Perception in Hand-Worn Haptics: Placement, Simultaneous Stimuli, and Vibration Motor Comparisons

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ABSTRACT
Glove-based tactile interfaces are used for augmented reality, rehabilitation, teaching, and consumer electronics control. Yet questions remain regarding perception of tactile stimuli on the hands. In an effort to inform the design of such tactile interfaces, we investigate participants' abilities to sense vibration on the hands. First, we examine the effect of stimulus location on recognition accuracy. Ventral (palm-side) placement on the fingers is critical: accuracy increases with proximity to the palm, linearly, on all fingers. Second, we study perception of multiple simultaneous vibrations on the fingers ("chords"). Chord recognition degrades with increasing number of simultaneous stimuli. Our third study compares the perception of Eccentric Rotating Mass (ERM) and Linear Resonant Actuator (LRA) vibration motors. Recognition accuracy was less using LRA motors, especially in placements on the palm side of the fingers (-20.3% versus -10.1% for ERM). Correct recognition of chords was also less or comparable using LRA motors, suggesting that the ERM motor is preferable.

INTRODUCTION
Haptic systems are used for a diverse range of applications such as microinteractions in mobile systems [26], alternative interfaces for accessibility [10], augmented reality in entertainment and gaming [21], and wearable interfaces for passive haptic learning [12, 13, 24]. Many applications that use tactile feedback focus on the hands [3, 5, 6, 12, 13, 16, 24, 26, 28, 29]. Our team researches wearable tactile interfaces to teach manual skills such as playing piano, typing Braille, and typing stenotype [12, 13, 24] while the user performs normal everyday tasks.

For applications like these, researchers seek to create gloves (hand-mounted haptics) that take into account several criteria: They should obstruct the hands minimally during everyday activities so the system has 'wearability.' Considerations must be made for things such as weight and movement; so small tactors and strategic placement are key. The system must also present stimuli that are easily detected. Users often need to perceive stimuli while performing other tasks. Conveying chorded (simultaneous multi-point) stimuli and multiple discrete points per finger are also important. For example, musical instruments and many typing systems require simultaneous key presses by multiple fingers, so conveying this through haptics requires conveying "chorded" stimuli. We present three studies that inform the design of such a haptic system.

The first study, containing 40 participants, investigates where to place stimuli points on the fingers so users can most easily sense and discriminate between them. Applications and systems that employ tactile interfaces can expand the number of stimulus points per finger that they use and optimize their designs based upon these results. In the second study, we present 16 users with multiple simultaneous vibrations ("chords") across the fingers and examine participants' accuracy in identifying what motors were activated. This study explores people's ability to perceive simultaneous haptic stimuli. We explore chorded stimuli because, in addition to multiple stimulus points per finger, simultaneous multiple-finger or multiple-location signals increase the density of conveyable information and may be needed in a haptic interface. The third study, with 20 participants, compares Eccentric Rotating Mass (ERM) and Linear Resonant Actuator (LRA) vibration motors for use in wearable, tactile interfaces. This experiment examines which motor type is preferable for use in wearables and the differences in performance between these haptic element types.

Specifically, we:

- Demonstrate trends important for placement of tactors on the hands
- Expose persistent error in human perception of simultaneous stimuli
- Compare perception performance using two common tactors

BACKGROUND AND MOTIVATION
Perception of haptic communication has been studied on many areas on the body, which have differing abilities to sense stimuli [7, 15, 19]. Application domains that focus on tactile feedback on the hands include rehabilitation [5, 14], accessibility [10, 29], gaming [28], teleoperation [3], learning

[6, 12, 13, 16, 24], and sensory augmentation for applications ranging from firefighting [26] to movie viewing [21]. These types of projects benefit from optimizing stimulator placement for discriminating between haptic signals. While many systems are mounted on or use the fingers, choosing ideal locations for haptic perception on the fingers is complex and requires study.

Simultaneous stimuli may be used to convey a composite of individual signals, create additional signals or enhance sensation effects. Applications include providing directions [25], conveying images [27], motor training [20], and Passive Haptic Learning [6, 8]. For example, haptic conveyance of motor tasks such as controlling a teleoperation device or typing often require "chorded" (simultaneous) stimuli. Typing Braille requires that multiple keys be pressed at once. Thus, in order to convey Braille [23], simultaneous stimuli would be used if their perception is possible.

Previous application research using simultaneous stimuli was unable to convey correct meanings to users [23, 28]. In other work, the counting of simultaneous stimuli across the whole body was studied for subitizing (rapid, accurate numerosity judgments, normally by the visual system, of up to about four items). No subitizing effect was found, and error occurred in counting judgments of the number of tactile stimuli across the entire body [9]. Our work expands on existing research to explore perception on the hands and of simultaneous stimuli; we also compare performance of popular tactors small enough to be integrated into mobile systems.

STUDY #1: PLACEMENT

Where on the fingers should you stimulate? We examine tactor placement points on the fingers to see if there are optimal positions that allow participants to perceive three conditions distinctly: top stimulus, bottom stimulus and both. The primary research question is as follows: How can we create a tactile interface with multiple stimulus points per finger that still allows the user to recognize what location(s) are vibrating? We hypothesize that locations farther from the fingertips will better stimulate the medial nerves of the hands, resulting in better stimulus recognition.

System

To produce the stimuli in this experiment, 8 mm Eccentric Rotating Mass (ERM) pancake vibration motors from Precision Microdrives were activated using a TI Darlington array chip and a programmed Teensy++ 2.0. Driving details are identical to those used in the Vibration Motors subsection. For the finger being tested, five motors were held in position (shown for the index finger in Figure 1) using their native adhesive inside a snug spandex finger sleeve. This test replicates the fit of vibration motors in a 4-way stretch glove, which uses a material chosen to allow the motors to rest flush against the skin for differing hand sizes, while not suppressing vibration with rigid fabrics.

Study

In this study, we test whether users can more accurately identify tactile stimuli depending on the stimulus location on the finger. Each participant is randomly assigned to one of five conditions, which determines which finger is tested on that participant. Users wear the finger sleeve on their assigned finger as we present stimuli. Participants respond to each stimulus with a key press, identifying whether a vibration was on the top ("dorsal") side of the hand, the bottom ("ventral") side of the hand, or a combination of both. During a trial, the system pauses for one second, vibration motor(s) are activated for 400 ms, and the system then waits for the participants' key response (on a 3-key keyboard). When the motor on the dorsal side of the hand (position A or B) is activated, the correct response is "up" on the keypad. Similarly, when the motor on the ventral side of the hand (position X, Y, or Z) is activated, the key associated with this stimulus is "down" on the keypad. When tactors on the dorsal and ventral sides of the hand are activated together, the correct answer is "both."

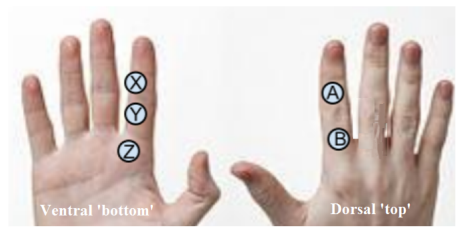

Figure 1. Motor positions used in the first study. Alphabetic labeling is for reference in this paper for simplicity and is never presented to participants.

The six different permutations of vibration-motor location pairings (AX, AY, AZ, BX, BY, and BZ in the above image) were tested for the assigned finger on both hands of each participant to examine whether motor placement has an effect on the participants' accuracy in perceiving the stimuli. The study design is within-subjects for the six different permutations of tactor placement, and between-subjects for testing of these arrangements on each of the five fingers. We recruited 40 participants for this study (eight participants for each of the five fingers). The study was randomized and counterbalanced for location and condition.

For each location pairing, only the motors in these positions are activated to make the 'top,' 'bottom' and 'both' conditions. The participant starts with a practice period of six randomly ordered stimuli, two for each stimulus condition (top, bottom, both). After the practice period, the participant is told if the response was correct, and if it was incorrect, the correct response is given. The participants then perform 18 trials in which stimulus conditions (top, bottom, both) are randomly ordered, with each condition being tested six times per trial. Their responses were recorded, and they were not given any feedback regarding correctness. This process was repeated for each of the six pair permutations on the finger, for one hand then the other, resulting in 216 total trials per participant.

Results

Results from study #1 exposed significant and consistent effects on perception accuracy depending on where the haptic stimuli points were located on the fingers.

We calculated participants' percentage of correct responses as 'accuracy' and performed a repeated measures ANOVA with Hyunh-Feldt correction to ignore sphericity. There was a significant effect of ventral (bottom) motor positioning on response accuracy ($F(3,2) = 31.472$, $p < 0.001$). The Bonferroni correction is omitted due to our a priori hypothesis regarding the physiological basis for these differences. In contrast to the strong effect of the bottom stimuli location, dorsal (top) location was not found to have a significant effect on accuracy. To analyze the effect of ventral positioning further, we performed pairwise comparisons of the ventral position results and found all three comparisons to be significant.

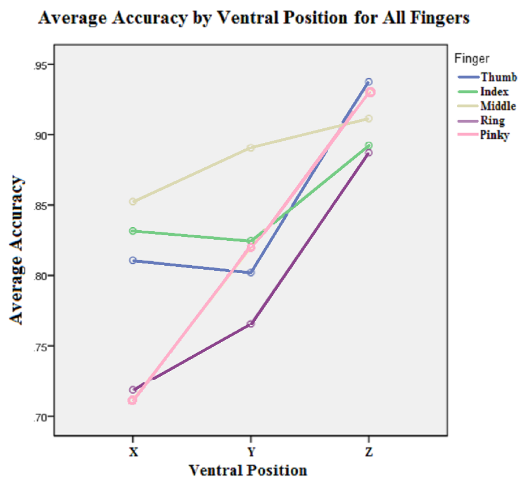

Figure 2. Plot of average accuracy by motor position on each finger.

There was a significant accuracy difference found between the three ventral (bottom) positions X, Y, and Z. We analyzed the contrasts between fingers for this interaction and discovered that the data fits to a linear trend. As highlighted by Figure 2, perception accuracy improves or shows no significant difference as the ventral motor position moves towards the center of the hand (away from the fingertip) in all five fingers.

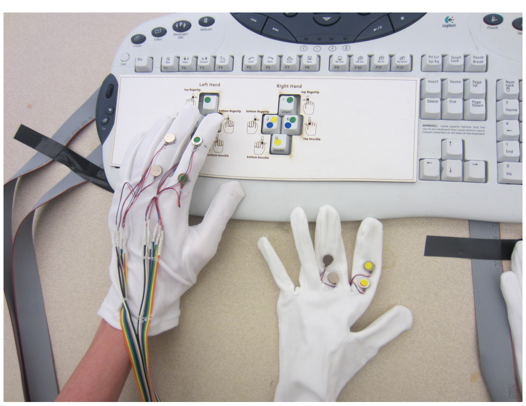

Figure 3. A glove pair and the input interface for studies #2 and #3.

Discussion

Given the vibration frequency of our motors, the Pacinian corpuscles in the hand should respond the most. Pacinian corpuscles are located primarily in the metacarpophalangeal ridge (the ventral region between the fingers and palm) and the tips of the fingers (preferentially in the thumb, index, and middle finger [4]). Thus, a hypothesis for the decline in perception accuracy as the motors are placed further from the palm on the ventral side is that the Pacinian corpuscles in the metacarpophalangeal ridge are primarily detecting the sensation (especially for the ring and pinky fingers). For the other fingers and thumb, perhaps as the motors are placed closer to the tips of the fingers, the Pacinian corpuscles there start to respond some, avoiding the larger drop in accuracy seen in the ring and pinky fingers. The fingertip is a common choice for designers of tactile input systems [3, 5, 6, 16, 26, 28, 29], and as shown here, this choice may not be ideal for some applications. Fortunately for us, the results are advantageous. Both the ventral and dorsal motors can be placed close to the palm, which allows the creation of fingerless gloves that minimally interfere with the wearer's use of the fingers.

APPARATUS FOR STUDIES #2 AND #3

Our second and third studies focus on simultaneous stimuli and user perception of two types of vibration motors. First, we describe the apparatus, followed by the studies themselves. For these studies, we created two pairs of gloves (see Figure 3), that administer haptic stimuli to different points on the hands. One pair uses Eccentric Rotating Mass (ERM) vibration motors while the other uses Linear Resonant Actuator (LRA) motors. Both motors are the "coin" form factor. Studies 2 and 3 are repeated for each pair of gloves, so results can also be compared by what vibration motor type is used to make the haptic interface.

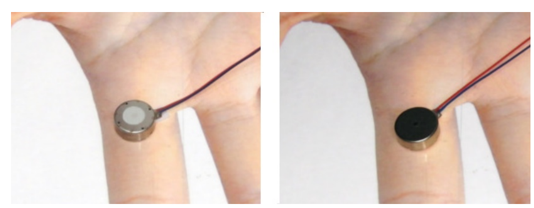

Figure 4. The ERM and LRA motors. These lightweight, 'coin' form motors are optimal haptic elements for wearable devices. From Precision Microdrives.

ERM vibration motors

Eccentric Rotating Mass (ERM) vibration motors contain an asymmetric mass and are powered by DC current [1]. For our Precison Microdrives ERMs (part #310-113), we use 3.3 V DC to provide the constant current required by this system for peak recommended vibration strength (1.38 G) and a 220 Hz vibration frequency (vibration frequency increases proportionally with applied voltage). These motors are driven by TI ULN2003 Darlington array chips to buffer the system's microcontroller and provide the necessary amplified current.

LRA vibration motors

Linear Resonant Actuator (LRA) vibration motors became available on the market relatively recently and are designed for a longer lifespan and a more precisely targeted vibration than the ERM motors. The mass inside an LRA motor vibrates along an axis (rather than eccentrically) and is most efficient (highest output amplitude) at its resonant frequency. The resonant frequency of the LRAs (Precision Microdrive part #C10-100) in our study is 175Hz [22] and is detected and maintained by 5 V DC Texas Instruments DRV2603 surface mount driver chips which provide AC current at the required resonant frequency. For these studies, we drive the LRA motors at their peak amplitude of 1.4 G.

Motor Placement

We focus on the index and middle fingers for the remaining studies. Each of these fingers is outfitted with four motors, two on the dorsal (top) side and two on the ventral (bottom) side (positions A, B, X, and Y in Figure 1). Thus, the LRA and ERM gloves each contained 16 vibration motors, eight per hand. We chose not to use position Z as the vibration motors interfere with gripping in this position, and we require our gloves to be practical during everyday activities.

Feedback Interface

In the studies we administer stimuli and ask the users what they felt. A standard desktop keyboard was adapted for our participants to indicate the perceived stimuli. Alphabet keys were removed, with the exception of keys we used to collect responses. A laser-cut overlay exposed only the keys used for the studies. The overlay also provided a diagram that reminded participants of the mapping between stimuli and responses (Figure 5).

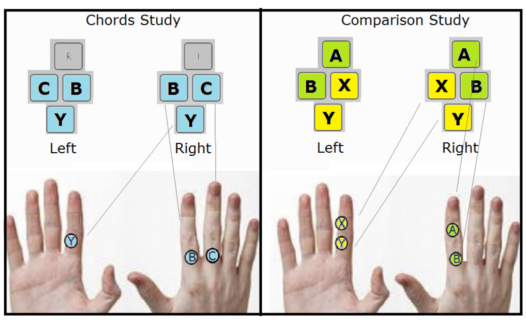

Figure 5. Key mappings used for the chords and comparison studies: each key's corresponding motor position is shown here on the right hand. Participants are told to use these mappings to input responses to stimuli. Users are presented reference diagrams and color codings, not the alphabetic codes in this image.

For study #2, only three keys for each hand are used as inputs, corresponding to positions B, C, and Y as shown in Figure 5. There is a one-to-one correspondence between vibrator motors and keys. For the right hand cluster of keys, the motor on the middle (right) finger on the right hand maps to the right key, the index (left) finger motor on the right hand maps to the left key, and the bottom (ventral) motor maps to the bottom key. A similar geometric mapping exists for the left hand. Resting the index and middle fingers above the input keys places the motors near their corresponding key. Participants use the stimulated finger to indicate their responses. These input mappings were chosen for their intuitiveness after testing on team members. Participants press the keys of the motors they identify as having vibrated in the last stimulus and may enter keys sequentially or simultaneously. For the motor comparison study (#3), users receive stimuli on only the index fingers, but all four positions (A, B, X, and Y) and corresponding keys are used.

Software

Studies were automated by a program that controlled the delivery of stimuli. The system software delivered the study's stimuli in a random order for each participant. Users attempt to identify the location of the stimuli and input their response via the keyboard before telling the administrator/proctor that they are finished with their input(s). The study then continues. The program logs delivered stimuli and user responses throughout each testing period.

STUDY #2: CHORDS

What about perceiving multiple stimuli at one time? We wish to create a wearable interface that presents simultaneous signals in a recognizable format. Thus, we conducted a study to examine whether participants can perceive and recognize multiple simultaneous tactile stimuli on the hands ("chords"). Based upon previous studies in which chorded haptic signals were not perceived correctly by our participants, we hypothesized that users may not be able to recognize multiple simultaneous stimuli. Sixteen users participated in this "chords" study.

Users are told to expect one or more simultaneous stimuli and to try and correctly identify all points of vibration and enter their answer on the keypad. Participants then don their assigned first pair of gloves (ERM or LRA), and the software begins delivering stimuli and logging response data. When all stimuli have been presented and users are done with their final input response, administrators help the user switch gloves, and the study repeats for the new pair. Glove orders are randomized and counterbalanced. Participants wear headphones to prevent audio localization cues.

We chose to use the dominant two fingers of each hand to compare adjacent-finger and two-hand simultaneous stimuli of up to four points in our chords study. If this study showed high perception accuracy, we would expand the study to include chords on all fingers. However, we first want to establish that chorded perception is possible. All permutations of one-, two-, three-, and four-motor combinations of motors in positions B, C, and Y on both hands were examined. This technique allows examination of chords on adjacent fingers on the same hand, chords across both hands, and chords containing stimuli on the top and bottom of the hands. It also tests the motors individually to examine whether users can identify multiple chorded stimuli versus single stimuli. Position X is not used as study #1 showed that position had less perception accuracy, and we wanted to test the strongest practical motor locations first.

Activation duration was consistent throughout the chords study. Simultaneous motor groups (or individual motors) were activated together for 300 ms during each stimulus. This duration was used in previous work [9, 12, 13, 24] and allows time for our ERM motors to reach full-speed. Each stimulus was delivered twice for each possible set of chords (four times total – twice for each glove type).

Results

Numerosity Judgments

The number of vibration points that users sensed and recorded (numerosity judgment) was calculated using the number of inputs they entered for each presented stimuli set. This data was averaged and grouped by the actual number of stimuli delivered in that set. As illustrated in Figure 6, users average 1.09 and 1.94 points sensed respectively for single stimuli and chords of two stimuli. T-tests suggest that for numerosity judgments of one and two stimuli there is not a statistically significant deviation from ground truth, for either motor type (ERM and LRA) or on the average. Users under-sense stimuli sets of three or four, with average points sensed of just 2.51 and 2.77. T-tests show a significant difference in user judgments compared to ground truth (presented stimuli number) for stimuli sets of three (ERM: $t(15) = 5.23$, $p < 6E-05$; LRA: $t(15) = 4.79$, $p < 0.0002$; Avg.: $t(15) = 5.40$, $p < 4E-05$) and four (ERM: $t(15) = 8.60$, $p < 2E-07$; LRA: $t(15) = 6.80$, $p < 3E-06$; Avg.: $t(15) = 8.31$, $p < 3E-07$).

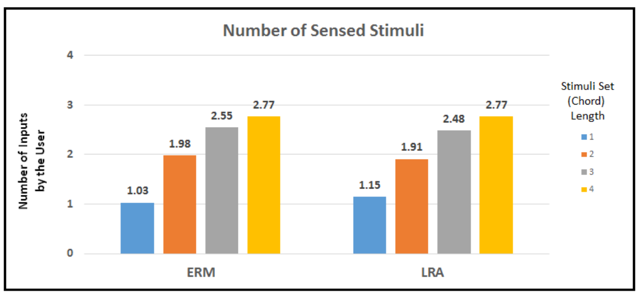

Figure 6. Average number of stimuli entered (sensed) grouped by actual number of stimuli and by motor type (which pair of gloves).

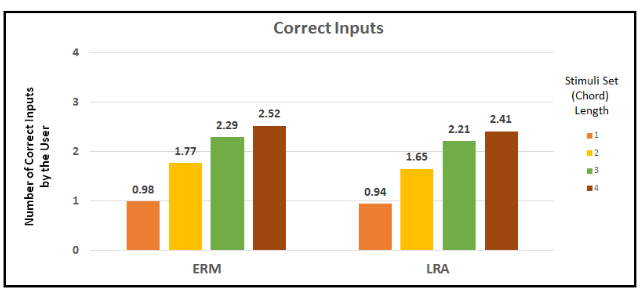

Figure 7. Correct content (average number of correctly identified stimulus points) by number of stimuli in the chord. Graph represents the correct/usable data perceived, regardless of other incorrect or missing user responses to that chord.

Points Correct (Content)

For each set size, we calculate the average number of points in each user response that are actually correct. This metric gives a sense of the content that users correctly perceive. Results show that content is lost or incorrectly sensed by participants for all chord lengths. T-tests confirm significant deviation from expected ground truth content scores, for all stimuli set lengths (one through four), for both motor types used. In addition to incorrect counting judgments (Figure 6), Figure 7 illustrates that the stimuli placements are often incorrectly identified. Thus, the usability of simultaneous tactile stimuli on the fingers is dubious due to the average 20-40% loss of data in every chord, regardless of which of the two motor types we used.

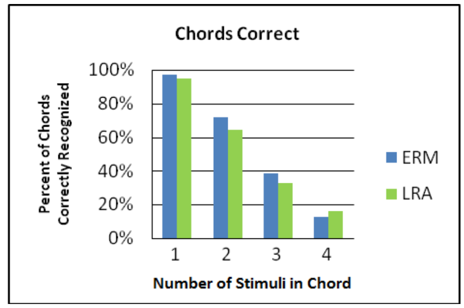

Figure 8. Percentage of chords recognized without any error (100% of stimuli presented were recognized and identified), for chords of different numbers of stimuli.

Chords Correct

User answers that exactly match the stimuli just presented are counted as totally correct. We calculated the percentage of totally correct answers for each chord (stimuli set) size and present this data in Figure 8. While chords of one and two stimuli maintain average accuracies of over 65%, correct recognition of all points in chords of three and four was less than 40% and less than 20% respectively.

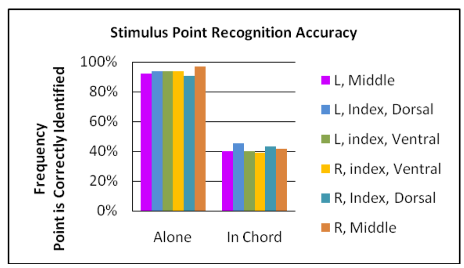

Figure 9. Recognition accuracy by stimulus location – when stimulus is alone versus when it comes simultaneously with other stimuli.

Examination of whether there were better-sensed locations for chorded stimuli points indicated no significant differences. Figure 9 depicts these findings. As illustrated, identification accuracy for each point drops by an average of 50% when in conjunction with other simultaneous stimuli, independent of motor location (alone M=93%, SE=0.0085 vs. in chord M=42%, SE=0.0093). T-tests suggest that this difference is significant ($t(15) = 39.21$, $p < 1E-06$).

Motor Comparison Findings in the Chords Experiment

We contrast results produced using the ERM and the LRA gloves in the chords experiment to draw further conclusions about how vibration motors compare with each other for usability. Contrary to expectation, the gloves with embedded LRA motors provide no significant benefit to numerosity judgments or localization/identification of stimulus points. Users exhibit similar performance for both motor types in counting judgments for all stimulus set sizes, and t-tests indicate that any performance differences are not significant.

LRA motors again provide no significant performance difference with respect to ERM motors when comparing correct points (chord content) in chords of three or four, and they actually provide significantly fewer correct stimuli identified when users receive one or two simultaneous stimuli (paired t-test: single stimulus t(15)=2.07, p <0.0281, two-stimuli sets t(15)=2.41, p <0.0148). Comparing total-chord recognition performance differences across the two glove pairs is again not significant for chorded stimuli, and the ERM gloves again outpace the LRA gloves for recognition of single stimuli. T-tests reveal performance differences between the two motor types to be significant (t(15)=2.52, p <0.0118).

Discussion

Study #2's results elucidate many details in chorded perception on the hands; most importantly they indicate that chorded stimuli cannot be delivered simultaneously if discrete perception is desired. Results are summarized in Figure 7 representing user performances on chords of different numbers of stimuli. As indicated by this data, human perception of multiple simultaneous tactile stimuli points is poor, particularly for sets of three or more stimuli. Due to content loss found in each chord set (missed or mis-identified stimuli), effective chorded stimuli delivery is not possible in either glove pair studied. Whether the interface's application values stimuli counting or localization, neither appears achievable via simultaneous tactile stimuli. In regards to counting judgments, the significant error present in sets of more than two stimuli suggests against subitizing–in contrast to human visual perception of simultaneous points and notably consistent with findings of no subitizing in counting judgments of tactile stimuli across the full body [9]. Users typically fail to report one stimuli point in the three- and four-stimuli chords, as opposed to misidentification of a point's location. This result may be because of sensory funneling on the hands due to the density of stimuli points. Human perception of multiple simultaneous tactile stimuli on the hands is poor. Simultaneous stimuli present a challenge to developers, designers and users, even when the user is focused on correct perception.

Analysis of motor-type performances indicates LRA motors provided no significant benefit, despite purported improved localization and added cost. These results, using simultaneous stimuli, will be combined with those of study #3, regarding single stimuli, to examine if these haptic elements provide any current benefit for our range of applications

STUDY #3: MOTOR TYPES COMPARISON

What haptic element should be integrated to create a device with high wearability and performance? Our third study directly examines perception differences in using ERM or LRA vibration motors. Do our LRA motors provide better perception/localization of stimuli? In this study, 20 participants attempt to pinpoint the origin of a single vibration of varying duration on their index fingers.

Users are asked to don their first assigned pair of gloves (ERM or LRA), providing the haptic stimuli at fixed points for this experiment. They are then presented with a stimulus and asked to input what they felt on the keypad (as described in the Feedback Interface section). Once they complete their response, they are presented with the next stimulus, and this continues until all stimuli have been presented. Upon completion, this procedure is repeated for the participant's second assigned pair of gloves (ERM or LRA). Condition orders are randomized and counterbalanced. The study concludes with a survey of user preferences and experience. Participants wear headphones throughout all studies to prevent audio localization cues.

Since we wish to examine performance differences by motor type, not differences between fingers, we use only the index fingers. The stimuli presented are all single stimuli (not chords). Two points on the dorsal side and two points on the ventral side of each index finger are tested on both hands (A, B, X and Y in Figure 1). These eight points are each activated for various durations during this experiment: 150 ms, 300 ms, 450 ms, and 600 ms. Stimuli are randomized.

Varying activation durations allows us to examine differences and ideals for each motor type. For example, we know the ERM motors require 120 ms to reach full amplitude [26] and a similar amount of time to spin down, whereas the LRA motors have much faster on and off times (<90 ms). Might these physical differences affect the results?

Results

Activation Duration

Accuracy for this study refers to whether a user's indication of which motor vibrated was correct or not. Response accuracies were examined by activation duration for each motor type. Figure 10 shows the percent of stimuli of each duration that were correctly identified for each motor type. Surprisingly, overall differences in user performance for each time are not significant, for either motor type, as indicated by a single-factor ANOVA comparing the effect on performance by time (F=0.373, p >0.772).

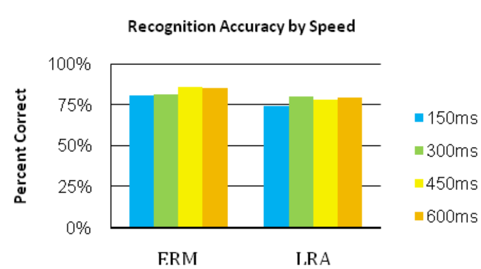

Figure 10. Recognition accuracy of single stimuli by motor activation duration.

Top and Bottom Differences

Accuracy for points on the dorsal (top) side of the fingers was significantly better than for points on the ventral (bottom) side of the hand. As presented in Figure 11, points on the dorsal side of the fingers were identified correctly 88.2% of the time on average, in contrast to 73.0% of the time for points on the ventral side. A gap in performance between LRA and ERM vibration motors becomes apparent in these results. Both motor types have comparable accuracies in dorsal-side stimulus points (M=88.2% and M=88.1%), but accuracy falls by 20.3% (down to M=67.8%, SE=0.044) for ventral locations using the LRA interface and only 10.1% (to M=78.1%, SE=0.055) for the ERM motors. These findings and study #1 suggest that the ventral side of the fingers is an area with reduced perception of the vibration stimuli, and accuracy varies with placement location. The difference in accuracy for dorsal and ventral stimuli points showed significance for both motor types ($t(19)=5.51$, $p < 1E\text{-}05$).

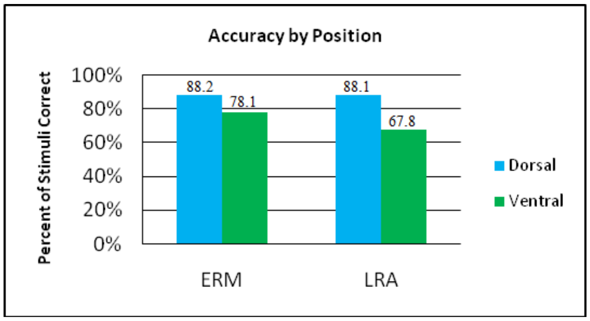

Figure 11. Identification accuracy by motor position and motor type.

Overall Motor Comparison

T-tests indicate a significant difference in response accuracy between motor types ($t(19)=2.10$, $p < 0.0247$); post-hoc tests suggest that differences in recognition accuracy of ventral-side stimuli between LRA and ERM interfaces are significant ($t(19)=2.48$, $p < 0.0114$).

Questionnaire

Study #3 sessions were followed by a survey. Initial observations from this data are presented here, and further analysis is in process. Seven-point Likert scales showed some differences between motors, with responses to "it was easy to sense what motor was vibrating" most often being "agree (6)" for ERM vibration motors as compared to most often "somewhat disagree (3)" for LRAs. Comments about "what differences did you notice between gloves" often contained the following observations: the ERMs vibrated "stronger" (seen as a positive) but sometimes caused "the entire finger to vibrate" making localization difficult for users.

Discussion

The LRA and ERM vibration motors presented here are some of the few commonly available tactors with a form factor usable for incorporation into wearable interfaces such as our glove system for teaching manual skills passively. We expected the LRA motors to perform better than the ERMs; however, they performed significantly worse on the ventral side of the hand and had comparable or worse performance in general. Perhaps, as these LRA motors become more mature and more models become available, new packaging will change this result. It is possible to select LRA motors capable of stronger vibration; however these motors are not ideal for integration in mobile or wearable systems due to weight, size, and cost. The ERM motors are simpler to drive, less costly, and have comparable or better performance in some cases when compared to LRA motors of the same form-factor. For now, the ERM motors may be preferable in the creation of wearable, tactile interfaces.

Comparable accuracies were found for each activation duration. While it is surprising that a 150 ms stimulus is perceived about as well as a 600 ms stimulus, the results are fortuitous in that it enables a variety of systems with either fast-paced or time-variant vibration signals.

The ERM gloves' decreased performance with larger numbers of stimuli (in the chords study) may be due to their "strong" vibration. Responses to the questionnaire mention this, as some users observe that the vibration caused by the ERM motors is sometimes "too much" and causes the entire glove to vibrate. Because of this vibration "strength" and the erratic motion of the Eccentric Rotating Mass motors, this motor type may not be best for use in simultaneous stimuli, or placement in multiples in close proximity. Though numerosity judgments were comparable using LRA motors in these circumstances, localization of the stimuli was comparable or worse than using ERMs. Instead, for chorded and close-proximity implementations, a mixture of motor types (LRA and ERM) may be ideal - with each type producing a different sensation resulting in better differentiation. Staggering onset or varying activation durations for chorded stimuli is another solution to aid to perception, and we have had success with this approach in recent work [24].

FUTURE WORK

Simultaneous stimulation was not successful in these studies. However, we have some evidence that short offsets in conveying each part of a "chord" is sufficient to communicate the required information. What is the optimal such offset for ERMs and LRAs? Does it vary depending on the finger and position of the tactor? Can we mix LRAs and ERMs to create more distinct signals? How far apart do tactors need to be on the dorsal side of the finger to be distinct? Can we reduce this distance so as to create a glove that interferes the least with wearers' everyday activities? We foresee a continuing set of optimizations that might be tested as we pursue the refinement of our Passive Haptic Learning gloves.

CONCLUSION

We presented the results of three studies regarding perception of haptic stimuli using small vibration motors suitable for embedding into a wearable, tactile interface. The Eccentric Rotating Mass (ERM) motors in this study proved easier to perceive than the Linear Resonant Actuator (LRA) motors in general. The ventral side of the hand presents challenges to perception, and trends related to stimulus location. Ventral positions closer to the palm (as opposed to the finger tip) proved significantly, linearly, more distinguishable. Simultaneous chorded stimulation is difficult to perceive; offseting the activation of the motors slightly may prove a better solution. We are using these results to design haptic interfaces for learning and rehabilitation. However, we hope the design implications found here will also be valuable to others creating wearable, tactile interfaces for applications such as microinteractions, augmented reality and teleoperation.

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