Ten Little Fingers, Ten Little Toes: Can Toes Match Fingers for Haptic Discrimination?

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***Abstract*—In comparison with fingers, toes are relatively unexplored candidates for multi-site haptic rendering. This is likely due to their reported susceptibility to erroneous perception of haptic stimuli, owing to their anatomical structure. We hypothesize that this shortcoming can be mitigated by careful design of the tactile encoding to account for the idiosyncrasies of toe perception. Our efforts to design such an encoding achieved an improved perceptual accuracy of 18% for poking and 16% for vibrotactile stimuli. As we demonstrate, the resulting perceptual accuracy achieved by the proposed tactile encoding approaches that of the fingers, allowing for consideration of the toes as a practical location to render multi-site haptic stimuli.**

***Index Terms*—L.2.0.c Tactile display, L.1.0.g Perception and psychophysics, L.2.0.f Haptic rendering,.**

I. Introduction

HAPTICS has been widely explored as an on-body communication modality. Prior work investigated single actuator haptic delivery to convey information using tactons created by varying parameters such as frequency, amplitude, waveform and duration [1], [2], [3]. However, the perceptual discriminability of these dimensions, within safe ranges, e.g., of amplitude, is limited. For this reason, exploiting spatial discrimination by a multi-actuator tactile information display represents a potentially superior approach. This has been explored at various parts of the body, including the back [4], waist [5], lower leg [6], and arm [7]. However, most of the skin, apart from fingertips, palm and sole, exhibit relatively low tactile resolution [8], which limits their effectiveness for multi-actuator tactile display. In contrast, the fingers not only exhibit high tactile resolution, but since there are ten of them, they provide physically independent loci for tactile information delivery [9], [10], [11], [12].

However, the fingers are typically occupied in day-to-day interactions with the everyday world, as we hold or manipulate objects, or perceive the environment through touch. In this respect, data gloves or similar actuated devices, used solely for the purpose of tactile information delivery, are generally undesirable [13], since they could interfere with the fingers' freedom of movement or reception of external sensory sensation.

One might expect that the toes would exhibit similar benefits, given that they are also separated into ten physically independent units. However, the ability to discriminate which toe received a particular stimulus is significantly inferior to that of the fingers, especially for the middle toes [14], [15]. If this limitation could be overcome, the use of toes for delivery of multi-point haptic information would present several compelling benefits: first, they are under-utilized and often idle for other purposes, especially while an individual is seated, and second, the mechanisms for delivery of haptic stimuli can be embedded in everyday footwear, thereby neither encumbering the user, nor being visible to third parties.

II. Background

Multi-actuator tactile rendering systems have been employed on different locations of the human body for a wide number of applications. Geldard [16] explored multi-site haptics with *Vibratese*, a tactile language consisting of alphanumeric symbols rendered at five locations, at three intensity and duration levels, for a total of $5 \times 3 \times 3 = 45$ combinations. Rendering of tactile icons, or *Tactons* [17], with multiple vibrotactile actuators, has been investigated by numerous researchers. Jones *et al.* [4] used a tactile vest consisting of a 4×4 array of actuators to convey navigation cues on a user's back. McDaniel *et al.* [5] designed a multi-actuator haptic belt to convey non-verbal communication cues to blind users during social interaction. Meier *et al.* [6] explored different multi-actuator setups such as sock bandages, wristband, insoles, and shoes for the purpose of pedestrian navigation. Cobus *et al.* [18] used multi-site tactile rendering to convey alarms from intensive care unit (ICU) on a vibrotactile wearable alarm system.

Hands and feet have ten physically isolated digits and thus can be used as a potential multi-site tactile rendering locations. Luzhnica *et al.* [19] and Nicolau *et al.* [10] designed systems to render alphanumeric information to the fingers. However, these are not suitable for applications where the hands are occupied, as they often interfere with manipulation and/or tactile perception of the environment. Wearables in the form factor of rings [20] avoid this problem, but can only convey a limited range of distinguishable patterns because of the constrained space available for housing actuators that are capable of rendering a wide range of effects. Newer actuators in development may offer greater flexibility to render multi-site haptics. Examples include *Tacttoo* [21], a thin, feel-through tattoo for on-skin tactile output, and *Springlets* [22], which offer expressive, non-vibrating, mechanotactile interfaces on the skin. However, we are unaware of any studies that have been conducted on the performance of these actuators for multi-site haptic rendering.

Researchers have explored perception of tactile stimuli on the toes, and compared this to fingers. Cicmil *et al.* [14] performed a study involving manual stimulation of the glabrous surfaces of fingers and toes. They found that recognition was robust when the big toe (99%) or little toe (94%) was stimulated, but individuals had difficulty discriminating between the middle toes, with perceptual accuracy of 57%, 60% and 79% for the second (immediately adjacent to the big toe), third, and fourth toes [14]. In contrast, all the fingers exhibited perceptual accuracy over 99%. Manser *et al.* [15] reported a similar

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trend in their follow-up study comparing tactile perception on both glabrous and hairy surface of fingers and toes.

The potential of a toe-based haptic information rendering system motivated us to examine whether a carefully designed encoding of the stimuli could allow subjects to better discriminate stimuli delivered to individual toes. We compared our proposed design to a simpler rendering of tactile stimuli [14], [15] to the fingers and toes in order to answer these research questions—Can such an encoding improve perceptual discriminability of the toes, and if so, can it be improved to approach the performance level of fingers?

In addition, we noted that delivery of vibrotactile stimulation in the closely spaced locations of toes risks propagation of the vibration to adjacent toes. This effect results in part from the large receptive fields of the Pacinian mechanoreceptors, located deep in the dermis layer. We speculated that the use of poking, instead, might allow for better localized stimuli since these are perceived by Merkel cells in the epidermis layer, which are sensitive to tissue movement at low frequencies, have relatively smaller receptive fields and well-defined borders [23], allowing for precise perception [24].

Various studies related to tactile information rendering have explored the use of multiple actuators [4], [25], [26] and several papers have specifically investigated poking stimuli [25], [27], [28], [26]. In a recent study using a 3×3 multi-actuator tactile watch display, Shim *et al.* found that participants recognized poking more accurately than vibrotactile stimuli [29]. Motivated by this body of work, we wished to determine whether the perceptual discriminability of the toes benefits more from poking over that of vibrational stimuli.

III. Tactile toe rendering

Two tactile toe rendering methods were used in this paper—default and encoded, each using two stimuli—vibration and poking. Each toe was identified by a number from 1 through 5, starting with the big toe corresponding to number 1 and increasing laterally such that the little toe corresponded to number 5. We used a default rendering to replicate the individual toe simulation as performed by Cicmil *et al.* [14].

According to Cicmil *et al.*'s results, there was a directional bias in the perception of toes, significantly for the middle toes, causing misidentification. The second and third toes were biased towards the little toe, whereas the fourth one was biased towards the big toe. We therefore wanted to implement an easy-to-understand tactile rendering strategy to differentiate the toes, helping to decrease the effects of toe misidentification.

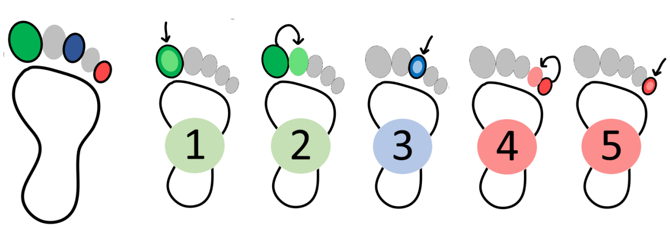

Fig. 1: Encoded tactile toe rendering for right foot: The first foot shows the directional toes (1, 3 and 5) highlighted in dark colors. For stimuli to be delivered to these toes, the target toe and directional toe are the same. For stimuli to toes 2 or 4, the corresponding directional toe is first stimulated, followed by the target toe.

We proposed an encoded rendering involving delivery of two consecutive stimuli, an initial stimulus to one of the directional toes (defined in Figure 1) followed by a stimulus to the targeted toe. For toes 1 and 2, the directional toe was 1; for toe 3, the directional toe was 3; and for toes 4 and 5, directional toe was 5. The initial stimulus to the directional toe was designed to serve as a cue for users, for which a short vibration or short poke seemed appropriate. The follow-up stimulus needed to be sufficiently different to emphasize that it identifies the targeted toe. As such, we chose to use a longer vibration or three small consecutive pokes, depending on the stimulus condition. Geldard [16] stated that for a range of 100 ms to 2000 ms, the skin can distinguish approximately 25 discrete, just-noticeable differences of stimulus duration, whereas durations below 100 ms are perceived as poke sensations on the skin. We thus kept the vibrational stimuli of our *Tactons* longer than 100 ms and the poking stimuli at 100 ms.

1) *Default Rendering:* a long vibration of 800 ms or a single poke of 100 ms on the targeted toe.
2) *Encoded Rendering:*
    - Vibration: a short stimulus of 400 ms on the directional toe, a pause of 500 ms and then a long stimulus of 800 ms on the targeted toe.
    - Poking: a single poke of 100 ms on the directional toe, a pause of 500 ms and then three pokes of 100 ms on the targeted toe, each separated by 100 ms pauses.

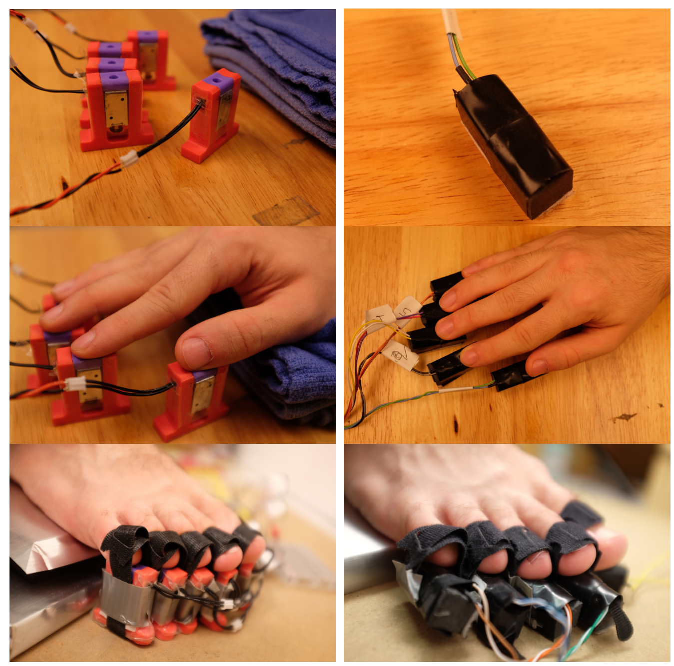

Fig. 2: Hardware setup for rendering poking (left panel) and vibration stimuli (right panel).

IV. User study

A. Apparatus

The prototype consists of ten ERM vibrotactile actuators (2 mm Mini Vibrating Disk Motor, RB-See-403, Seeed Studio) for rendering vibration stimuli, and ten small push-pull solenoids (Solenoid-5V, ROB-11015, SparkFun) for rendering poking stimuli. They were controlled by a microcontroller (Teensy 3.2) driving an H-bridge for the ERMs and driving a relay for the solenoids. The vibrotactile actuators were mounted on individual foam cutouts to localize the vibrations and avoid undesirable propagation. The push-pull solenoids were mounted on individual 3D printed encasings to allow an adequate clearance between the push-pin and the digit, such that a poking sensation is achievable. These foam pieces or 3D printed encasings were attached to the user's toes via velcro® straps to ensure proper placement in case participants accidentally moved their toes. Since participants had more control over the movement of their fingers during the experiment as compared to toes, velcro® straps were not used for these. Both the vibrotactile actuator and the solenoid provided a contact force of 80 g. The former was operated at 3.3 V, rotating at 10 000 RPM (167 Hz) whereas the latter was operated at 5 V. The experimental setup is shown in Figure 2.

B. Methodology

For the experiment, we followed a protocol similar to Cicmil *et al.* [14]. Each participant was tested individually in a laboratory setting, sitting comfortably on a chair with legs uncrossed, and their bare feet resting flat on elevated platform of 2 cm for vibration and 4 cm for the poking apparatus (Figure 2). For finger stimulation, the hand was positioned flat with the palm down on the padded surface of a table with the fingers comfortably spread. Participants were instructed to strap the actuators comfortably tight to the toes of their dominant foot and rest the fingers of their dominant hand such that each actuator was at the center of the distal tip of their digit. The experimenter then verified that all the actuators were in place and properly coupled. Each digit was identified by a number from 1 (thumb and big toe) through 5 (little finger and little toe). One digit was stimulated per trial. The participants were instructed to respond after each trial by verbally identifying quickly and accurately their first impression of the stimulated digit. They wore headphones playing pink noise to mask the sound of the actuators and were asked not to look at their fingers or their toes during the trials. Their individual response times were not recorded.

The experiment followed a repeated measures (within subject) design. We tested three conditions: default rendering on fingers (DF), default rendering on toes (DT) and encoded rendering on toes (ET), each for blocks of poking (P) and vibrotactile (V) stimuli. All possible orders of the three conditions (DF, DT, ET) were repeated twice and used across the participants. This order was the same for blocks of poking and vibration. The poking and vibrotactile blocks were counterbalanced across participants. We did not implement encoded rendering on the fingers since prior work reported perceptual accuracy as high as 99% for all the fingers [14].

After setup, consent form and pre-test questionnaire delivery, we ran a short exercise to familiarize the participants with the number identification of the digits: the experimenter pointed at one of the participant's fingers or toes and asked them to say the number with which it is associated. This was repeated for all the digits (maximum of two times per digit) to ensure that they understood the mapping. Before the trials for a particular condition started, the experimenter explained the rendering to the participants and gave them a demo trial, stimulating all the digits sequentially from 1 to 5. For each condition, 50 trials were rendered such that every digit, either toe or finger, was stimulated ten times in random order. The numbers were shuffled in blocks of ten (1 through 5, each appeared twice) using a Fisher–Yates [30] shuffle and five shuffled blocks were appended together. After each experimental block of poking or vibration, participants completed a post-test questionnaire.

C. Hypotheses

We expected that our tactile toe encoding would help participants to better differentiate toes, while avoiding confusion amongst the three middle toes. As per the conclusions of Cicmil *et al.* [14] and Manser *et al.* [15], we assumed fingers to have reasonably accurate perception. We expected that the perceptional discriminability of toes would be similar or better than that of fingers when an encoded rendering was used. Since poking is a localized stimulus, and does not propagate as much as vibration, we expected that poking stimuli might be better discriminated than vibration.

D. Participants

We recruited 16 participants from the McGill University community and compensated them CAD$10 for approximately an hour-long experiment. Data from the first two participants were not used as we made changes in the post-test questionnaire to solicit information regarding poking and vibration separately. For two other participants, hardware-related interruptions required us to cancel the experiment session. We analyzed data from the remaining 12 participants (7 male, 5 female; ages 18–33, median = 24.5).

E. Results

1) Pre-Questionnaire Results: All the participants reported their right hand and foot as dominant. Participants' foot widths measured at the toes were in the range of 8.9–11.4 cm (median = 10.0 cm) and shoe sizes were in the range of 23.8–27.6 cm (median = 27.0 cm).

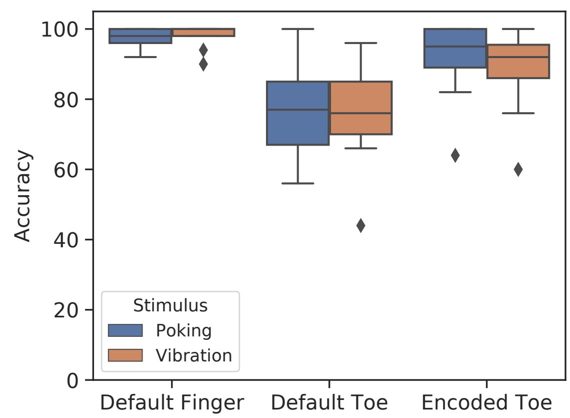

Fig. 3: Boxplot of accuracy under each condition

2) Accuracy and Confusion Matrix: Trials for which participants responded by verbally identifying the correct number against the stimulated digit were considered accurate. A lack of response to a trial was counted as an error. Across all participants, there were a total of 6 trials with a lack of response (2 in P-ET, 1 in P-DT, 2 in P-DF, and 1 in V-DT).

We compared the accuracy of identification of perceived digits for all three conditions (DF, DT, ET) rendered with poking and vibration stimuli. As shown in Figure 3, the perceptual accuracy for default rendering on fingers had a range of 94 % to 100 %, with medians of 98% for poking and 100% for vibration. As expected, these values decreased to medians of 77% for poking and 76% for vibration to the toes under default rendering. These results are consistent with those of previously published perception studies [14], [15].

As seen in the confusion matrices of Figure 4, only a few errors were observed for the fingers. In contrast, a fair number of errors were observed for the default rendering of poking and vibration stimuli on the toes. These aligned with the confusion matrix presented by Manser *et al.* [15] for their perception study. In Figure 4, the responses for toes 2, 3 and 4 were often confused with the adjacent middle toe(s), while toe 5 was sometimes confused with toe 4.

For our encoded toe rendering, we observed median accuracy of 95% for poking and 92% for vibration, with relatively fewer errors compared to the default toe rendering (Figure 4). This was accompanied by a reduction in the confusion between the middle toes, with the proportion of accurate responses increasing an average

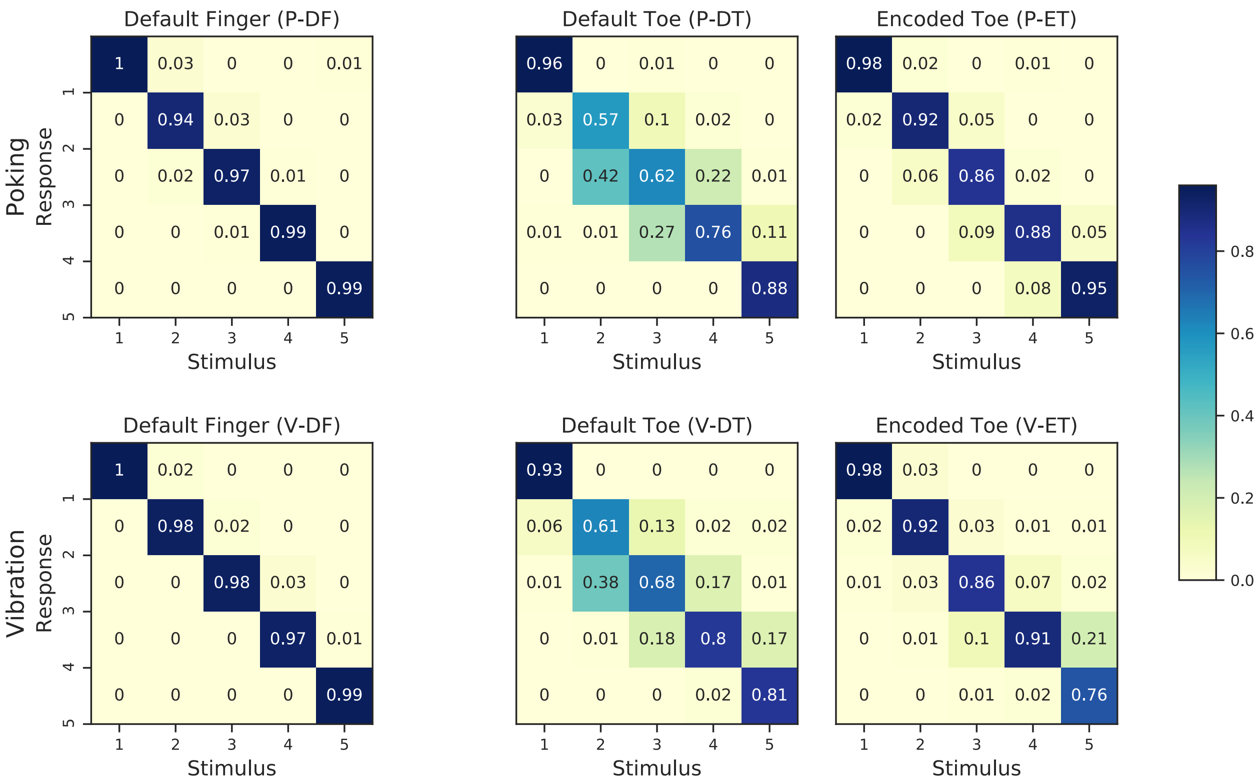

Fig. 4: Confusion matrices showing the proportion of stimuli responded as located on each of the five digits as a function of which digit was actually stimulated. Digits were identified by numbers 1 (thumb, big toe) through 5 (little finger, little toe). Data from the poking block are shown in the upper panel and those from the vibration block in the lower panel. The proportion of correct responses for each digit is shown along the diagonal from the top-left to the bottom-right. The values represented here only include the trials for which the participants responded.

of 24% for toes 2, 3 and 4 in the poking condition and 20% in the vibration condition.

A Friedman's test [31] as implemented by Vallat [32] found a statistically significant difference when analyzing all renderings (DF, DT and ET) in poking block, $\chi^2(2) = 13.087$, p<0.005. A non-parametric pairwise t-test [32] with Holm–Bonferroni correction [33] was then performed, and found statistically significant differences for two comparisons—between P-DF and P-DT, $p < 0.01$, and between P-DT and P-ET, $p < 0.05$, with a large effect size. No significant difference was found between P-DF and P-ET (Table I).

TABLE I: Comparison between different renderings for poking corrected by Bonferroni-Holm. Uncorrected (p-unc) and corrected (p-corr) p-values are reported along with the CLES [34] and Hedges' g effect size [35]. Corrected p-values with statistical significance are highlighted.

Condition A	**Condition B**	**p-unc**	**p-corr**	**CLES**	**hedges**
P-DF	P-DT	0.0032	**0.0097**	0.910	-2.505
P-DF	P-ET	0.0673	0.0673	0.562	-0.831
P-DT	P-ET	0.0073	**0.0147**	0.812	1.250

A similar series of tests was performed for renderings in the vibration block as well. The Friedman's test found a statistically significant difference when analyzing all renderings (DF, DT and ET), $\chi^2(2) = 16.979$, $p < 0.001$. The non-parametric pairwise t-test found statistically significant differences for all the three comparisons with a large effect size (Table II).

We also wanted to analyze how the different renderings performed under blocks of poking and vibration. Hence, we performed Wilcoxon tests [32] for the three blocks, DF; DT; and ET to compare if there is any difference in perceptual accuracy based on the used stimuli. The results of these three tests are available in Table III. We failed to reject the null hypothesis and could not find any statistically significant difference between poking and vibration for each comparison.

TABLE II: Comparison between different renderings for vibration corrected by Bonferroni-Holm. Uncorrected (p-unc) and corrected (p-corr) p-values are reported along with the CLES [34] and Hedges' g effect size [35]. Corrected p-values with statistical significance are highlighted.

Condition A	**Condition B**	**p-unc**	**p-corr**	**CLES**	**hedges**
V-DF	V-DT	0.0025	**0.0074**	0.958	-2.392
V-DF	V-ET	0.0206	**0.0206**	0.715	-1.277
V-DT	V-ET	0.0053	**0.0105**	0.722	0.886

TABLE III: Comparison between poking and vibration stimuli for different renderings. Uncorrected p-values (p-unc) are reported along with the CLES [34] and Hedges' g effect size [35].

Condition A	**Condition B**	**p-unc**	**CLES**	**hedges**
P-DF	V-DF	0.51	0.507	0.280
P-DT	V-DT	1.00	0.507	0.045
P-ET	V-ET	0.44	0.549	-0.289

3) Post-Questionnaire Results: In the subjective questionnaire, eight out of twelve participants reported encoded rendering to be better than default for distinguishing the toes. Three participants (P4, P9, P12) stated that they had difficulty recognizing the middle toes under the default encoding. P9 mentioned, "…for toes [toe] default, it is quite hard to distinguish 2,3,4 but toes [toe] encoded solve this problem by grouping". However, three participants (P7, P10, P11) preferred the default over the encoded rendering in terms of effort. P10 wrote "…encoded method [has] cognitive load, default [method is] easy to guess…".

P11 mentioned, "I was not properly able to recognize the difference between 2,3,4 [in encoded rendering]". We found out that their individual performance indicated a much higher proportion of errors (36% for poking, 34% for vibration block) relative to the median (5% for poking, 8% for vibration block) for the encoded rendering. It is possible that they were unable to understand the encoding properly.

Two participants compared default finger and encoded toes, and they had diverging opinions. P5 wrote "perception was better in the encoded method than default method but was still lesser than that for fingers" where as P9 mentioned "by grouping toes, [the encoded rendering] is even better than fingers"

There was also disagreement with regards to the preference between vibration or poking stimuli, e.g., "the poking was more concentrated and helped identify the stimuli; the vibrations were diffused and could not clearly identify" (P2), "for toes poke was better as [it is] well separated" (P4), "[vibration] is more hazier than pokes" (P7), whereas others (P5, P11) expressed the opposite.

Commenting further on the differences between poking and vibration, P1 mentioned that "on toes, poking was better but on fingers, vibrations was better". This might be explained by the fact that fingers are well separated, and there is thus less propagation of vibration as compared to toes.

V. Discussion

The results of our study follow the same trend as previously published work by Cicmil et al. [14] and Manser et al. [15]. While both fingers and toes offer ten sites for tactile rendering, a default haptic rendering strategy on the fingers achieves higher perceptual accuracy with very few errors. In contrast, the default rendering on toes exhibited many errors due to the confusion between the middle toes. With this in mind, our proposed method helps tackle the difficulties in discrimination of haptic stimuli to the toes, apparent from a simple rendering approach. These problems, clearly in evidence in the confusion matrices, were addressed by the addition of our novel tactile cues. Toe discrimination using the resulting encoded rendering demonstrated significant improvement, both for vibration and poking stimuli.

Since toes have lower spatial separation than fingers, they are more prone to erroneous perception of tactile stimuli. To compensate for this limitation, we designed our encoded rendering to provide an initial cue to the "directional toes". This affords the participant an initial localization to a subset of the toes, followed by delivery of the final cue to the targeted toe. Although, performance of the encoded rendering on toes did not surpass that of the default rendering on fingers in terms of perceptual accuracy, it did nevertheless achieve a level that was close. This suggests that toes can be used as a viable tactile display in the many situations for which the fingers are inappropriate. Further studies may prove the effectiveness of our proposed rendering for conveying semantic information on toes. As the perceptual discrimination performance we have achieved for the toes remains imperfect, further improvements in pattern design may be considered, varying amplitude, frequency and time duration in an attempt to increase the perceptual accuracy. The designed encoding schemes can be compared based upon their accuracy as well as information transmission rates.

Two commonly used tactile renderings, poking and vibration, were employed for our study, but we failed to find a statistically significant difference in performance between them. Although such differences are likely to be more pronounced in the case of a single site multi-actuator tactile display, as shown by Shim et al. [29], we suspect that whatever the advantages of poking stimuli are, these are eclipsed by the ambiguity in tactile perception among the middle toes.

In the absence of further data to indicate a clear winner, we opt to employ vibration because of the more compact actuators that can be fitted comfortably in a wearable device for practical use. Alternatives of compact actuators to deliver poking stimuli are being developed, but are not yet commercially available. Future work may also explore other haptic stimuli such as squeezing or lifting of the toes, as well as consider stimulation of the non-glabrous surfaces of the toes.

A particular benefit of our encoded toe rendering is its simplicity. Participants in the study received minimal training to learn how to interpret the rendering. Only a scripted description of the rendering and a few demonstrative trials were presented to participants to prepare them for the experiment. The remainder of the learning occurred throughout the trials. Nevertheless, participants were still able to perform quite well in identifying the stimulated toes.

VI. Conclusion

We proposed an encoded tactile toe rendering method to help distinguish stimuli applied to individual toes. The results from our study indicated that our proposed rendering outperforms a simpler default rendering, conveyed by either poking and vibration stimuli. Moreover, the perceptual accuracy attained for our encoded toe rendering approached the discrimination performance achieved at the fingers. This provides strong encouragement for consideration of the toes as a suitable location for multi-site tactile toe display.

Although we obtained fairly good results for our proposed rendering on toes, one drawback of haptic interfaces located on the feet is the haptic noise and tactile gating created while standing or walking. We expect that the performance of any haptic foot system will degrade while the user is standing, walking, or running. While the performance of this rendering with a user in motion has yet to be assessed, there are many scenarios where a foot-based interface is viable. Seated musicians, office workers or plant operators, for example, are typically in situations where the feet are unused and largely undisturbed. Thus, even if we cannot claim that the toe-based system described in this work is usable for all situations, there is considerable utility even in an apparatus that is limited to seated use. In addition, future work that improves foot-based haptic interfaces may result in the rendering techniques described in this work becoming viable for a broader range of user activities in the future. Furthermore, this style of encoded rendering can be adapted for other multi-site haptic applications to distinguish perception from different sites while minimizing confusion between adjacent locations.

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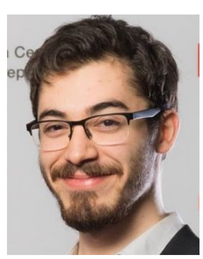

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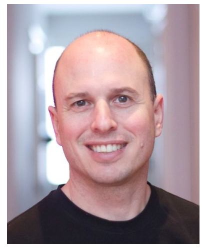

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