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Multi-channel Tactile Feedback Based on User Finger Speed

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Alongside vision and sound, hardware systems can be readily designed to support various forms of tactile feedback; however, while a significant body of work has explored enriching visual and auditory communication with interactive systems, tactile information has not received the same level of attention. In this work, we explore increasing the expressivity of tactile feedback by allowing the user to dynamically select between several channels of tactile feedback using variations in finger speed. In a controlled experiment, we show that a user can learn the dynamics of eyes-free tactile channel selection among different channels, and can reliable discriminate between different tactile patterns during multi-channel selection with an accuracy up to 90% when using two finger speed levels. We discuss the implications of this work for richer, more interactive tactile interfaces.

1 INTRODUCTION

Interactive systems are a complex combination of hardware and software, combined together in order to enable the user to perform classes of tasks. Among possible ways for the system to provide information to the user, vision and hearing have been, since interactive computing systems have emerged, the primary perception channels for user feedback. Hardware and software technologies for feedback (displays, VR or AR headsets, projectors for visual feedback; sound rendering systems for auditory feedback) are mature, and include the ability to render information

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(of very different type, either physically plausible, or conceptual). Significant work has been done by the human-computer interaction community on interaction techniques that leverage these output modalities.

By comparison, the sense of touch remains less exploited in interactive systems, despite its many advantages in, for example, areas as broad as well-being [9], immersion [22], and assistive technologies [4]. However, researchers are beginning to address this problem: hardware systems continue to evolve in their ability to provide subtle forms of tactile feedback [13, 15, 21], and researchers continue to identify the ways in which tactile feedback can enhance performance [5, 11]. One primary benefit of touch is that the feedback can be acquired eyes-free [19, 23, 25, 27]. As a result, there is an interest in developing techniques that fully exploit touch as an output modality in human-computer interaction, including in increasing the bandwidth of touch output [11, 20].

Our approach to increase the bandwidth of tactile output is to consider multi-channel tactile feedback, where different haptic or tactile signals can be monitored selectively by the user. There is some interest in multi-channel haptic monitoring: a recent patent filing describes leveraging device orientation to output different haptic signals on different haptic output devices [3]. Alongside orientation, obvious approaches for providing multiple haptic signals include assigning tactile effects to different on-screen locations, an approach that has been used in aid of target acquisition [5], immersion [22], and eyes-free interaction [23], but, in such systems, the information provided is as a proxy to or aid to visual input. What if, instead, we wished to preserve the eyes-free nature of tactile sensing while adding multi-channel capability to it, but primarily to sense conceptual, as opposed to augmenting visual information? From assistive technology to pervasive computing, the benefits of eyes-free sensing are well-explored, so we believe that the idea of eyes-free, multi-channel tactile sensing is worthy of inquiry.

To explore eyes-free, multi-channel, tactile feedback, in this paper we explore increasing the expressivity of tactile feedback by allowing the user to dynamically select between several channels of tactile feedback using variations in finger speed. The goal, then, becomes to enhance tactile feedback by allowing user-selectable and user-monitorable channels which can be exploited eyes-free to provide richer forms of tactile or haptic feedback. Through a controlled experiment leveraging three levels of finger speed and three different textures, we show that, with training, users can perform accurate tactile channel selection using two levels of finger speed with up to 90% accuracy.

In the remainder of this paper, we introduce the concept of multi-channel tactile feedback. In particular, we develop our design rationale for tactile channel selection using finger speed and present practical applications enabled by this multi-channel tactile feedback concept. We then present a controlled experiment that shows that a user can learn the dynamics of tactile channel selection. Finally, we conclude by discussing the scalability of tactile channel selection and avenues of future work.

2 RELATED WORK

We review previous work on tactile feedback in terms of devices, rendering techniques and interaction techniques.

2.1 Tactile feedback based devices

Touch interaction is the primary input modality of many modern smartphone and mobile computing devices, a result of increasingly affordable multi-touch sensors. The ubiquity of these multi-touch devices means that a large number of users have extensive experience using touch as an input modality. Alongside input, touch interaction can be enhanced with a tactile feedback to provide stimulation when touching the surface. While, at present, with the exception of vibration, rich patterns of tactile feedback have been largely relegated to research systems, it is clear that the overall aim of tactile feedback research is eventual integration with mobile, multi-touch devices. With this in mind, two main technologies have emerged to support mobile device-based tactile feedback: (1) electrovibration technologies [2, 18] which enhance the friction between the finger and the interaction surface and (2) ultrasonic technologies which reduce the friction through the "squeeze film effect" [1, 5, 13, 26]). In the remainder of this paper, we leverage the latter type of tactile feedback, ultrasonic-based tactile feedback.

2.2 Tactile feedback rendering techniques

Most existing surface haptic devices (*e.g.*, [1, 2, 12, 13, 18]) use the Surface Haptic Object (SHO) technique [21, 26] to render a tactile texture. SHO is based on mapping a given texture with a discrete sampling of position. Vezzoli et al [21, 26] introduced a new rendering technique, namely Surface Haptic Texture (SHT) , which relies on real time finger speed. With SHT, a texture can be reproduced with the correct spatial period, but not with an exact starting position as the texture is attached to velocity estimation and not to position. Rekik et al. [21] compared the SHO and SHT techniques through a controlled experiment using three finger speeds (slow, moderate and fast). Their findings indicate that SHT leads to the highest level of quality of tactile rendering for dense textures with either fast or moderate velocity; whereas SHO is still more accurate for sparser textures with moderate velocity due to positional shift. Considering these results, Rekik et al. [21] introduced the Localized Haptic Texture (LHT), a new rendering technique [21]. LHT separates the tactile rendering into two different processes: first, the finger position is retrieved from the hardware, and the corresponding texture is selected through a search in a grid of taxels (tactile elements). The taxel texture is then rendered locally by defining only one period of the texture and then repeated in a loop at a rate that depends on the finger's speed. LHT was shown to provide a high-fidelity between the tactile texture and its visual representation. For instance, LHT leads to the highest level of quality of tactile rendering for both dense and sparse textures. In addition, the performance benefits of LHT were consistent across different finger speeds. In our work we use the LHT technique to render the textures.

2.3 Tactile textures perception

The current practice of tactile feedback surface design has outlined several guidelines to assist practitioners in how users feel and identify objects through the sense of touch [7, 11, 14, 20, 21]. In [21], the authors investigated the user ability to perceive the texture when using different fingers speeds. In [11], the authors determined the smallest tactile texture size that user can accurately perceive. Other researchers have investigated the users ability to perceive simultaneous but different textures [20] and provided the semantic perceptual space of tactile textures [**?**]. In [7, 8], the authors studied how a physical challenging activity, an attention saturating task and a cognitive load task affect the user perception of tactile texture.

2.4 Tactile feedback texture based interaction techniques

Recently, a patent filing describes leveraging device orientation to output different haptic signals on different haptic output devices[3]. If the desire is to tender multiple tactile patterns simultateously, alongside device orientation, obvious approaches to this problem involve assigning tactile effects to different on-screen locations, an approach that has been used in aid of target acquisition [5], immersion [22], and eyes-free interaction [23]. However, in such systems, the information that tactile output provides is as a proxy to or aid to visual input.

In this paper, we introduce the concept of multi-channel tactile feedback that allows the user to dynamically select between several channels by varying his finger speed. We then use this new concept to explore increasing the expressivity of tactile feedback based interaction.

3 MULTI-CHANNEL TACTILE FEEDBACK VIA SPEED

3.1 Motivating Multi-Channel Feedback

Tactile Feedback – as with touch in the real world – is primarily considered both as an output modality and a complement to visual information. However, there are real world scenarios where touch perception is used eyes-free or even in the absence of visual information; for example, a user may quickly tap a coffee mug to check its temperature, stroke the surface of a woodworking project to identify irregularities, or rub braille lettering on a doorway to determine his or her location.

In modern multi-touch devices, tactile feedback can be considered both as input and output. One potential benefit of multi-channel tactile feedback is that it enables richer output (alongside the richness of multi-touch input), *i.e.*, a richer interactive experience. To illustrate the benefits of multi-channel tactile feedback, we consider the following example scenarios:

- A user places his cellphone in do not disturb mode or a user puts his cellphone in his pocket during a meeting or a conversation with another person, but wishes to check for new mail, text messages, or calls on her cellphone [23]. Rather than looking at the display or turning on his phone, he can leverage multi-channel tactile feedback to determine whether he has new messages and which type of new messages they are. This would enable a less obtrusive way to check messages especially in social scenarios (*e.g.*, having a conversation with another person).
- A user is walking or driving and wishes to monitor various communication channels, but needs to visually attend to his primary task, driving the car. Eyes-free haptic feedback can be performed without the need to visually attend to the screen while driving.
- In a similar vein, shoulder surfing is a significant problem in the field of privacy and security research because, with visual information, any passer-by behind the primary user can catch glimpses of on-screen information. Multi-channel haptic feedback can be used to communicate limited information surreptitiously to modify sensitive information that one would not want “shoulder-surfed”; as one simple example, tactile feedback could be used to help the user select between multiple passwords, making passwords more should-surfing resistant.

3.2 Motivating Speed-Based Selection

In tactile feedback based systems, the user must refer to his sense of touch to interact with the system. This task can be done eyes-free (*i.e.*, non-visual, non-auditory). Thus, when designing a tactile feedback based system, considerations must be given to the number and type of tactile textures used as these factors can significantly influence the user experience. In terms of interaction expressivity, one can ask how can we enhance the bandwidth of tactile output without saturating the user’s sense of touch with too many textures. For example, should each texture represent different information or can we mix and match as desired depending on application context? While these decisions must be made by designers based on the context of their applications, they will nonetheless benefit from guidelines that can systematically introduce new information associated to the textures without overly complicating the interaction.

The question then becomes how best to multiplex information on the tactile channel. As the user perceives a texture only when moving his finger over the surface, the use of finger movement to define different input channels seems obvious. We did consider other parameters including the movement direction (*e.g.*, east-west, north-south, north east - south west, north west - south east), the movement sense (*e.g.*, east to west vs west to east, clockwise vs counterclockwise, etc), and the finger trajectory (*e.g.*, linear, circular, etc). However, given that a finger must move to perceive tactile feedback, finger speed (*e.g.*, slow, moderate and fast) seemed an opportunistic parameter for channel section and prior work [21] has showed that users are able to recognize correctly tactile texture when using slow, moderate and fast speed.

In the next section, we study the potential of using two and three levels of finger speed combined with three textures to increase the expressiveness of tactile feedback based surfaces.

4 EXPERIMENT

We conducted an experiment that measured participants' ability to extract information from the tactile surface. We were interested in understanding whether our participants could reliably distinguish between different information assigned to different textures perceived at different finger speeds. More specifically, our goal is to determine the number of levels of finger speed that our participants will be able to use and the learnability of finger-speed-based channel selection in multi-channel tactile feedback, *i.e.*, in how accurately participants could leverage speed to select from the available channels.

4.1 Research Questions

Our goal was to understand the learning performance of the expert level of multi-channel tactile feedback based on finger speed. We expect expert level to be both slower and more error prone than novice mode. Given this assumption, the goal of this experiment is not to prove that expert level is worse than novice level – *i.e.*, to count failures for expert level when compared to novice level – but instead to determine the number of finger speed channel and understand the learning performance of multi-channel tactile feedback based on user finger speed. We were more curious about learnability than absolute speed performance because multi-channel tactile feedback based on user finger speed has been unexplored, and we wished to determine how easily the finger speeds, perceived textures, and associated information could be memorized. With this in mind, we will examine overall speed and accuracy, but then focus specifically on the two finger speeds level (task3) and three finger speeds level (task4) to determine the number of levels of finger speed that our participants will be able to use and prefer.

4.2 Participants

Ten participants (two female) volunteered to take part in our experiment. Participants ages were between 22 and 36 years (mean=28, sd=4.53). All participants were right handed.

4.3 Method

We use *E-vita* [26] a tactile feedback tablet that supports friction modulation by mean of ultrasonic vibrations [26], where the squeeze film effect generates an ultra-thin film of air between the finger and the surface when an ultrasound frequency is applied to a display overlay. *E-vita* includes both visual and tactile feedback; alongside the tactile display, the E-VITA device [26] is equipped with a 5-inch LCD display including a capacitive sensor which allows a sampling frequency of 50 Hz, similar to the capabilities of commercial mobile devices.

We recall the definition of a tactile texture. A tactile texture (see Fig.1) refers to a sequence of periodic tactile feedback [20, 21, 26] such that the period to be reproduced inside the texture can be formed by some specific signal (periodic, structured noise, micro-geometry extracted, etc.). We, then consider three different tactile textures. We encode the different textures with respect to different texture densities by considering the following spatial periodicity: *D*ense – 1.2 mm; *M*edium – 10 mm and *S*parse – 25 mm. In Fig.1, the tactile textures are shown by alternating black and white bars; high friction is associated with the black color and low friction with the white color. Given that we use the Evita, which, when vibrating, reduces friction, this maps black to off and white to on to create tactile patterns.

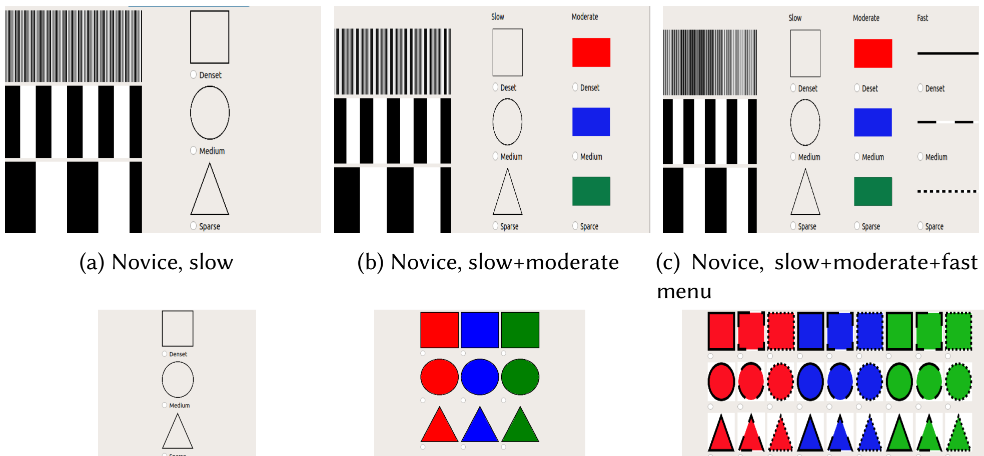
The set of considered textures follows the set used by Rekik et al. [21], because, for these textures, users have been able to distinguish them independently regardless of finger speed, a challenge in user perception of tactile textures (e.g., [11, 20, 26]). The set of textures is also limited to one-dimensional textures in order to simplify the task. To render a given texture we used the Localized Haptic Texture (LHT) rendering technique [21].For finger speed thresholds, we follow Rekik et al. [21] and use the same thresholds: the slow speed is slower than 30 mm/s; the moderate speed is faster than 30 mm/s and slower than 180 mm/s; and, the fast speed is faster than 180 mm/s.

4.4 Tasks and design

We designed the following four tasks:
Task 1: one Speed. In the first task, participants were asked to move their finger at a specific speed and to identify the perceived texture. In this task, each participant identified 54 textures = 3 finger speed (slow, moderate and fast) × 2 expertise levels (novice and expert) × 3 textures (D, M, S) × 3 repetitions. The experiment took on average 15 minutes to complete.

Task 2: one finger speed channel. In the second task, participants were asked to move their finger at a specific speed, identify the texture, and further identify the corresponding association of information. The slow speed is associated to the form, moderate speed is associated to the color and fast speed is associated to the contour line. In this task, each participant identified 54 pieces of information = 3 finger speed × 2 expertise levels × 3 textures (D, M, S) × 3 repetitions. For example, for slow speed condition, Figure 1 (a) and (d) depict the interface used to represent the textures and map the textures onto associated information in respectively the novice and the expert levels. The experiment took on average 15 minutes to complete.

Task 3: two finger speeds channels. In the third task, participants were asked to move their finger at two different speeds, identify the texture that is perceived at each speed, and further identify the corresponding association of information. In this task, each participant identified 162 pieces of information = 3 sets of finger speed (slow+moderate, slow+fast, moderate+fast) × 2 expertise levels × 9 sets of textures (DD,DM, DS, MD,MM, MS, SD, SM, SS) × 3 repetitions. For example, for slow+moderate condition, Figure 1 (b) and (e) depict the interface used to represent



(a) Novice, slow
(b) Novice, slow+moderate
(c) Novice, slow+moderate+fast menu
(d) Expert, slow
(e) Expert, slow+moderate
(f) Expert, slow+moderate+fast menu

Fig. 1. The interface for choosing the information at novice level (up) and expert level (down) for the different finger speeds conditions: (a; d) slow condition, (b; e) slow+moderate condition and (c; f) slow+moderate+fast condition. As example, for slow+moderate condition, in the novice level, the application shows the visual representation of the three texture (dense, medium and sparse) and the associated information according to each finger speed, *i.e.*, the geometrical form for slow speed, and the color for moderate speed. For the expert level, the participant is shown all possible information at once, *e.g.*, red triangle with continuous line contour when perceiving sparse texture at slow speed and dense texture at moderate speed.

the textures and map the textures onto associated information in respectively the novice and the expert levels. The experiment took on average 90 minutes to complete.

Task 4: three finger speeds channels. In the fourth task, participants were asked to move their finger at three different speeds, identify the texture that is perceived at each speed, and further identify the corresponding association of information. In this task, each participant identified 54 pieces of information = 1 set of finger speed (slow+moderate+fast) × 2 expertise levels × 9 sets of textures × 3 repetitions. We decided to limit the set of used textures to only 9 sets to minimize fatigue and keep data consistency, the sets used were: DDS, DMM, DSD, MDM, MMD, MSS, SDD, SMM, SSS. Figure 1 (c) and (d) depict the interface used to represent the textures and map the textures onto associated information in respectively the novice and the expert levels. The experiment took on average 45 minutes to complete.

4.5 Procedure

During the experiment, we began with the first task, our simplest configuration, then allowed the complexity of the interface to gradually increase (*i.e.*, *task2*, then *task3* and finally *task4*). We did this so we could allow users to gradually learn finger speed (*task1*) and then the associated information with each texture for each finger speed (*task2*), then two associated information for two different finger speeds (*task3*) and finally three associated information for the three different finger speeds (*task4*). After each task and after each finger speed condition, participants take a break to avoid fatigue accumulation.

In task 1, 2 and 3, the different finger speed conditions (*i.e.*, slow, moderate, fast in task 1 and 2 and slow+moderate, slow+fast, moderate+fast in task 3) were administered randomly. For each task, inside each finger speed condition, we did not counterbalance condition (novice vs expert) between users. Instead, each user tested the novice condition first to learn the finger speeds (and the associated information for task 2, 3 and 4) with each perceived texture, and then tested the expert condition. This strategy was informed by our goal to evaluate user reproducibility of the finger speed and the information associated with the perceived texture in expert level given their experience in novice level. Inside each expertise level, the different texture sets ($times$ 3 repetition) were also administered randomly. The user was also provided a tactile texture only if his finger speed corresponded to the allowed speeds *i.e.*, no texture is provided to the user if the finger speed is greater than the finger speed thresholds allowed in the trial.

In the novice condition, to foster training, a message with the actual finger speed was displayed on the screen in a black color *i.e.*, slow, moderate or fast. If the finger speed corresponds to one of the speeds evaluated in that trial, the finger speed message is then displayed with a green color. For example, if the finger speed condition corresponds to *slow+moderate*, the user is shown the word "slow" or "moderate" in a green color, if his finger is moving at that speed, otherwise, the finger speed is displayed in black (in this example, the word "fast" is show with a black color for the *fast* condition). In the expert level, no information about the finger speed is provided. In both levels, the order of execution of the different finger speed conditions were counterbalanced

In addition, as long as, the trial is on-going, the participant can reassess a previous speed. For example, in the task 4, the participant can start with the moderate speed, then the fast speed, then the slow speed, and then finish by reassess the moderate speed. The exploration time was not limited and participants were free to move their index finger from the dominant hand from left to right and back to perceive the texture, without a starting finger position or time restrictions or the obligation to keep the finger on the surface over the trial.

In both levels, when perceiving the texture no visual feedback of the perceived texture was shown on the surface, only tactile feedback was sent to the participant, to preserve a simulated eyes-free input condition. In addition, as the Evita device makes noise when alternating high and low friction, the participants were equipped with noise reduction headphones to avoid any bias. Tactile feedback was hence made both eyes and ears-free since the participants were not able to see any visual nor to hear any audio rendering on the surface.

A trial ended once the participant pressed on the "enter" button on the top of the surface. Once the "enter" button was pressed the participant had to select the identified information according to the perceived texture(s) and the finger speed(s). Each finger speed defines the type of output channel while the perceived texture must be matched to the output channel. For example, the moderate speed is associated with the object color. Sparse texture is, then, associated with the green color, medium texture is associated with blue color and dense texture is associated with red color (please refer to Figure 1 for the other speed conditions).

Given the above example, the information content of the multi-channel tactile effects corresponds exactly to the information in the trial. For example, for the *slow+moderate*, participants have to identify the object form (*i.e.*, the information associated with the slow speed) and the object color (*i.e.*, the information associated with the moderate speed).

In the novice condition, to select information after the experiment, the participant is provided with a table showing a visual of the texture and the associated information according to each finger speed. The participant selects sequentially the associated information for each finger speed. For the expert level, the participant is shown all possible information at once. For example for task 4 (*slow+moderate+fast*), while in the novice level, the participant had to select sequentially the geometrical form, its color, and the contour line; in the expert level, the participant selects only the information that corresponds to the final desired information *e.g.*, red circle with continuous line contour (see Figure 1.

For task 3 and 4, after each of finger speed condition, participants were asked to comment on the interface used and respond to both a NASA TLX and a SUS (System Usability Scale) questionnaires, plus a 5-point Likert-scale question (strongly disagree to strongly agree) for measuring enjoyment while interaction with the haptic device. At the end of the experiment, we asked participants to describe their experience with multi-channel tactile feedback including whether they would use this type of interaction, what number of levels of finger speeds they prefer, and why.

5 RESULTS

The dependent measures are the *accuracy* and *trial time*. The *accuracy* is defined as the proportion of correct identifications of the information. For example, in task3, in the *slow+moderate* condition, the accuracy corresponds to correct identifications of the object form (*i.e.*, the information associated with the slow speed) and the object color (*i.e.*, the information associated with the moderate speed). The *trial time* is defined as the time that a user takes from starting moving his finger on the surface until pressing the "enter" button. The *accuracy* provides a measures of whether the users are able to perceive the different textures associated with different velocity-selected channel and to identify correctly the information provided. The *trial time* is defined as the time that a user takes from starting moving his finger on the surface until pressing the "enter" button. The *trial time* is more subjective and can only provide an estimate of how difficult the identification task is for participants. Due to a technical issue, the data of two participants were not completely logged. Consequently, we excluded these two participants from the analyses. Below, we report results for each of the dependent variables for our eight remaining participants.

5.1 Task 1

Accuracy. There were no significant main effect on accuracy nor interaction (p>.28) (overall: mean 83.79%, s.d= 3.47).

Recognition time. There was significant main effect of speed ($F_{2,14} = 28.51$, $p < .0001$) on recognition time. Without surprise, Post-hoc tests revealed that the slow speed (mean 14.39s, s.d. 2.47s) is significantly slower than both the moderate (mean 7.93s, s.d. .92s) and fast (mean 4.65s, s.d. .55s) speeds (p<.05).

5.2 Task 2

Accuracy. There was significant main effect of expertise ($F_{1,7} = 7.46$, $p = .02$) on accuracy. Post-hoc tests revealed that the expert level (mean 94.44%, s.d. 3.06s) is significantly more accurate than the novice level (mean 87.03%, s.d. 4.48%s) (p<.05). There was no significant interaction (p>.05) suggesting that the benefits of expert level are consistent across different speed conditions.

Recognition time. There was significant main effects of speed ($F_{2,14} = 8.03$, $p = .0004$) and expertise ($F_{1,7} = 5.65$, $p = .04$) on recognition time. Post-hoc tests revealed that the slow speed (mean 7.78s, s.d. 1.34s) is significantly slower than both moderate (mean 5.65s, s.d. .94s) and fast (mean 4.22s, s.d. .63s) speeds (p<.05). We also found that the expert level (mean 5.13s, s.d. .89s) is significantly faster than the novice level (mean 6.64s, s.d. .79) (p<.05).

5.3 Task 3

Accuracy. There was significant main effect of speed ($F_{2,14} = 4.98$, $p = .0231$) on accuracy. Post-hoc tests revealed that slow+moderate (mean. 90%, s.d. 2.85%) is significantly more accurate than both slow+fast (mean. 81.01%, s.d. 3.70%) and moderate+fast (mean. 78.70%, s.d. 3.86%) (p<.05).

Recognition time. There were no significant main effects on recognition time nor interaction (p>.24) with a total mean of 15.37s (s.d=.541s).

5.4 Task 4

Accuracy. A Wilcoxon Signed-rank test showed that the expert level (mean. 85.18%, s.d. 4.74%) is significantly less accurate than the novice level (mean. 70.83%, s.d. 6.07%) (Z = 3.57, p < .0001).

Recognition time. A Wilcoxon Signed-rank test showed that there was no significant difference between the expert level (mean. 26.46 s, s.d. 1.71s) and the novice level (mean. 24.77s, s.d. 1.71s) (Z = -1.51, p = .13).

Summary. The key finding is that both trial time and accuracy do not drop in the expert level comparing to the novice level in the one and two speed levels channel conditions, with expert level both faster and more accurate than the novice one in the one speed channel conditions. These findings suggest that people can easily learn to perform tactile channel selection via two finger speeds sets. Additionally, the two finger speeds slow+moderate is the best performing two level channels input with an accuracy of 90% in average and a reasonable time to recognize the two textures and their associated information (15s). In contrast, the three finger speeds channel demands 26s in average to recognize the information associated to three textures perceived at the three speeds with an accuracy that drops in the expert level from 85% to 70%. This findings suggest that for three finger speeds channel, people need a longer learning step to permit users to discover the different finger speeds and the information associated with the different textures before switching to expert level.

5.5 Subjective Results

All participants found that giving the user different information depending on finger speed and the perceived texture was effective and enjoyable (see Table 1), noting: "*providing different information to the same perceived texture depending on the finger speed is absolutely useful and enjoyable*" and "*it is very enjoyable and smart way to get information*".

Nasa TLX responses (Table 1) show that mean ratings for slow+moderate+fast were least appreciative for all six questions followed by moderate+fast, but only significantly so for mental demand, physical demand, temporal demand and effort. Pairwise comparison using Bonferroni correction showed that slow+moderate+fast (respectively moderate+fast) is significantly more demanding mentally, physically and temporal and implies more effort than slow+moderate and slow+fast (respectively, slow+moderate) (p<.05).

When analysing the ease of use of the two finger speeds channels and three finger speeds channel through a SUS questionnaire (Table 2, we found that the average SUS score for the slow+moderate

	slow+moderate		***slow+fast***		***moderate+fast***		***slow+moderate+fast***		***Friedman***
	Mean	s.d	Mean	s.d	Mean	s.d	Mean	s.d	$\chi^2(3)$
NASA TLX questionnaire									
1. Mental demand	2.5	.64	3.625	.51	3.87	.93	4.5	.52	13.01
2. Physical demand	1.87	.68	2.75	.32	3.12	.57	4.12	.44	14.25
3. Temporal demand	2.12	.57	2.5	.52	3.25	.80	3.37	.51	12.28
4. Performance	4.37	.35	4	.37	3.62	.73	3.37	.51	6.59
5.Frustration	1.62	.63	2.25	.71	2.62	.82	2.75	.80	7.10
6. Effort	2.12	.57	2.87	.68	3.75	.48	3.87	.68	17.73
5-point Likert scale									
1. Enjoyment	3.75	.48	3.37	.63	2.87	.78	3.25	.48	3.17
SUS questionnaire									
1. Frequency of use	3.75	.71	3.375	.82	3.12	.93	2.5	.52	6.68
2. Complexity	1.5	.37	2.25	.61	2.62	.82	3.25	.80	10.47
3. Easiness	4	.52	3.125	.86	2.87	.78	2.37	.63	7.37
4.Support demand	1.12	.245	1.375	.51	1.62	.97	1.87	.68	7.57
5. Functions integration	4	.52	4.5	.52	4.25	.71	4.12	.44	4.45
6. Inconsistency	1.62	.51	1.75	.71	1.62	.51	1.87	.68	.34
7. Learning	4.25	.32	3.875	.57	3.12	.78	2.75	.48	13.08
8. Cumbersome	1.62	.73	2.25	.48	2.62	.73	3	.74	6.80
9. Confidence	4.12	.78	3.62	.73	3.37	.73	3.375	.73	2.65
10. Leaning a lot of things	1.12	.24	1.5	.74	1.87	.93	2	.74	9.14

Note: Friedman tests are reported at p=.05 (*) significance levels. The significant tests are highlighted.

Table 1. Mean and s.d questionnaire responses for the two and three channels conditions, with 1=very low, and 5 = very high.

	slow+moderate	***slow+fast***	***moderate+fast***	***slow+moderate+fast***
SUS Score	82.81	73.44	65.94	57.81
Grade	A	B	D	D
Adjective Rating	Excellent	Good	Poor	Poor

Table 2. SUS Score, grade and adjective rating for the two and three channels conditions.

channel is 82.81, suggesting that this speed channel has an excellent perceived usability. The slow+fast channel has also a good perceived usability with an average SUS score of 73.44. In contrast, the SUS score for the moderate+fast and slow+moderate+fast channels were respectively 65.94 and 57.81, suggesting that these two speeds channels have a poor perceived usability.

These findings are correlated with our participants preferences and comments. For instance, all our participants preferred using two finger speeds channels over three as it was perceived to be easier. In addition, two participants found "*the fast speed is very fast which demands more physical effort to perform the task*" and consequently they preferred slow+moderate. Two other participant commented that "*it is difficult to switch from the fast speed to the moderate one*", as it was difficult to know if they have not slowed down enough (or inversely) without the finger speed indicator and so they preferred the slow+moderate. Meanwhile, two other participants found that slow+fast channel was best as they found "*the gap between the slow and fast finger speed easier to differentiate between the two speeds*". One of them said: "*slow with fast was easier because I had a dip between the* *two speeds*". On the other hand, another participant preferred to combine moderate speed with fast speed as he found "*the slow speed very slow*" for him. He added: "*slow speed demands more time to identify the texture than moderate and fast speeds which makes the task annoying and demanding more concentration*".

While there was a stated preference for two speeds, six of our participants noted that they would prefer three finger speeds if the system allowed them to either personalize the finger speed thresholds at the beginning of the task or if the indicator for the finger speed was always displayed. Specifically, participants noted: "*I will appreciate using a three finger speeds if there was more space between the defined velocities*", "*three finger speeds would be more convenient if the slow and moderate velocity were more separated*" and "*in the novice level, I could adjust my speed along the way since it is displayed, but not in the expert level... I will prefer three speeds if the finger speed is always displayed*".

Based on the SUS questionnaire, we found that in term of complexity of the task, the three finger speeds channel is perceived more complex (Q2) and less easy to use (Q3) than the two channels conditions but this was significant only for complexity. Pairwise comparisons using Bonferroni corrections revealed that slow+moderate+fast is significantly more complex than slow+moderate ($p<.05$). Similarly, in terms of learning, the three channel demands more support (Q4), a learning step (Q7), and to learn a lot of things before using (Q10) but was significant only for a learning. Pairwise comparisons using Bonferroni corrections revealed that slow+moderate+fast demands significantly more learning than slow+moderate ($p=.02$).

Interestingly, three participants associated the finger speed used to specify the level of the detail of the output information. For example, for the first participant noted that "*adjusting the speed was a manner to get information depending on their importance: slow for important information and the opposite for the fast speed*". For the two remaining participants, the finger speed was associated with the precision of the information delivered by the tactile surface: slow speed can be associated with fined-grained information, while fast speed can be associated with coarse-grained information. The moderate speed can be associated with basic information. One participant said: "*the slow speed may be necessary to get more precise details about the information being delivered, however, the fast speed is just for checking the existence of this latter as it can be made quickly, especially for contexts that demands attention like driving*". Meanwhile, the second participant declared that "*the slow speed is for precise information with enough available time, for example, getting the content of a text message, while the fast speed is when we need to get the information as fast as possible, for example, getting just the idea of the message*".

6 DISCUSSION

The results presented in this paper argue that participants can effectively use finger speeds to discriminate between channels of tactile input. Specifically, our findings indicate both that users are able to control the speed with which they move their fingers and to recognize the perceived textures and to identify the associated output information, in particular when using two finger speeds. In addition, our findings indicate that the slow+moderate channel outperformed both slow+fast and moderate+fast channels when considering accuracy (90%) while having an excellent perceived usability, being the least demanding mentally, physically and temporally and the most appreciated by the user in terms of learning and ease of use. We consequently, recommend to privilege slow+moderate as a two level channel input when using finger speed.

Our findings also indicate that the slow+fast has also a good perceived usability with an accuracy of 81% on average, suggesting that this two finger speed channel is also interesting to exploit.

However, moderate+fast channel has a poor perceived usability score with an accuracy of 78% while being more demanding mentally, physically and temporally than slow+moderate. These results could be explained by the fact that fast finger speed has a higher physical demand than other speeds and when associated with moderate speed; due to the limited difference between moderate and fast, discrimination between the speeds places participants under greater physical/mental/temporal demand, a fact commented on by our participants. These findings suggest that this two finger speed channel should be used with care.

When considering the three finger speed channel, the accuracy drops in the expert level to 70% on average compared to the novice level (85%). The three speed channel also has a poor perceived usability score, is perceived to be the most demanding task mentally, physically and temporally, and is the least appreciate by participants in terms of learning, ease and preference. These findings suggest that the three finger speed channel may be too difficult for users and, consequently, we do not recommend its use. However, as noted by our participants, the three finger speed channel could be exploited with either a longer learning step to permit users to discover the different finger speeds and the information associated with the different textures before switching to expert level, or by permitting users to personalize the finger speed thresholds at the beginning of the task. Further studies focusing on this transition can assess the amount of training needed and the potential benefits of customized speed thresholds.

One thing that surprised us in the results was that measures of time showed that expert level was typically statistically as fast or faster than novice level. Our assumption was that users would be slower with expert level. In effect, we were more interested in how easy it was for participants to perform with limited learning, but the novice-to-expert transition in our study seemed easy for users to surmount. In addition, we note that the trial time did not double or triple when moving from one speed condition (7s on average) to either two or three speeds. Our results are consistent with the results of Rekik et al. [21] who found slow speed (12.22s average) demanded more time to recognize a texture than both moderate (7.48s in average) and fast (10.31s average) speeds. Our findings suggest that multi-channel sensing does not imply additional time to identify the different textures and their associated information.

Finally, it is interesting to note that our participants generated design ideas for the type of information they associated to each finger speed level: the importance of the information (slow for important information and the opposite for fast) or the precision of the information (slow for fine-grained information, moderate for basic information and fast for coarse-grained information). This feedback indicates that multi-channel tactile feedback based on user finger speed is perceived of, by our participants, as an intuitive way to differentiate information saliency.

6.1 Future Work

One aspect of our study which may, initially, appear troubling is the limited number of textures we used (three) to map between the multi-channels of tactile input. First, we note that our rationale for limiting the number of levels was grounded in past work. For instance, previous work reported that users can identify approximately four textures [21]. However, even with four textures, the identification accuracy is generally limited (approximately 80%accuracy identifying all four textures). In addition, users spend more time identifying a texture when the number of textures increases; for example, in [21] users needed 10 s to identify a texture when the number of textures exceeds four. One primary goal in limiting the number of textures was to minimize the texture identification time and improve perceived efficiency.

However, even with a limited number of textures and input channels, there are many ways that information could be scaled. Examples include:

- Textures could be re-used to create compound textures, thus reducing the number of textures users need to identify. Users spend a certain amount of time acquiring the texture; if the texture varied over time, then the pattern of texture could be leveraged to create a richer set of messages. As an example of this, Morse code supports character-by-character messaging using only two patterns, a long and short dash. Three pattern codes, when chained together, could be an even richer mechanism for message expressivity.
- While we fixed the mapping of pattern to speed in this experiment, it is possible that the pattern of speeds could also be used to elicit different information. For example, moving the finger slowly, then moderately could yield different information than moving the finger moderately, then slowly. Essentially, the specific permutation of finger speed variation used by the user could map to different signals representing different channels, again significantly increasing the available patters that can be represented.
- Finally, in this work we only considered the speed of the sliding gesture, primarily because we were interested in whether or not participants could leverage speed to accurately select tactile channels. However, other parameters of position and movement could be leveraged while still preserving the eyes-free nature of the input. For example, directional swipes can be easily performed eyes-free, so different channels of tactile information could be provided depending on finger speed and finger direction. As well, while smaller on-screen targets are impossible to acquire eyes-free, researchers have used larger on-screen targets (e.g. carving the display screen into four large button as in [16]). Used in combination with speed, these eyes-free targeting and directional swiping techniques could, again, significantly enhance the number of tactile channels available to the user.

While each of these future research directions could be leveraged to further increase the richness of tactile feedback, they do require additional work. For example, compound textures and different code patterns based on order of channel use, the first two points above, result in the user needing to master a larger set of codes. In other words, rich alternating codes like those described in the first two options are typically geared toward expert level use, and the learning curve is quite shallow (it takes significant time to acquire expertise). This leads to research in users' ability to master and identify tactile patterns and ordered tactile channel selection: by understanding the learning curve for perceiving alternating patterns or performing ordered selection of channels, designers can better determine whether the cost versus benefit of complex code learning is sufficiently advantageous to justify the investment.

Perhaps the easiest way to boost the number of channels is to add additional aspects of direction and/or starting position to the tactile channels being selected. Here, Negulescu et al. [16] provide some guidance in their work on eyes-free input for mobile phones. In their work, they carve the smartphone display screen into four large, pie-shaped buttons and leverage four canonical directions (up, down, left, right) to allow eyes-free, on-screen taps and swipes. Direction and location, when leveraged like this, could be used as a quasi-hierarchy on information (e.g. up could be mapped to one three-channel monitoring task, down to another) and this quasi-hierarchy could aid the user in learning a larger set of channels available for selection. However, with differing directions of differing locations on-screen, users may have different capabilities in terms of speed selection and/or speed thresholds may, potentially, have to be tuned per direction (*e.g.*, if moving right, for example, is typically slower than moving left).

Finally, while our scenarios provide evidence of the potential benefits of eyes-free multi-channel tactile monitoring, we also believe that additional scenarios (*e.g.*, productivity applications, gaming, other areas of privacy and security) might all benefit from multi-channel haptic feedback. Future work could explore the potential of richer tactile feedback as it applies to a multitude of individual application scenarios.

While these avenues for future work exist, one important thing to note is that each of these pieces of future work is predicated on a measure of a user's pre-existing ability to perform multi-channel tactile monitoring, the topic of this paper. As a result, the work described in this paper – measuring participants' ability to leverage speed to perform multi-channel tactile pattern acquisition – is an important first step toward each of these variants of richer tactile feedback techniques.

6.2 Limitations

As with any work, ours had limitations. For example, in our studies participants were younger than the population average, were right-handed and all are students at the university. Undoubtedly, older people, children, left-handed or uneducated participants could behave differently. These issues are worthy of investigation, but are beyond the scope of the current work.

One aspect of this work that may prove a significant hurdle is the basic concept of multi-channel tactile feedback. Specifically, the idea of multi-channel tactile feedback is at odds with our experience with physical objects (where physical objects do not have different tactile characteristic to be chosen between) and thus multi-channel tactile feedback may be both unintuitive and less discoverable for users. A learning step is important to inform users how to elicit information from the tactile surface. As a result, one important limitation of multi-channel tactile feedback, in general, is that it is primarily appropriate for application domains where learning is appropriate. However, there are a number of examples of these domains, including productivity applications and gaming, where, if appropriately incorporated, the burden of learning might be effectively off-set by the perceived advantages of skilled performance yielded by eyes-free monitoring.

Finally, our study was evaluated in a lab setting, where participants had to focus only on the tactile feedback based task. Therefore, it is unclear how the user perception of multi-channel tactile feedback based on user finger speed could be impacted by real-world scenarios (*e.g.*, being in the tramway, walking or running [6, 7, 10, 17, 24], driving, text-tapping [6, 8]), which make environmental demands, visual loads and mental resources another parameters to take into account when interacting with the touch devices. Future work will investigate how the user perception of multi-channel tactile feedback based on finger speed will be impacted by such real-world scenarios.

7 CONCLUSION

In this paper, we explore multi-channel tactile feedback design for mobile interaction. In particular, we explored increasing the expressivity of tactile feedback based interaction by allowing the user to dynamically select between several channels of tactile feedback using variations in finger speed. In a controlled experiment, we showed that the user can learn two different haptic channels using slow and moderate finger speed or slow and fast speed. We hope that these findings will contribute towards the adoption of multi-channel tactile feedback and will enable the design of multi-channel tactile feedback in haptically enabled applications.

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