BrushTouch: Exploring an Alternative Tactile Method for Wearable Haptics

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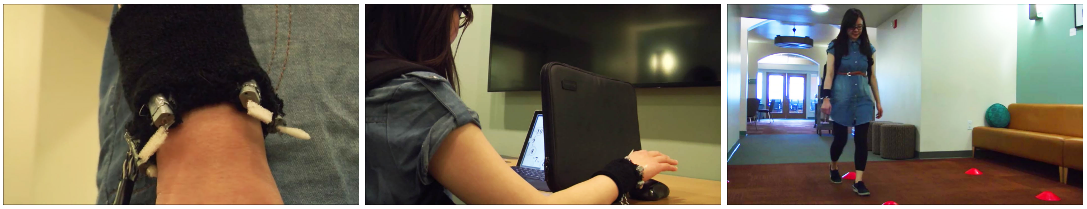

Figure 1. Left to right: A user wearing a novel haptic wearable prototype, comparing the recognizability of haptic cues with different forms of tactile stimulation, following navigational instructions through haptic cues.

ABSTRACT
Haptic interfaces are ideal in situations where visual/auditory attention is impossible, unsafe, or socially unacceptable. However, conventional (vibrotactile) wearable interfaces often possess a limited bandwidth for expressing information. We explore a novel form of tactile stimulation through brushing, and demonstrate BrushTouch, a wearable prototype for brushing haptics. We also present schemes for conveying information such as time and direction through multi-tactor wrist-worn haptic interfaces. To evaluate BrushTouch, two user studies were run, comparing it to a conventional vibrotactile wristband across a number of tasks in both lab and mobile conditions. We show that for certain cues brushing can be more accurately recognized than vibration, enabling more effective spatial schemes for presenting information through haptic means. We then show that BrushTouch is capable of greater information transfer using such cues. We believe that brushing, as with other non-vibrotactile haptic techniques, merits further investigation as potential vehicles for richer haptic feedback.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation: Haptic I/O

Author Keywords
haptics; tactile; wearables; vibrotactile; wayfinding; brush; brushtouch;

INTRODUCTION AND RELATED WORK
Numerous scenarios exist where visual attention is either unavailable (e.g., one is driving), undesirable (e.g., it is socially unacceptable), or impossible (e.g., for the visually impaired). Similarly, audio can be difficult to hear in many environments, and wearing headphones may even be dangerous. Thus, we require systems that are discreet, can be used without sacrificing visual or auditory attention, and are usable for individuals with sensory impairments.

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Wearable haptic solutions have taken a variety of form factors including watches [4], belts [20, 23], vests [7], gloves [26], and shoes [25]. Typical use cases include wayfinding [23, 25, 26], guidance of physical motion [13], and driving [10].

Such systems require an informational bandwidth large enough to be both expressive and efficient. Though vibrotactile (VT) techniques have a number of advantages making them ideal for many devices, a single VT element is in fact a low-bandwidth channel for information transfer [22]. Prior work investigated "tactons", structured units of VT stimulus, to encode messages [2]. They present a limited recognition rate under variations of parameters, such as 80% recognition for roughness (amplitude) [3] and frequency [11]. These rates decline considerably outside of a controlled laboratory setting for Duration, Interval, and Intensity [17].

Vibrotactile Stimulations
Thus, to reliably express even simple messages, it becomes necessary to build complex cues consisting of multiple stimuli across the temporal domain (encoding "patterns"). Patterns are consistently the most recognizable of features [3], with ActiVibe [4] reaching 96% recognition rate in the lab and 89% *in-situ*. Yet, such patterns quickly grow towards unusable lengths for messages beyond the most basic, and conveying real world information can require substantial learning.

An alternate approach is to extend across the spatial domain. For example, a wrist-worn device could utilize the space around the wrist, signaling different cues by activating tactors at different locations. We note several advantages to varying signals across space instead of time. Firstly, signals can be sent in a shorter duration of time, reducing draws on the user's attention. Moreover, there are numerous types of real-world information that already utilize a radial metaphor (e.g., time).

We expect that prior familiarity with the representation will result in a reduced learning phase.

Previous studies have demonstrated that properly distributing multiple tactors improves informational bandwidth. A 41.6% increase in bitrate is found for a 4-motor system arranged around the wrist as opposed to on the top of it [16]. Yet, there are limits to the number of tactors we can utilize in an area, primarily dictated by the spatial resolution of human perception. Thus, we reason that by improving the resolution with which haptic stimuli can be localized, we can increase the informational bandwidth of a wrist-worn haptic device.

The literature shows relatively low spatial acuity for VT stimuli on the wrist and forearm. Chen et al. were able to obtain ~50% recognition on the wrist using a 3x3 VT array with sites spaced 25 mm apart [5]. Cholewiak and Collins found that increasing the distance between stimulus sites on the wrist from 25 to 50 mm improved recognition by nearly 15% [6]. Jones et al. characterized the effects of surface waves that propagate across the skin as a result of vibration, finding that at least 6 cm of separation was necessary between tactors on the forearm to prevent mislocalizations [14].

Non-Vibrational Haptic Stimulation

Diverse non-VT haptic wearable devices have emerged, often claiming increased recognition rates over VT analogues. Feedback mechanisms include shape change [9], skin stretch/drag [8, 12], tapping [13], squeezing [1], and tickling [15]. As each modality is likely to evoke a different response across the range of mechanoreceptors in human skin [24], it to our advantage to explore their properties and uses in haptic devices. For example, tapping, dragging, squeezing, and twisting methods all differed qualitatively and quantitatively from VT output on a wrist rotation guidance task [21]. To the best of our knowledge, light brushing against the surface of the skin - perhaps less impacted by the surface waves characteristic of vibration - remains unexplored in this way.

BRUSHTOUCH PROTOTYPE

To explore the possibility of brush-based tactile stimulation, we created BrushTouch, a haptic wearable prototype (Figure 1). It consists of six individually-controllable cylindrical DC rotational motors equally spaced about a stretchable wristband (Figure 2). The number of tactors is based on prior findings that six (VT) motors on the wrist is an ideal compromise between spatial acuity and informational bandwidth [18]. We designed BrushTouch to allow for a valid comparison to an equivalent VT band.

A piece of soft foam is attached to the shaft of each motor via removable Gorilla Tape. As the motors rotate (~100 Hz), the foam brushes against the skin, resulting in a unique tactile sensation. Different lengths of brush are used to accommodate the wrist size of the user (width = 10 mm, thickness = 1 mm). Each device was worn with the tactors arranged as shown in Figure 4, as in [19]. We used PKN12 3V DC motors (NMB technologies), driven by an Arduino controller. The Arduino receives commands via Bluetooth from an Android smartphone and triggers the appropriate motor response. The entire system is portable and powered by a USB 5V supply.

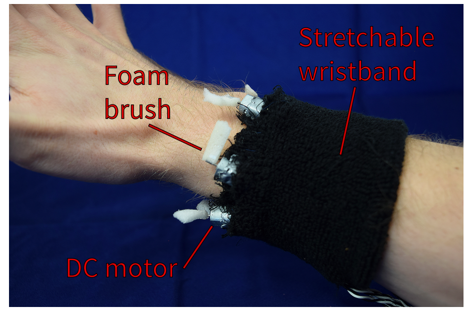

Figure 2. The BrushTouch prototype, composed of a stretchable wristband and 6 DC motors with foam brushes.

Figure 3. The vibration-style device.

VALIDATION

BrushTouch was evaluated with two user studies: first to gauge its performance relative to a conventional VT device across a variety of tasks in the lab, and then to compare these devices in a real-world mobile setting. We designed a VT wristband analogous to those found in prior work [18, 19]. The band (Figure 3) consists of six cylindrical vibration motors, arranged around the wrist in the same configuration as BrushTouch. The motors are 2000 RPM, 3V DC motors, run at the same current as the BrushTouch prototype.

Experiment 1

The first study compared BrushTouch to an equivalent VT device in terms of participants' ability to 1) recognize the activation of a specific motor or combination of motors, and 2) extract semantic information from that haptic cue.

Setup

We recruited 14 volunteers (9 m) from our institution, aged 18-30, all right-handed. The study lasted one hour, and participants were compensated $20 for their time. Each participant carried out a total of five tasks in each of the two device conditions (Brush vs. Vibration). The tasks were presented in the same order on each device, and the ordering of the two device conditions was counterbalanced between participants.

Training

Users performed the study while seated at a computer. For each device condition, participants were fit with the device on their right wrists, then underwent a calibration to make sure that they could perceive each motor at equal amplitude and in the correct location. For each trial, to avoid any differences in sensation caused by varying the arm or hand position, the participant would lift their hand from the mouse to an outstretched neutral position in midair to receive a haptic pulse, then return

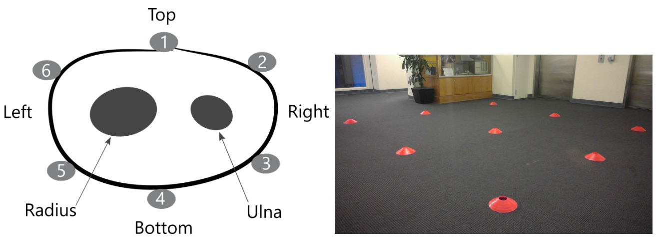

Figure 4. Left: Tactor layout on the wrist for both devices. Right: Setup for the walking study (Experiment 2).

to the mouse to select their response. Participants positioned their right hand behind a screen to prevent seeing the device during the trials, and listened to music through headphones to ensure that auditory cues from the motors could not be heard.

After each task was explained, the participant completed six training trials prior to beginning the experimental trials. At the conclusion of the study, the participant filled out a qualitative evaluation of the two devices.

Pilot Study

The design of our tasks was informed by a pilot study (N = 6) conducted to explore how to optimally design multi-motor schemes for encoding information. Notably, for the simultaneous activation of multiple motors, participants were able to far more accurately identify motor combinations that were adjacent as opposed to non-adjacent ($p < .005$). Thus, our semantic schemes were designed to utilize adjacent motor pairs when simultaneous stimuli were required.

Tasks

Participants completed the following tasks, in order, on each device. Responses were indicated by clicking the corresponding label on a diagram displayed on a screen in front of them:

- *Single Motor Identification (SINGLE)*
  Each trial consisted of the activation (2 s) of a single motor. Participants indicated the perceived motor on a diagram similar to Figure 4. (24 trials)
- *Multiple Motor Identification (MULTI)*
  Each trial consisted of the simultaneous activation (2 s) of two nonidentical motors. Participants indicated the perceived motors on a diagram similar to Figure 4. (30 trials)
- *Single/Adjacent Motor Identification (MIXED-ADJ)*
  Each trial consisted of the activation (2 s) of either a single motor or two adjacent motors (each with 50% probability). Participants indicated the perceived motor(s) on a diagram similar to Figure 4. This task was designed to dissociate the discrimination of the stimuli used in the TIME and DIRECTION tasks from the additional cognitive load of translating these cues into semantic meanings. (20 trials)
- *Determining Time (TIME)*
  Participants were asked to determine the time (to 5-minute resolution) from haptic cues. Each trial consisted of an hour cue and a minute cue (1s each) being sent with a 500 ms pause in between. Hour and minute cues were represented either by the activation of a single motor (indicating one of the six even digits on a clock located directly on the position of a motor) or by the simultaneous activation of two adjacent motors (indicating the odd digit on a clock located in between the two positions matching those two motors). Participants indicated the time that they perceived by clicking first the hour then the minute position on an interactive clock face. (20 trials)
- *Determining Direction (DIRECTION)*
  Participants were asked to determine a cardinal direction from haptic cues. Each trial consisted of the activation of either a single motor (indicating one of the cardinal directions aligned with the motors with the top motor is designated as North [N, NE, NW, S, SE, SW]), the two adjacent motors on the right side of the wrist (indicating East), or the two adjacent motors on the left side of the wrist (indicating West). Participants indicated the direction that they perceived by clicking the corresponding position on an interactive compass rose. (20 trials)

Task	*Vibration %accuracy*	*Brush %accuracy*	*p Value*
SINGLE	89.0	93.5	**.036**
MULTI	64.8	75.0	**.001**
MIXED-ADJ	73.6	75.7	.544
TIME	55.7	58.2	.513
DIRECTION	87.1	86.1	.699

Table 1. Averaged accuracy for each task across the two devices in Experiment 1, and p-value resulting from repeated-measures ANOVA.

Experiment 2

A follow-up study was carried out to compare the performance of the devices under close to real world conditions. Ten new participants (6 m), aged 18-26, were recruited from our institution. Participants were first trained to identify directional cues as in Experiment 1, and then used these cues in a turn-by-turn navigation task (20 trials). The experiment took place in an open indoor space with a grid of 8 possible locations marked by a perimeter of cones (Figure 4). Each participant performed the task with both devices in a counterbalanced order.

For each trial, participants would walk towards the central cone in a natural manner with their arm down by their side. They would then receive a haptic signal and change their course to end up at the indicated target cone along the perimeter. When the participant had finished at their destination, their choice of direction was recorded. All eight directions were possible in each trial. Participants wore a light backpack while walking to hold the power supply and circuitry.

EXPERIMENTAL RESULTS

For each task, a repeated-measures ANOVA was performed to compare participants' accuracy rates across each of the two device conditions (Table 1). Significant differences between the device conditions are observed in both the SINGLE and MULTI tasks. No significant differences in time to completion between the two devices were observed in any task ($p = .05$).

To further investigate these differences and why they do not persist into the remaining three tasks, we analyzed separately the adjacent and non-adjacent stimulus combinations in the

Task: MULTI	*Vibration*	*BrushTouch*
IT_{est}	2.5085	2.8705
2^{ITest}	5.69	7.31
Number of discriminable signals	> 5	> 7
Task: SINGLE	*Vibration*	*BrushTouch*
IT_{est}	1.9980	2.2439
2^{ITest}	3.99	4.74
Number of discriminable signals	<= 4	> 4

Table 2. Information Transfer for the SINGLE and MULTI tasks.

Qualitative Measure	*Vibration*	*Brush*	*p Value (2-tail)*
Effort on Time Task	5.92	5.67	.571
Confidence on Time Task	3.42	3.67	.586
Effort on Direction Task	4.50	4.17	.457
Confidence on Direction Task	4.75	5.00	.429
Comfort	5.58	4.33	.003

Table 3. Mean values from a 7-point Likert qualitative evaluation of the two devices.

MULTI task. For activations of adjacent motors, the accuracy was 79.8% for the VT device and 82.7% for the brush device (not significant). However, for non-adjacent combinations, the accuracy was only 54.8% for the VT device and 69.8% for the brush device ($p < .05$).

To assess the differences in capability for expressing information between the two devices in this task, we use the Information Transfer measure described by Chen et al. [5]:

$$IT_{est} = \sum_{j=1}^{k} \sum_{i=1}^{k} \left(\frac{n_{ij}}{n} \log_2\left(\frac{n_{ij} \cdot n}{n_i \cdot n_j}\right)\right)$$

where k is the number of distinct stimuli, n is the total number of trials, n_i is the number of trials where stimulus i appeared, n_j is the number of trials where response j was given, and n_{ij} is the number of trials where stimulus i was responded to by response j.

This formula estimates the amount of information, in bits, transmitted from each stimuli to the response. The integer part of $2^{IT_{est}}$ is interpreted as the number of distinct cues which can be reliably distinguished using the device. Table 2 compares the information transfer of the two devices, as well as the number of distinct cues that can be identified by each.

The qualitative survey compared effort required to complete each task, confidence in cues received on each task, and general comfort of the devices. Participants were asked to agree with sentiments on a 7-point Likert scale. Means were lower for effort and higher for confidence on the brush device, but failed to reach statistical significance (Table 3). Comfort was rated as significantly lower ($p < .01$) on the brush device.

Experiment 2

The mean accuracy was 84.5% for the VT device and 83.5% for the brush device (not significant). These results show no significant decrease in performance from the lab study in either condition. Participants were able to quickly learn the directional scheme with little training, despite not having been first trained on simpler tasks as in Experiment 1.

DISCUSSION

BrushTouch demonstrated a significant improvement in recognition over the VT device for both single and 2-tactor stimuli. This difference corresponded to a $5 \rightarrow 7$ increase in number of identifiable cues for a 2-tactor scheme, suggesting that it is indeed possible to convey information more efficiently using brushing. However, the significant differences are exhibited only in *non-adjacent* stimuli pairs, and thus the two devices performed similarly on the DIRECTION and TIME tasks.

Interestingly, these results imply a difference between adjacent and non-adjacent cues which may prove useful in designing multi-stimulus schemes on haptic wearables. When stimuli were adjacent, both devices showed significantly better performance, and the disparity in accuracy between the two shrunk considerably. We suspect that users may apply different cognitive heuristics in determining the source of a stimuli in the adjacent and non-adjacent cases. When users feel two activated tactors in adjacent proximity, they can choose with confidence the two neighboring tactors in the rough area where the stimuli was felt. This reduces ambiguity as compared to feeling two distinct stimuli in different locations, which must each be resolved to a single motor among neighbors. Whether or not such heuristics generalize to more complicated tasks than raw identification requires additional investigation.

In general, both devices were able to convey direction relatively successfully in both a controlled and mobile setting, whereas the TIME task proved too difficult, even in the lab setting. The mean accuracies for single tactor identification are consistent with prior results in the literature [18].

LIMITATIONS AND FUTURE WORK

The prototype does present limitations in comparison to its VT counterpart. It requires a greater degree of calibration to each user's wrist, as the various brushes need to be sized properly to make contact with the skin without dragging or stalling. In addition, the mechanism does not actuate if covered by clothing or pressed against a surface. Comfort was also rated as lower, though familiarity may play a role in this rating.

While our prototype was used as a proof-of-concept to explore brushing sensations, the next iteration will focus on engineering a more robust, comfortable brushing wearable. A full design process is needed to explore the various shapes, sizes, and materials of brushes, as well as the motors, band, and drive parameters to optimize the sensation. More generally, in addition to exploring other new modes of haptic stimulation, future work should examine how more complex stimuli (e.g. dynamic actuation patterns from prior work) compare across these alternative output modalities.

CONCLUSION

We created BrushTouch, a wearable prototype that uses brushing as an alternative to VT sensation to more effectively convey haptic cues. The results of our evaluation show that haptic interfaces using spatially distributed tactors can be made more effective using non-VT forms of tactile stimulation. We hope that this work will inspire others to continue to explore alternatives to VT haptics, enabling richer and more usable haptic interfaces.

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