Localized Haptic Texture: A Rendering Technique Based on Taxels for High Density Tactile Feedback

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ABSTRACT
We investigate the relevance of surface haptic rendering techniques for tactile devices. We focus on the two major existing techniques and show that they have complementary benefits. The first one, called Surface Haptic Object (SHO), which is based on finger position, is shown to be more suitable to render sparse textures ; while the second one, called Surface Haptic Texture (SHT), which is based on finger velocity, is shown to be more suitable for dense textures and fast finger movements. We hence propose a new rendering technique, called Localized Haptic Texture (LHT), which is based on the concept of *taxel* considered as an elementary tactile information that is rendered on the screen. By using a grid of taxels to encode a texture, LHT is shown to provide a consistent tactile rendering across different velocities for high density textures, and is found to reduce user *error rate* by up to 77.68% compared to SHO.

ACM Classification Keywords
H.5.2. Information Interfaces and Presentation (e.g. HCI): User Interfaces

Author Keywords
Tactile feedback; texture; identification; density; velocity; rendering techniques; SHO; SHT; LHT; taxel

INTRODUCTION
Touch interactions with most current mobile devices are flat as they lack physicality [11] in general, even more in specific situations such as when dealing with objects having inherently different textures (*e.g.*, a 'cuddly toy', a 'dragon', 'a glass'). Different approaches have been considered in order to better capture the richness of real world objects and to better render it when using and designing haptic surfaces and interfaces, *e.g.*, [9]. Tactile feedback that provides stimulation when touching the surface of haptic devices [2, 1, 6, 11, 24, 10, 19] is a promising opportunity for enhancing touch interaction with the subsequent aim of increasing physicality for tablet and mobile-based interaction. However, this comes with several challenges especially when considering large-scale production, low-cost commercial devices for which hardware issues can constitute a bottleneck [19].

In this context, a tactile rendering allowing users to properly distinguish textures with different densities is of major importance in order to strengthen user interaction experience. This should ideally hold even in an eye-free setting (non-visual) as the user may interact with the mobile device without actually looking at it (*e.g.*, interact without taking the mobile out of the bag [15] or while walking [16]). In addition to that, the perception of the tactile rendering should be consistent across different finger velocities (which is the case when interacting with physical objects in the real world [23]). Despite the rich panel of design options that one might consider to enhance the expressiveness of tactile feedback (*e.g.*, when mapping it with command parameters), actual tactile feedback devices have not exploited them fully yet. This can be explained by today's relative lack of studies addressing the design of high-quality tactile rendering techniques.

In this work, we examine the quality of tactile rendering and its impact on users' perception of eyes-free tactile textures in terms of density and finger velocities. More precisely, we identify the contributions of this work as three-fold : (1) we conduct the first investigation of the user perception of tactile rendering, and deliver a comprehensive comparison between the two main existing techniques (namely, Surface Haptic Object (SHO) that relies on finger position and Surface Haptic Texture (SHT) that relies on finger velocity) when using a cheap hardware device. We highlight novel findings on how complementary are these two techniques. We show that SHT is more suitable for dense textures and fast finger movements, whereas SHO is more suitable for sparse textures ; (2) from

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our previous study, that details differences and similarities between these rendering techniques, we discuss the concept of *taxel* (the tactile element, which we identify as a key ground concept for tactile feedback systems in the future, hopefully as useful for tactile feedback technologies as the concept of *pixel* has been for display technologies) in order to design a new rendering technique, namely Localized Haptic Texture (LHT) that separates the tactile rendering in 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. The taxel texture is then rendered locally using SHT. Finally (3) we evaluate the relative quality of LHT for which we show a consistent tactile rendering across different velocities for high density textures, and a reduction of error rate by up to 77.68% over SHO without compromising accuracy for the sparse textures.

SHO AND SHT RENDERING TECHNIQUES

Before reviewing existing tactile rendering techniques, we recall some basic considerations when dealing with a tactile texture. Just like real texture (*e.g.*, plastic, glass, etc), a tactile texture refers to a sequence of periodic tactile feedback [21, 20] such that the period to be reproduced inside the texture can be formed by some specific signal (periodic, structured noise, micro-geometry extracted, etc...). During exploration, a real texture induces a tactile feedback $T_r(x,y)$ according to finger position. In this paper, we consider periodical textures oriented along the x axis, leading to $T_r(x,y) = A(x)$ where A is a periodical function. The two-dimension case can further be treated in a standard manner as two one-dimension problems.

A haptic device is able to produce a high bandwidth tactile feedback defined over time, namely $T_s(t)$. Standard technological approaches for improving tactile feedback try to replicate a simulated texture to be as close as possible to the real one. This can only be done for some relevant examples that are, by nature, far from purely logical information. This leads to : $T_s(t) = A(x)$. From an HCI and interaction design point of view, how the designer maps the relation between x and $T_s(t)$ is then crucial to give user the feeling of textures. One can find in [21] a way to get the pattern of $T_s(t)$ when dealing with an accurate and fast system.

Usually, A is encoded using a discrete approximation (over screen coordinates), on a sampling scale that relates to standard screen sampling. Associated rendering technique is SHO (described below). In the case of dense texture, A may need a sampling that is way beyond standard display sampling. Associated rendering technique is SHT (described below).

In this work, we are interested in both dense and sparse textures. A dense (respectively, sparse) texture is composed by a sequence of patterns having a relatively small (respectively, large) periodicity. It is worth noticing that a tactile feedback display may be composed by multiple textures with various densities.

Surface Haptic Object (SHO)

Most existing surface haptic devices (*e.g.*, [2, 11, 1, 13, 8]) use the so-called Surface Haptic Object (SHO) technique [19] to

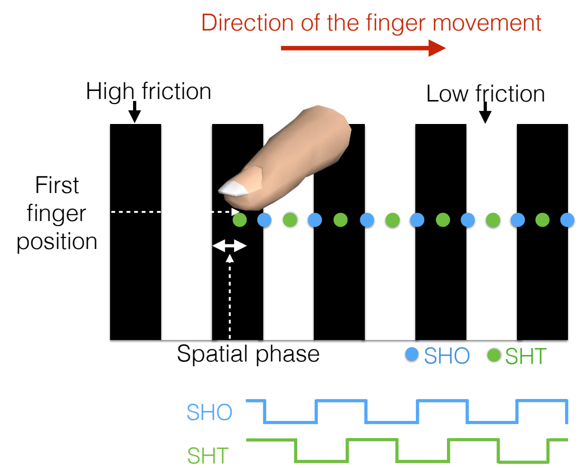

Figure 1: SHO and SHT production of the friction.

render a tactile texture. Most of approaches derive a physical-driven modeling of the device behavior. As a result, SHO is based on mapping a given texture with a discrete sampling of position, leading to $T_s(t) = A(\tilde{x})$, where $\tilde{x}$ is the discretized and sampled value of x.

SHO technique is based on an infinite loop that reads finger position x and y (*e.g.*, directly retrieved from capacitive screen), and from this, activates the corresponding $T_s(t)$. Figure 1 provides an example of texture. Friction values are encoded into a matrix by associating each element of the black lines to a high level of friction, and each element of the white lines to a low level of friction. Each time a new finger position is retrieved from touchscreen, it is processed using SHO which computes the level of friction according to the friction matrix and depending on whether the finger is touching the black or white lines.

More generally, SHO is similar to the way a grayscale image is encoded, *i.e.*, the value of each friction area (respectively pixel) is a single sample that encodes the intensity of the friction (*respectively*, information). Therefore, the actual size of the friction area (*i.e.*, the density of the encoded matrix) constitutes a limitation of the quality of the tactile rendering. For example, a spatial period of 10 microns results into a friction matrix of 82 MB for a standard 5 inches screen (110 x 75 mm^2). Another limitation of SHO is due to the ability of the hardware to acquire the position of the finger. In fact, the period of the reproduction loop of SHO is given by the sampling rate of the position sensor. Ideally, it should match the perceptual properties of the finger. To reproduce a tactile signal with a bandwidth of 500 Hz [5] and considering the theorem of Shannon, this implies a minimal sampling rate of the position of the finger of 1kHz [17]. However, the actual standard value for smartphones and tablets is 50 Hz. This value corresponds to a stimulation density of 1 stim/mm for a finger moving at 25 mm/s, which is far under the perceptual capabilities of the finger [18]. A common alternative is to use finger position interpolation algorithms in order to reproduce denser textures between the finger acquisition cycles provided by the hardware [7]. But this method is not general enough since it is still heavily dependent on both the position acquisition hardware and the implemented algorithm.

Surface Haptic Texture (SHT)

Recently, a new rendering technique has been introduced, namely Surface Haptic Texture (SHT) [19], which relies on finger velocity instead of position. In SHT, the tactile feedback $T_s(t)$ is repeated in a loop at a rate that depends on finger's velocity. When a new position sample is available from the hardware, the finger velocity is estimated and the reproduction rate is updated accordingly, leading to $T_s(t) = A(\int v_x dt)$. Notice that the position of the the finger is only needed in SHT in order to compute an estimation of the finger velocity. Consequently, the reproduction loop does not rely on the position acquisition frequency and it becomes possible to implement a reproduction loop at 1kHz or more, thus fulfilling Shannon's requirements.

In this respect, SHT ensures the right reproduction rate of textures ; however, because it is based on velocity estimation and not on position, a texture can be reproduced with the right spatial period, but not with the right starting position. This is illustrated in Figure 1, where SHT reproduces the same pattern as SHO, but with a spatial shift (or phase), which depends on the initial position of the finger. Moreover, SHT is not memory demanding as only one period of the texture is defined, but it only enables to render images composed of a single periodic texture which is to contrast with SHO.

In the rest of this paper, we first address in a comprehensive manner when these two techniques are similarly perceived, and study their relative consistency, when using a cheap capacitive touchscreen, different texture densities and different finger velocities. This shall allow us to propose a new rendering technique with enhanced quality.

EXPERIMENT 1 : TEXTURE IDENTIFICATION

The goal of this first experiment is to study the rendering quality of SHO and SHT when considering a relatively simple texture, as a function of both the position acquisition rate and the spatial phase, which are by definition the two main ingredients used respectively by these two techniques. In particular, we expect that the quality of the tactile rendering is highly related to the finger velocity, as well as to the density of the texture for which the feedback is intended. The rationale behind our first experiment is that the better the quality of the tactile rendering (*i.e.*, the rendering technique is delivering a high-fidelity between the eyes-free tactile texture and its visual representation), the more the user is able to match the eyes-free tactile texture with its visual representation.

Participants

Ten participants (2 females and 8 males) volunteered (not paid) to take part into our experiment. The range of participants' age was between 21 and 31 years (mean=26.33, s.d=3.35). All participants were right handed.

Method

We use the same device, namely E-VITA [19] (Figure 2), for both rendering techniques, in order to eliminate the effect of extraneous intra-devices differences such as ergonomics, size and sensitivity precision. E-vita is a tactile feedback tablet using ultrasonic vibrations to control the friction between a user's fingertip and the device's touchscreen. Textures rendering is achieved by modulating the friction according to finger's displacement. The relations between the vibration amplitude $W(t)$, the friction $\mu(t)$ and the tactile feedback $T_s(t)$ can found in [22].

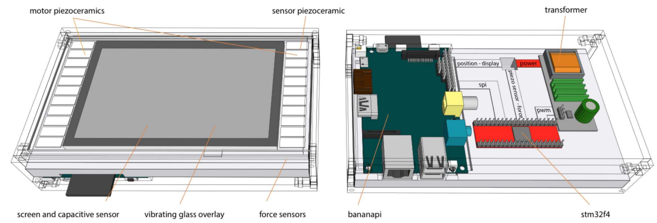

Figure 2: The E-vita device.

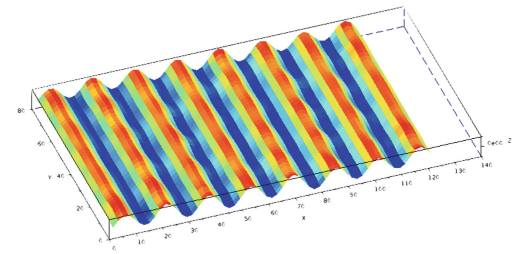

Figure 3: The cartography of the ultrasonic vibrating plate.

The device is based on a banana pi (Shenzhen LeMaker Technology Co. Ltd, China) single board computer featuring a 1 GHz ARM Cortex-A7 dual-core CPU with 1 GB of ram working in parallel. It is equipped with a 5 inches LCD display including a cheap capacitive sensor which allows a sampling frequency of 50 Hz, similar to the capabilities of commercial mobile devices.

On top of the display, a 154 $\times$ 81 $\times$ 1.6 mm glass plate, resonating at 60750 Hz with a half wavelength of 8 mm, is fixed and actuated by twenty 14 $\times$ 6 $\times$ 0.5 mm piezoelectric cells. A cartography of the vibration amplitude of the plate is reported in Figure 3. A power electronic circuit converts a 12V DC voltage source into an AC voltage, controlled in amplitude and frequency and supplied to the piezoelectric cells. A microcontroller (stm32f4, STMicroelectronics, France) runs in parallel with the banana pi and adjusts the circuit's control signals in order to obtain the required vibration amplitude of the plate. For that purpose, two additional piezoelectric cells are used as vibration sensors, and the vibration amplitude is controlled in a closed loop by the microcontroller. The reference value is sent by the banana pi to the microcontroller through a Serial Peripheral Interface (SPI) connection.

We then encode tactile rendering with respect to different texture densities. We consider five different tactile textures having the following spatial periodicity (see Figure 4) : extra fine (XF) – 1.2 mm ; fine (F) – 5.1 mm ; medium (M) – 25.5 mm ; large (L) – 51 mm and extra large (XL) – 110 mm. This

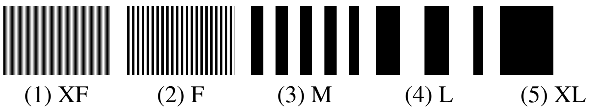

Figure 4: The five visual of the five textures numbered from left to right (1-5)

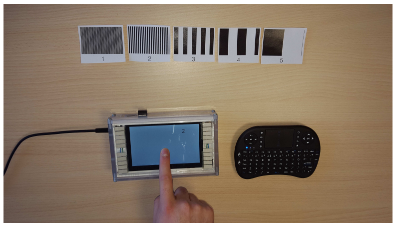

Figure 5: Experiment 1 set-up

five textures are selected in accordance to other studies from the literature [4, 14, 19]. High friction was associated with black color and low friction was associated with white color.

For SHO, the feedback signal for a given texture was encoded as follows : we associated a friction to each position sensed by the capacitive touch screen using a resolution of 0.15 mm. For each texture, its corresponding friction matrix is then pre-computed and provided beforehand as input to SHO. For SHT, the value of the friction period is defined at each micrometer. For both rendering techniques, high friction is associated to the value 0 while low friction is associated to the value 128.

Task, Procedure and Design

We proceed in two phases : a training phase followed by the experiment phase. In both phases, no visual feedback was shown on the surface, only tactile feedback was sent to the participant (see Figure 5). However, five sheets of paper illustrating the visual of the five tactile textures were given to participants. Each visual is given a number between 1 and 5 (see Figure 4). Participants were instructed to move one finger on the surface to perceive the texture. Then, participants were asked to identify the visual of the perceived texture, among the five visualized ones. To end (or start) a trial, participants had to press on the "enter" button on the keyboard connected to the E-vita device (see Figure 5) ; then to enter the id of the texture by tapping its number. Participants were instructed to use their preferred finger. They could also start in any position and perform multiple swipes without time restriction. In addition, as the Evita device makes noise when alternating high and low frictions, the participants were equipped with noise reduction headphones to avoid any bias. Tactile feedback was hence made eyes-free since the participants were not able to see any visual (nor to hear any audio) rendering on the surface.

In the training phase, participants were instructed to move their finger at the preferred speed. Overall, each participant completed 10 training trials. Five were completed with each rendering technique with a randomized order of exposure. The two techniques were tested separately.

In the experiment phase, independent measures are analyzed using a $2 \times 3 \times 5$ repeated measures within-subjects analysis of variance for the factors : the rendering *technique* (SHO and SHT), the finger *velocity* (slow, moderate and fast) and the tactile *textures* (XF, F, M, L and XL). To control the finger velocity, we printed and updated its value in real time on the screen and we asked participants to respect the following bounds : for the slow condition, participants were instructed to move their finger with a velocity lower than 30 mm/s ; for the moderate condition, participants had to proceed faster than 30 mm/s and lower than 180 mm/s ; and, for fast condition, participants were instructed to move their finger faster than 180 mm/s. The velocity bounds were determined empirically based on preliminary tests that we conducted with three external users who were asked to move their finger slowly, moderately and fast. For the three *velocity* conditions, participants were instructed to perform as much as possible within the previously mentioned bounds, without any time or posture constraints. For each, trial, the average finger velocity was logged. As it will be commented later on the paper, participants had no trouble in matching their actual finger movements to the required bounds. For each *velocity* condition, and for each of the five aforementioned *textures*, participants were asked to sense the tactile texture and to identify the corresponding visual image among those provided in the paper sheets.

Participants' identifications were administered as 6 (randomized) blocks of 25 trials each as follows. Under each *velocity* condition, the two rendering *technique* conditions were experimented consecutively, in a random order in order to allow questionnaire assessments. For each *technique* condition, each tactile texture was experimented five times (25 trials overall). The order of these trials was randomized. Overall, we hence have a total of 3 *velocity* $\times$ 2 *technique* $\times$ 5 *textures* $\times$ 5 repetitions = 150 trials performed by each participant.

After each of the six experimental blocks, participants responded to 5-point Likert-scale questions (strongly disagree to strongly agree) : i) I identified well, ii) I needed to concentrate to identify well ; iii) I felt frustrated ; iv) I felt confident in my ability to identify the visual representation and v) I enjoyed interacting with this technique. After terminating all the trials for each velocity condition, participants were asked to rank the two techniques according to their preferences. The average duration of the experiment was 30 mins.

Results

The dependent measures are *error rate* and *identification time*. The *error rate* is defined as the proportion of incorrect identifications with respect to a given texture. The *identification time* is defined as the time that a user takes from starting an identification until entering his response (*i.e.*, trial time). The *error rate* obviously provides a sound measure of the quality of the tactile rendering and can be straightforwardly used to inform about the accuracy of the technique. The *identification time* is more subjective and can only provide an estimation of how difficult might be the identification for participants. We also analyzed subjective responses. All

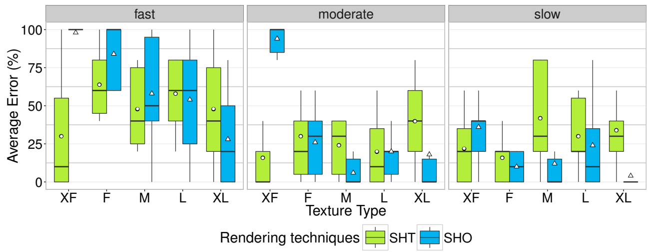

Figure 6: Distribution of error rate of TEXTURES (x-axis). Results are grouped by VELOCITY (facet top labels) and by technique (legend). Box-plots give median and inter-quantile range. Circle and triangle show the mean and the 95% CI.

analyses are repeated-measures ANOVA. Tukey tests are used post-hoc when significant effects are found.

Before starting the analysis of the collected data, we first checked how well the participants performed when comparing the recorded finger velocities to the instructed bounds. We found that all participants trials satisfied the required velocity bounds. Interestingly, we found that in the fast condition, participants moved their finger faster when using SHT than when using SHO. Wilcoxon Signed-rank test confirmed that this difference was significant ($z = 2.58$, $p < .01$, $r = .25$). This observation suggests that participants were more careful when experimenting SHO using fast finger movements. In the following, we report our main findings.

Error rate

There was no significant main effect of the *technique* ($F_{1,9} = 1.67$, $p = .22$) on *error rate*. However, there were significant main effects of *velocity* ($F_{2,18} = 44.92$, $p < .001$) and *textures* ($F_{4,36} = 4.01$, $p < .01$) on *error rate*. Post-hoc tests revealed that *error rate* was significantly higher for fast velocity than for both moderate and slow ($p < .05$). The *error rate* was also significantly higher for the XF texture than for the M and the XL textures ($p < .05$).

As anticipated, there were significant *technique* × *velocity* ($F_{2,18} = 9.05$, $p < .001$), *technique* × *textures* ($F_{4,36} = 23.55$, $p < .001$), *velocity* × *textures* ($F_{8,72} = 4.14$, $p < .001$) and *technique* × *velocity* × *textures* ($F_{8,72} = 2.28$, $p = .03$) interactions.

Post-hoc comparisons revealed that SHT was significantly more accurate than SHO when rendering the denser textures XF and F ; with fast velocity ($p < .01$) by respectively 75% and 23%, as well as, when rendering the densest texture XF with the moderate velocity ($p < .01$) (by 82%) (see Figure 6). On the other hand, we found that SHO was significantly more accurate than SHT when rendering the sparsest texture XL with moderate velocity ($p < .05$) (by 55%). Interestingly, we found that there were difference between the two techniques when moving at slow velocity or when rendering M or L textures.

When rendering either XF or F textures, the SHO performance deteriorated more significantly across increasing finger velocity ($p < .05$). Similarly, moving at fast velocity while rendering M texture with SHO, leads to significantly more errors than when moving at moderate or slow velocities ($p < .05$). Interestingly, the performance of SHO is significantly higher when rendering the sparsest texture XL than when rendering the denser textures XF and F with fast velocity ($p < .001$) or XF with moderate velocity ($p < .05$). Finally, when rendering F texture with SHT, we found that the *error rate* is significantly bigger when moving fast than when moving slowly ($p < .05$).

In light of our results, the influence of the fast finger velocity on the loss in the performance of SHO can be understood by considering the sampling of the finger position by the capacitive touchscreen. For example, in the fast condition, the velocity is greater then 180 mm/s, resulting in a position acquisition period of $\sim$3 mm. This value is larger than the XF period, hence SHO is totally unable to render the dense sensation. The relative accuracy of SHT when rendering sparse textures can also be explained by considering the ability of the user to perceive the difference in spatial phase between the tactile texture and its visual. For instance, for the XL texture, the user expect a tactile signal at the half of the screen, however, if the starting position of the finger is at 1/4 of the screen, the user will perceive the tactile signal at 3/4 of the screen.

	FAST		moderate		slow	
	SHO	SHT	SHO	SHT	SHO	SHT
Performance	2.4 (.59)	3.6 (.59)	3.5 (.43)	3.9 (.54)	3.6 (.52)	3.3 (.82)
Concentration	3.9 (.84)	3.3 (.82)	2.9 (.54)	2.8 (.76)	3.7 (.65)	3.7 (.71)
Frustration	2.9 (.79)	2.4 (.59)	2.8 (.48)	1.9 (.54)	2.6 (.72)	2.5 (.66)
Confidence	2.8 (.56)	3.4 (.50)	3.5 (.43)	4.1 (.61)	3.1 (.74)	3.4 (.66)
Enjoyment	2.7 (.82)	3.1 (.61)	3.5 (.66)	3.6 (.43)	3.5 (.78)	3.1 (.61)

Table 1: Mean (s.d) questionnaire responses, with 1=strongly disagree, and 5 = strongly agree.

Identification time

There was a significant main effect of *velocity* ($F_{2,18} = 9.06$, $p < .001$) on *identification time*. We found that using moderate velocity induced significantly smaller identification time (mean = 7.48s, s.d = .93s), than fast velocity (mean = 10.31s, s.d. = 1.93s) and slow velocity (mean = 12.22s, s.d = 1.35s) ($p < .05$). Importantly, we found no significant main effect of *technique* nor of *texture* on *identification time* with no significant interaction suggesting that the time needed to identify a texture is independent from the rendering technique and texture density (mean = 10, s.d = 1.18s).

Subjective results and observations

We recall that participants were asked to rank the technique conditions after completing the trial blocks corresponding to each finger velocity. Overall, SHT was ranked first 100% of the time for fast velocity, 70% of the time for moderate velocity and 40% of the time for slow velocity.

Participants were also asked to rate each technique condition. This is summarized in Table 1. Wilcoxon Signed-rank tests showed that participants found that SHT was significantly better performing ($z = 2.86$, $p < .01$, $r = .63$) and implies more confidence ($z = 2.44$, $p < .01$, $r = .54$) when moving at fast velocity, while being less frustrating ($z = -2.6$, $p < .01$, $r = .58$) when moving at moderate velocity than SHO.

Interestingly, Friedman tests revealed that there is non significant effect of finger velocity on each rating score for SHT. However, for SHO, there was significant effect of finger velocity on performance rating ($\chi^2(2)$ = 7.03, p < .05), concentration rating ($\chi^2(2)$ = 6.93, p < .05) and enjoyment rating ($\chi^2(2)$ = 7.52, p < .05), with faster velocity inducing a decrease in performance and enjoyment and an increase in concentration.

We correlate these findings with participants comments that felt that SHT delivers high-fidelity tactile feedback especially for the densest textures. Some quotes are : *"with this technique, I am able to identify easily the textures number 1 and 2 even with fast movement"*, *"the association between the denser images and its tactile feedback is easy to identify here as the feedback is clearly and cleanly perceived."*. In contrast, our participants felt that SHO is more suitable for rendering sparser textures. For instance, one participant said : *"Contrary to the other technique where denser textures are easily identifiable, with this one, it is just impossible. Only the largest ones are correctly perceived !"* while an other participant witnessed : *"this technique is more suitable for the largest signals"*. Importantly, all our participants felt that SHO renders the tactile textures in a fuzzy way when moving fast or when rendering denser textures. In particular for fast velocity, some quotes are : *"I feel confused with this technique when moving rapidly because for me there is almost no difference between all the trials... All are texture number 4 or 5 !"*, *"I am unable to differentiate between the textures, I responsed randomly"*, *"There are no difference between all the trials"*, *"I feel the same sensations for all the trials, is it normal ?"*, *"I think I never succeed to identify the two densest textures... it is really very difficult to perceive them correctly"* and *"There is a mismatch between the visual textures I see and tactile feedback that I perceived. The signal seems to be not periodic !"*. Similarly, our participants felt that SHT renders the sparsest texture in a fuzzy way. One participant said : *"For the largest texture, I felt as if the tactile feedback is shifted comparing to its visual image... Is it normal ?"*.

Summary. Our key finding is that SHT leads to the highest level of quality of tactile rendering for dense textures with either fast or moderate velocity, increases confidence and decreases frustration over SHO. On the other hand, SHO is still more accurate for sparser textures with moderate velocity. Importantly, we find that the tactile rendering of SHO and SHT is perceived as similar when rendering either M or L textures. This finding indicates that the user cannot perceive the difference between two signals with the same spatial period, but different spatial phase (*i.e.*, different starting finger position). It is also important to note that there are no difference between the two rendering techniques when moving slowly. Finally, our analysis suggests that the time needed to identify an eye-free tactile texture is independent from the rendering technique and the texture density, but is dependant on finger velocity.

In order to deal with "simple" textures with uniform and regular patterns, one may argue that these findings allow interaction designer to decide beforehand which of SHO or SHT to use for an optimal rendering quality ; thus ending up with one new simplistic technique. Obviously, this reasoning cannot hold for more versatile and sophisticated tactile images containing multiple textures. As a result we propose a new rendering technique, namely Localized Haptic Texture (LHT) based on the concept of *taxel*, and to design a second experiment in which we study the quality of the rendering when considering pairs of textures. In the next section, we first start by describing the design principles of the proposed LHT technique.

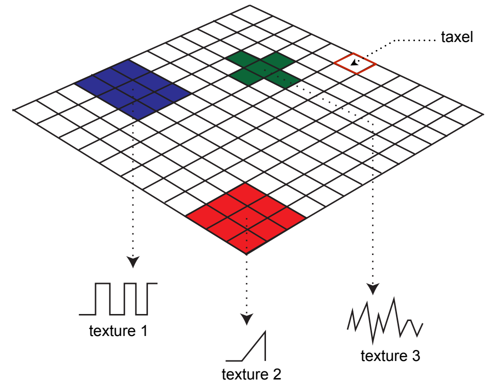

Figure 7: A grid of taxels.

TAXEL AND LOCALIZED HAPTIC TEXTURE TECHNIQUE

The smallest period T_{min} for which the user cannot perceive the difference between two signals with the same spatial period T, but different spatial phases (*i.e.*, different starting finger position), allows us to introduce the concept of *Taxel* in the context of tactile feedback rendering. We define a *taxel* (elementary tactile element), as the area unit that defines a texture and in which the spatial phase of the reproduced signal does not matter. This definition allow us to encode a texture using a grid of taxels. The dimension of a taxel is of major importance to define the resolution of the tactile grid (or matrix) that encodes a whole texture such that each taxel is connected to the other taxels using spatial phase. It is important to remark that the use of taxels has previously been considered in the past ; however, it has been so in quite different settings. To the bestof our knowledge, the concept of enabling texture rendering through the use of a carefully defined grid of taxels is novel. For example, in robotics oriented studies [12, 3], and in the context of tactile object recognition using a sensor device (LTS-210), a taxel refered to the elementary element that can be sensed by the sensor device. In these works, a grid of taxels is also acquired from the hardware device and used during processing the tactile sensed image, for example, for recognition purposes. In our work, the inverse process is adopted in the sense that a set of taxels with a carefully defined dimension is used to accurately encode the different parts of a texture and hence to output a high quality feedback.

In experiment 1, SHO and SHT were found to have similar rendering quality for the textures M (T = 25.5mm) and L (T = 51mm) ; whereas they behave differently for the other textures ($T < 5.1$mm or $T = 110$mm). This finding indicates that T_{min} is in the range $]5.1, 25.5]$ mm which sets the top boundary of the width of a taxel in $]2.55, 12.25]$ mm ; since in one spatial period T, the tactile rendering is delivered two times : on the rising (black color) and falling (white color) of the vibration amplitude. This range has to be considered as a design rule to be refined in future studies.

We are then able to design a new rendering technique called Localized Haptic Texture (LHT), which is to be considered as a hybridization of both previous techniques. In fact, LHT merges the advantages of both existing techniques and operates by separating the tactile rendering in two different processes : the first process operates similarly to SHO by acquiring the finger position and comparing it with a grid of taxels (see Figure 7) ; and then rendering the texture associated to this taxel by using SHT. This makes it possible to keep the accuracy of the spatial division for sparse areas as accurate as with SHO and to leverage the extended range of sensation for greater spatial density signals as with SHT. Notice that LHT, just like SHO, is by definition able to render an image composed of multiple textures which is to contrast to SHT. Technically, the software handling the tactile reproduction is divided in two separated running processes on the Banana Pi, the low level code runs in background and handles the acquisition of finger position, and the reproduction of the selected texture in parallel with the micro-controller in SHT. The high level code communicates with the background process through software communication receiving the finger position and sending the code of the tactile texture to reproduce.

The process used in LHT is similar to the one used for the monitors where there is a grid of pixels (respectively, taxels), the smallest single unit emitting light (respectively, haptic signals), which is singularly programmed to reproduce a color (respectively, texture). Notice that, as for a pixel, the taxel as defined in our work is not the smallest area where we can perceive a texture (respectively, the pixel is not the smallest area where we can distinguish a color). However, a set of taxels (respectively, a set of pixels) can encode a distinguishable texture (respectively, color). An informal experiment conducted with three participants confirmed that it is not possible to identify a texture having the same dimension than a taxel as defined in our study.

EXPERIMENT 2 : PAIR OF TEXTURES IDENTIFICATION

Our second experiment is motivated by analyzing the rendering quality of LHT when considering more sophisticated textures for which neither SHO nor SHT can be expected to perform optimally. Hence, we extend our study in order to deal with pairs of textures. Since we used five textures in Experiment 1, mixing all of them leads to 25 possible pairs, which is relatively intensive to experiment. To limit the experiment duration, we consider five representative ones (Figure 8, textures 1 ; 3 ; 5 ; 6 and 8). However, with only five pairs, it can be still questionable how challenging it is for the participants to identify them, especially if some elimination strategies can be adopted to guess textures. To fully appreciate the quality of the feedback, we hence introduce five fake

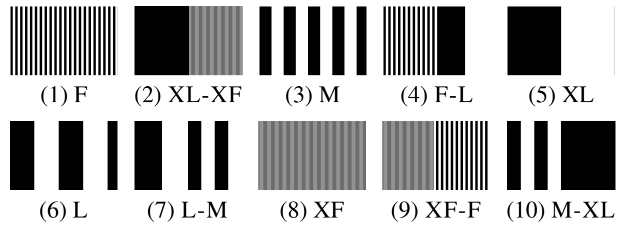

Figure 8: The set of 10 textures numbered from left to right (1-10) as presented to the participants. The pair of textures (2 ; 4 ; 7 ; 9 ; 10) are the evaluated textures and unique textures (1 ; 3 ; 5 ; 6 ; 8) are the distractors.

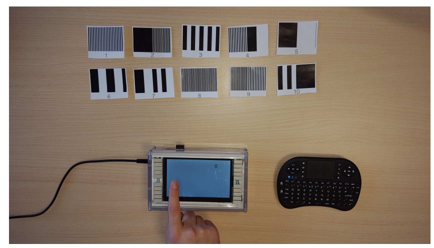

Figure 9: Experiment 2 set-up

textures playing the role of distractors and which are proposed as possible responses (Figure 8, textures 2 ; 4 ; 7 ; 9 and 10). Accordingly, the experiment set-up is shown in Figure 9, the arrangement of the paper-sheet representing the 10 textures as presented to participants was exactly the same than in Figure 8. We then follow exactly the same experimental procedure than in experiment 1 to evaluate the relative accuracy of LHT when compared to SHO. Notice that SHT was not considered since it does not enable to deal with pairs of textures.

Given the output of our first experiment, we hypothesize that :

H. LHT will always provide better or equal quality of tactile rendering compared to SHO.

We then use the same procedure and design ($2 \times 3 \times 5$) repeated measures within-subjects for the factors *technique*, *velocity* and pair of *textures* as in experiment 1. We choose to set the dimension of the implemented taxels to a square of 12.5mm $\times$ 12.5mm which is in accordance with the fingertip dimension and our findings in experiment 1. The average duration of the experiment was 40 mins.

Ten (10) new participants (two females) volunteered (not paid) to take part in our experiment. Participants' ages varied between 21 and 32 years (mean age=27, s.d=3.01 years). All participants were right handed.

Error rate

There was significant main effect of *technique* ($F_{1,9} = 8.57$, $p < .01$) on *error rate* with LHT reduced significantly ($p < .0001$) the *error rate* by 44% compared to SHO. In addition, there were significant main effects of *velocity* ($F_{2,18} = 12.54$, $p < .0001$), and *textures* ($F_{4,36} = 14.19$, $p < .0001$) on *error rate*, but there was also a significant *technique* $\times$ *textures* ($F_{4,36} = 28.18$, $p < .0001$) interaction.

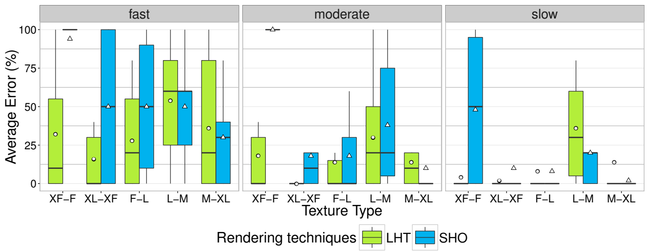

Figure 10: Distribution of error rate of TEXTURES (x-axis). Results are grouped by VELOCITY (facet top labels) and by technique (legend). Box-plots give median and inter-quantile range. Circle and triangle show the mean and the 95% CI.

Post-hoc tests revealed that LHT consistently outperformed SHO ($p < .0001$) by 77.68% when rendering the pair of textures composed of denser textures, *i.e.*, the XF-F texture. To our surprise, there were differences between the two techniques where rendering pair of textures merging sparser and denser textures, *i.e.*, XL-XF or F-L. This seems likely to be related to the strategies used by our participants to identify the textures as it will be discussed later in this paper. Interestingly, there were no significant differences between pair of textures composed of medium and sparser textures, *i.e.*, L-M and M-XL. There was also no significant *technique* × *velocity* interaction ($p = .07$), suggesting that the benefits of LHT are consistent across velocities. These results support the hypothesis **H**. Interestingly, we found that with SHO, rendering the XF-F texture lead to significantly more errors than when rendering the remainder textures. Similarly, we found that with LHT, rendering the L-M texture leads to significantly more errors than when rendering either F-L or XL-XF textures.

To additionally elicit where wrong identifications occurred most often, we computed confusion matrices informing about the percentages of associations between the actual and the perceived textures (see Table 2). Each cell of the table corresponds to the average, over all *velocity* conditions, of times a participant's response with respect to the texture depicted in the row was equal the the texture depicted in the column. The analysis of these confusion matrices shows that the dense pair of textures XF-F was often confused in the case of SHO with single textures in 68.7% of all trials (36.7% with F, 21.3% with M and 10.7% with XF). In contrast, it was confused in only 12% of the time with XF when using LHT. We also found that the XL-XF texture is 13.3% of the time confused with L-M when using SHO, while it is seemingly not confused when using LHT. Finally, we found that the L-M texture was confused with the M texture and the L texture, 10.7% and 11.3% of the time respectively, when using SHO, while it was confused by 13.3% and 17.3% of the time respectively when using LHT.

Subjective results and observations

LHT was ranked first 100% of the time for both fast and moderate velocities, and first 80% of the time for slow velocity. Participants were also asked to rate each technique condition. This is summarized in Table 3. Wilcoxon Signed-rank tests showed that participants found that LHT was significantly

	LHT										SHO									
	Perceived Texture																			
Actual Texture	XF-F	XL-XF	F-L	L-M	M-XL	XF	F	M	L	XL	XF-F	XL-XF	F-L	L-M	M-XL	XF	F	M	L	XL
XF-F	82.0	0.0	0.7	0.0	0.0	12.0	4.7	0.7	0.0	0.0	19.3	0.0	6.0	3.3	1.3	10.7	36.7	21.3	0.7	0.7
XL-XF	2.0	94.0	0.7	0.0	0.0	2.0	1.3	0.0	0.0	0.0	0.7	74.0	0.7	13.3	0.7	0.0	0.0	0.7	2.7	7.3
F-L	4.7	0.7	83.3	4.0	0.7	0.7	2.0	3.3	0.7	0.0	1.3	0.0	74.7	4.0	1.3	0.0	4.0	8.7	5.3	0.7
L-M	0.0	0.7	2.7	60.0	2.7	0.7	2.7	13.3	17.3	0.0	7.3	2.7	64.0	1.3	0.0	1.3	10.7	11.3	1.3	
M-XL	0.0	1.3	4.7	3.3	78.7	0.0	0.0	0.7	2.0	9.3	0.7	0.7	5.3	1.3	86.0	0.0	0.0	1.3	2.0	2.7

Table 2: Confusion matrices for LHT (left) and SHO (right) controls for the *textures* condition. Cell values show percentages of associations between actual and perceived textures.

better performing ($z = 2.92$, $p < .01$, $r = .65$), implies less frustration ($z = -2.40$, $p < .05$, $r = .53$), while being more confident ($z = 2.60$, $p < .05$, $r = .58$) when moving fast, and demands less concentration ($z = 1.41$, $p < .05$, $r = .31$) while being more enjoyable ($z = -1.41$, $p < .05$, $r = .31$) when moving slowly than SHO.

Friedman tests revealed that no significant effect of finger velocity on each rating score for LHT can be reported. However, for the SHO technique, Friedman tests revealed a significant effect of finger velocity on performance rating ($\chi^2(2) = 8.85$, $p < .01$), frustration rating ($\chi^2(2) = 8.58$, $p < .01$) and confidence rating ($\chi^2(2) = 8.66$, $p < .01$), with faster velocity inducing a decrease in performance and confidence and an increase in frustration.

We correlate these findings with comments from participants that felt that LHT provided them with a clear and clean tactile feedback being faithful to the visual texture representation. Some quotes are : *"This technique provide high fidelity between the visual and the haptic feedback contrary to the other one"*, *"I prefer this technique, the tactile feedback is clearly perceived"* and *"Now, I am testing the good technique !"* . In contrast, SHO is described as less faithful to the visual representation. For instance, one participant quoted : *"I felt very confused with this technique, I perceived the feedback in a fuzzy way."*, another participant said *"I am not able to differentiate between the dense signals"* and then added *"I felt like if the signals are randomly sent... I have to stay very concentrated with this technique"*.

Methodology for identifying the textures

To better understand how participants were performing, we report hereafter the different strategies elaborated by participants in order to match the tactile rendering with a given visual texture ; which is the by-product of the discussions that followed the whole experiment. Based on participants comments, we are able to state the following :

❶ **Determining the number of textures.** Most of the participants first tried to figure out how many textures they are able to perceive. For this purpose, three main strategies are

	FAST		moderate		slow	
	SHO	LHT	SHO	LHT	SHO	LHT
Performance	2.3 (.51)	3.3 (.41)	3 (.58)	3.7 (.51)	3.9 (.61)	3.8 (.76)
Concentration	4.3 (.51)	3.9 (.54)	3.8 (.70)	3.5 (.60)	3.2 (.86)	3.4 (.88)
Frustration	3.8 (.56)	2.8 (.70)	3 (.65)	2.7 (.29)	2.3 (.77)	2.2 (.76)
Confidence	2.3 (.58)	3.1 (.54)	3.1 (.68)	3.6 (.52)	3.7 (.71)	3.9 (.54)
Enjoyment	2.9 (.74)	3.4 (.59)	3.1 (.68)	3.5 (.43)	3.5 (.60)	3.2 (.76)

Table 3: Mean (s.d) questionnaire responses, with 1=strongly disagree, and 5 = strongly agree.

used : (1) most participants moved their finger in one direction (east-west or west-east) and then the opposite direction in order to determine if they *"feel the same sensation or not"*, (2) some participants moved their finger many times in the middle of the screen trying to *"detect a change in the pattern type"*, and (3) some participants explored many times the right half of the texture then the left half (or inversely) to determine whether it *"holds the same pattern type"* or not. If the texture is judged as containing two textures, then participants divided the surface to two sub-space and explored each one separately using the next strategies.

❷ **Counting the number of all tactile feedback.** Most of the participants counted the number of all tactile feedback and then tried to match the tactile feedback position with the visual texture.

❸ **Searching the larger and thinner texture patterns.** While most participants used a counting methodology to correctly identify a texture, some noticed that, in addition, *"sparser and denser textures were helpful to classify the texture"* by eliminating the textures that do not contain those type of textures and inversely.

❹ **Making small finger movement.** One participant explored the tactile surface by making small finger movement in both directions arguing that this *"enables to identify more quickly the actual texture"*.

Summary. The key finding of our second experiment is that LHT led to the highest quality of the tactile rendering for the dense pairs of textures without compromising it for the other pairs. The analysis of confusion matrices showed that there was no negative effect of the distractors on LHT. In contrast, with SHO, the denser pair of textures were often confused with the dense single textures. This reinforces our belief that LHT enables a high quality tactile rendering and can be used to provide the user with a faithful feedback. In addition, participants did not make any negative comment on the tactile feedback associated to LHT. Participants found that LHT increases the confidence and enjoyment and decreases the frustration and concentration over conventional SHO. This makes LHT a promising alternative to render complex tactile image composed of multiple textures.

CONCLUSION AND NEXT STEPS

We showed the benefits and the limitations of current tactile rendering techniques (SHO which is extensively used and the more recently proposed SHT) when using a cheap capacitive hardware device. We then present the concept of *Taxel*, as the area unit that defines the resolution of a tactile textures grid. From this concept, we present a new rendering technique (LHT). Our experimental results demonstrate that LHT improved the quality of the tactile rendering for denser textures over SHO by up to 77.68%, without compromising it for the sparser ones. The performance benefits of LHT were consistent across different finger velocities. These findings were correlated with subjective results where participants found that tactile rendering provided by LHT is cleanly and clearly perceived as it is faithful to the visual texture representation. We hope our results will enable a deeper understanding of rendering techniques for tactile feedback which subsequently will be useful to researchers and practitioners for improving user experience on tactile feedback touch-screens.

Tightly related to our work, an important next step is to study the level of density that users can perceive when the tactile feedback is rendered by LHT. In fact, the density of the experimented textures was chosen empirically in order to cover a relatively wide representative range. It will be interesting to measure the accuracy of the tactile feedback more finely. First, the most dense texture used in our study has spatial periodicity of 1.2 mm. It is an open issue to elicit the densest texture for which users are still able to perceive an accurate and enjoyable tactile feedback. Second, given two textures having different but relatively close densities, it will be useful to evaluate how much differences can be perceived by users, *i.e.*, what is the difference range between two textures that would allow a user to perceive their respective tactile feedback as different ? These questions are all the more difficult as learning from real (non numerical) world suggest to human that tactile sense is complementary to eye, and usually not devoted to the same scale of information (usually much small sized information).

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