasks such as physically exploring a printed page to read text or to gain spatial layout information (*e.g.*, [10, 31]). In these cases, the haptic stimulus should dynamically update to guide the user across an object or towards a target. In our study, vibrations were constant and did not update based on the user's movement (*e.g.*, to help correct an erroneous movement). This decision was purposeful so that our task would be more fundamental, but a more dynamic approach would likely result in higher accuracy. Of course, in any real-world task, potential sensory adaptation to the haptic vibration would need to be considered [12].

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