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M. Biet, Géry Casiez, Frédéric Giraud, Betty Lemaire-Semail

Institutions: university of lille

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Discrimination of Virtual Square Gratings by Dynamic Touch on Friction Based Tactile Displays

Mélisande Biet* — L2EP & INRIA Futurs, University of Lille, France

Géry Casiez† — LIFL & INRIA Futurs, University of Lille, France

Frédéric Giraud‡ — L2EP & INRIA Futurs, University of Lille, France

Betty Lemaire-Semail§ — L2EP & INRIA Futurs, University of Lille, France

Abstract

In this paper, we investigate the use of friction based tactile displays for the simulation of finely textured surfaces, as such displays offer a promising way for the development of devices with co-located vision and tactile feedback. The resolution of the textures rendered with such devices and their matching to real textures have never been investigated. The paper first contributes to the evaluation of the texture resolution of friction based tactile displays. In a controlled experiment, we investigate the differential thresholds for square gratings simulated with a friction based tactile device by dynamic touch. Then we compare them to the differential thresholds of real square wave gratings. We found that the Weber fraction remains constant across the different spatial period at 9%, which is close to the Weber fraction found for corresponding real square gratings. This study inclines us to conclude that friction based tactile displays offers a realistic alternative to pin based arrays and can be used for co-located vision and tactile rendering. From the results of the experiment, we also give the design guidelines to improve the perception of textures on friction based tactile displays.

Keywords: Tactile displays, co-located tactile displays, friction based tactile displays, JND experiment, discrimination thresholds.

Index Terms: H.5.2 [User Interfaces]: Haptic I/O—Evaluation/methodology;

1 Introduction

In our daily life, touch and vision are co-located during the exploration of objects. The perception of textures through the exploration of surfaces with fingers is guided and influenced by vision. Some properties of textures, like friction, roughness or stickiness, can be inferred from the visual flow [9, 8] which in turn influences the way of touching a surface. However, most tactile displays nowadays use a de-located interaction where the perception of textures through touch and view are separated [25, 24]. Thus, the user perceives the visual and haptic flows through different channels that are integrated in her brain [11].

The development of co-located tactile displays where the display and simulation of textures occur at the same place constrains to work with transparent tactile devices (Fig. 1). However the most straightforward and intuitive way to simulate a texture is to reproduce its three dimension profile in a discrete way. This is usually achieved with pin based arrays where each pin can be translated independently along the direction normal to the surface of simulation [27, 34, 32, 33, 17, 28]. Considering this design, even if this kind of technology is valid for other applications, it is not well appropriate for co-located interactions. One exception though to notice is the Feelex developed by Iwata et al. that allows to feel and see the shape of virtual objects in a co-located way [11]. However this device is not portable and produces shadows beneath the finger that reduce the fidelity of simulation.

Touching what one sees imposes to work with transparent continuous tactile devices. In a first effort towards this goal, some devices intended to improve the experience of touchscreens start to emerge on the market [23, 10]. The actuators used are made of multilayer piezoceramic sandwiches, also called ”bending motor”. With these devices, the whole screen vibrates to give, for instance, the feeling of pushing buttons when they are touched. Even if it is a first step towards the simulation of real textures, the tactile information remains coarse since the tactile tactile feedback is a succession of impulses coming from the rear of the screen.

To improve the texture rendering on co-located displays, Takasaki et al. [30] proposed a device that simulates variable friction on a transparent surface to simulate sand paper. The use of such devices, providing finely textured surfaces, is today the most promising way to simulate realistic co-located tactile-display textures. A first experiment showed that this device can simulate different levels of roughness [19] but to the best of our knowledge, there is no evaluation showing to what extend such devices can reproduce real textures.

The technique of simulating textures on a variable friction device is less straightforward than the one used on pin based arrays devices. With variable friction devices, the simulation of textures consists in modifying the surface friction depending on the finger tip position. In contrast, with pin arrays devices, the texture is reproduced in three dimensions.

To evaluate to what extend virtual textures can match real textures, one can measure the difference in perception through the determination of differential thresholds. The difference between the differential thresholds of real and virtual textures can give a mea-

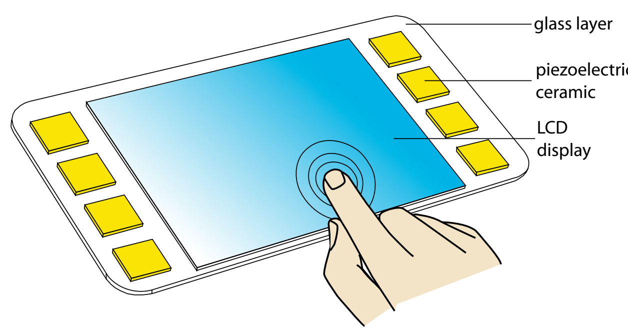

Figure 1: Illustration of a design for the simulation of co-located vision and tactile rendering with a friction based tactile display. The device is composed of a glass layer with piezoelectric ceramics glued under the surface to change the amount of friction of the surface. An LCD screen fixed under the surface displays the visual representation of the texture haptically rendered on the surface.

*e-mail: melisande.biet@polytech-lille.fr
†e-mail:gery.casiez@lifl.fr
‡e-mail: frederic.giraud@polytech-lille.fr
§e-mail: betty.semail@polytech-lille.fr

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sure of the quality of the simulation. Our aim is not to determine if the simulated textures match exactly real textures in terms of perception. Here we want evaluate if the resolution with which virtual textures are simulated on friction based tactile displays can reach the one of real textures.

In this paper we present an experiment evaluating the differential thresholds of square gratings simulated with a variable friction display by dynamic touch (when the finger moves). Unlike previous work [19] providing no clear answer on the quality of textures simulated with this kind of device, we compared the just noticeable difference (JND), also called differential (or discrimination) threshold, for different standard spatial periods of virtual square wave gratings (Fig. 5) with real square wave gratings. This method was initiated by Tan et al. [31] but with a force feedback device. In this way, we can conclude on the precision with which such devices can reproduce real gratings.

2 Background and Related Work

2.1 Continuous Tactile Displays

We can distinguish two categories of devices using that approach. The first category gathers the devices having the ability to produce bumps by impulses on the surface [23, 12, 10]. The second category gathers devices able to dynamically change the coefficient of friction between the finger and the surface [35, 18, 29, 37]. As these devices apply the same stimulation on the whole surface, the usual way to create a texture is to update the coefficient of friction of the surface according to the finger position.

2.1.1 Impulse Based Continuous Tactile Displays

Among the continuous tactile devices producing bumps by impulses, Poupyrev et al. [23] presented a device that can be integrated in the touchscreen of a PDA (Personal Digital Assistant). They have introduced four actuators between the flat screen and the sensitive glass layer. These actuators are made of thin layers of piezoelectric ceramics which bend under the action of an electric field. With this setup, when the user applies her finger on the glass layer, the actuator suddenly bends and pushes the glass layer against the user's finger. This technology has later been introduced in a mobile phone [12]. This phone proposed four applications using this technology: numeric keypad displayed on the screen, text selection, scrolling and a "drag and drop" function. Besides these applications, it is also possible to buy actuators [10] designed to produce this effect on larger screen surfaces. With these actuators the tactile effect produced by the vibration on the surface depends on the duration, frequency, amplitude and shape of the impulse generated by the actuators.

2.1.2 Friction Based Continuous Tactile Displays

The devices of the second category have the ability to create a variable friction that can be controlled. Two main phenomena are exploited in order to produce this kind of simulation: the first one uses the principle of variable friction with intermittent contact and the second one is able of generating an air gap between the finger and a high frequency vibrating surface.

To achieve *variable friction with intermittent contact*, Takasaki et al. [29, 30] have used surface acoustic wave (SAW) transducers. They are made of an interdigital transducer (IDT) arranged on a piezoelectric substrate (in Lithium Niobate, $LiNb0_3$). The IDT consists of a metal strip array. When an alternative driving voltage is applied to the IDT, it generates ultrasonic deformations on the crystal surface called "Rayleigh waves" which propagates on the substrate surface. A stationary wave (whose frequency is around 10 Mhz) is generated on the device by using the superposition of two travelling waves. The tactile feeling is then produced by the mean of a slider covered with small steel balls directly in contact with the vibrating surface. The tactile feeling is obtained in the following manner: when a material hard as a steel ball is in contact with the surface of the wave, the duration of contact seems to change as a function of the vibration frequency. In this way, the average friction coefficient decreases when the vibration is really fast. If low frequency wave trains are applied in addition, it is then possible to create a time-dependent friction on the device.

Watanabe et al. [35] have proposed another method to control the roughness of the surface. They excite the extremities of a beam with two Langevin transducers (ultrasonic transducer). In this way they generate on the surface of this beam a wave of a few micrometers of amplitude with an ultrasonic frequency (up to 20 kHz). Once the finger is in contact, *an air gap is created between the finger an the beam*, which gives a sliding sensation. Watanabe's device is not co-located. However, the vibrating surface in steel used in their experiment could be easily replaced by a glass layer, as we know that the vibrating properties of glass are close to the one of steel.

The device used in the experiment is based on the same physical principle as the one used by Watanabe et al. Moreover, we have taken into account the spatio-temporal aspect of finger movement in our tactile display to provide controlled textures, as it was previously described by Biet et al [2] and then by Winfield et al. [36].

2.2 Evaluation of Gratings Perception by Dynamic Touch

2.2.1 Evaluation of friction based tactile displays

The evaluation method of a tactile device is often determined by the kind of stimulus that it is possible to simulate. For instance, Watanabe et al. [35] use a qualitative method allowing the classification of samples by different levels of roughness. For their tactile device, Nara et al. [19] use a method based on pair comparisons to build a scale of roughness for real and virtual textures using the Scheffe's method. The relationship between real and virtual textures is made through a correlation between the scales of roughness perception. These experiments show that these devices are able to reproduce a number of distinct sensations. However the use of a small number of stimuli and the large differences in intensity between the stimuli used only provide a narrow idea of the scope of performance of such devices. These studies are interesting for the simulation of surfaces with variable friction. However they do not tell to what extend such device can reproduce real textures.

2.2.2 Determination of the spatial acuity of real gratings

The spatial acuity is often measured with a two points discrimination threshold experiment. The detection thresholds have also been applied on textured surfaces. For instance, Philips and Johnson [21] or Van Boven and Johnson [4] use surfaces with gratings or matrices constituted of small points. However these studies do not give the differential thresholds for other textured surfaces because the differential thresholds found in these studies cannot be generalized to any kind of stimuli and that the spatial resolution measured by two points discrimination experiments or the orientation of textures are not sufficient. As a result, the studies by Craig and Johnson [5] give only the minimum groove width that it is possible to detect but do not tell anything on the performance of the perceptual system for larger groove widths. Another limitation of these studies comes from the fact that only passive touch is used (when the finger does not move), whereas it is not a natural exploratory procedure to explore finely textured surfaces. Lederman et al. have indeed shown that the dedicated exploratory procedure to scan roughness is a lateral movement of the finger [14]. The main motivation to use passive touch in these experiments is to reduce the sources of variance [21, 6]. However, touch is not simply a matter of static contact between the surface and the skin as it also implies an active exploration of the surface.

In psychophysics, the ability of users to distinguish between stimuli of the same nature can be measure with the JND and the

Weber fraction (See Appendix for more details). The literature provides two examples of the discrimination of square and sinusoidal gratings with real samples by dynamic touch [16, 20].

2.2.3 Differential Thresholds of Real Gratings by Dynamic Touch

Differential Thresholds of Real Square Gratings In the experiment presented by Morley et al. [16], four participants were asked to discriminate between two standard square gratings (0.77 mm and 1.002 mm) by dynamic exploration of a surface. After a long training session (1h40), participants were forced to determine between three gratings, among which two were identical, the one that was different.

The gratings were designed so that the groove part could not be touched by the finger. Only the spatial period was varied and the groove width to ridge width ratio was held constant at nine.

They found a constant Weber fraction around 5% for the two standard square gratings.

Differential Thresholds of Real Sinusoidal Gratings The study presented by Nefs et al. gives the differential thresholds for the amplitude and spatial period of sinusoidal gratings by dynamic touch [20]. The amplitudes chosen are a multiple of the detection threshold of the amplitude and the spatial periods range from 2.5 mm to 10 mm. The upper bound is justified by the largest distance allowing the finger to keep touching two ridges and the lower bound was chosen so that it corresponds to the minimum distance that can be detected between two epidermal ridges on the fingertip. This value is debated in the literature and it ranges from 0.8 to 3 mm [4] [26]. The method used for the differential threshold is a constant method with forced choice.

In a first experiment, they measured the differential thresholds for different amplitudes as a function of the spatial period. The thresholds found are between 10.8% and 15.8% of the standard amplitude. They showed that a difference in amplitude as small as 2 mm can be detected. They found also that the Weber fractions for the discrimination in amplitude remain constant for the range of amplitude evaluated but they showed that the discrimination was better when the spatial period increases. In a second experiment the authors have determined the differential thresholds for the spatial period. Using the same experimental procedure, they found Weber fractions between 6.4% and 11.8%. In this case, the amplitude has no effect on the Weber fractions for the discrimination of the spatial period. However, the Weber fraction decreases as the spatial period increases.

3 Experiment

3.1 Goals

Since no previous work has shown if continuous tactile devices can be used to simulate real gratings with the same resolution, we conducted an experiment to measure the differential thresholds for four spatial periods with a fixed vibration amplitude. With this design, our goal is to compare the Weber fraction for each spatial period with equivalent real gratings to measure the gap between simulation and reality.

As making high precision gratings is a very time consuming process requiring specific high precision machines [20], we focus the experiment on the determination of the differential thresholds of virtual gratings. The differential thresholds found in our experiment are then compared and discussed with the results found on real gratings by Morley et al. [16] and later Nefs et al. [20].

3.2 Apparatus

3.2.1 Friction based tactile device used in the experiment

As we previously mentioned, the friction based tactile device used in this experiment is based on the generation of an air-gap between the finger and a high frequency vibrating plate. However, the way the actuator operates is somewhat different from Watanabe et al.'s device [35] since the flexural wave propagating along the plate is not generated from a piston motion as it is the case with Langevin transducer. It is instead generated by piezoelectric ceramics glued below the touch surface, which in turn contract and relax (Fig. 2).

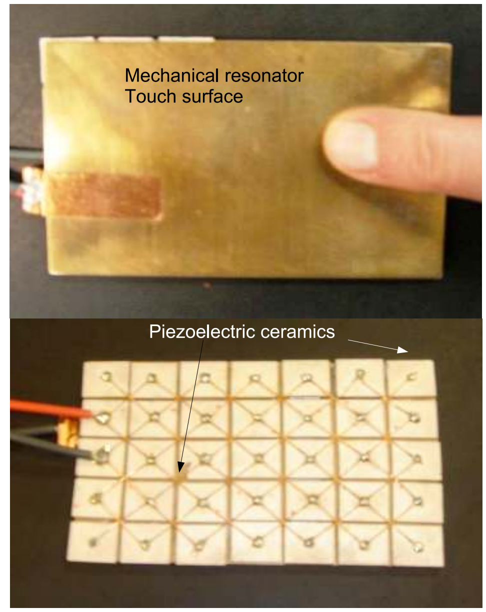

Figure 2: Picture of the tactile display with the touch surface (top view) and the piezo-ceramic matrix (bottom view).

Our tactile device, actuated by a supply tension at a resonance frequency of 30.5 KHz, generates a stationary flexural wave along the length of the surface thanks to an appropriate positioning of the ceramics and their initial polarization. The dimensions of the tactile display are 83 mm by 49 mm.

The vibration amplitude is measured using a single-point LASER Doppler Vibrometer (Model OFV505, Polytec GmbH, Waldbronn, Germany [22]) linked to a controller (OFV-5000) that is connected to an oscilloscope. As the results show (Fig. 3), a deflection amplitude of about 2.3 μm peak to peak is obtained by applying a voltage of 15 V.

In these conditions, the squeeze film effect is generated between the finger and the vibrating plate. This effect is thus able to decrease the friction coefficient between the fingertip and the plate as

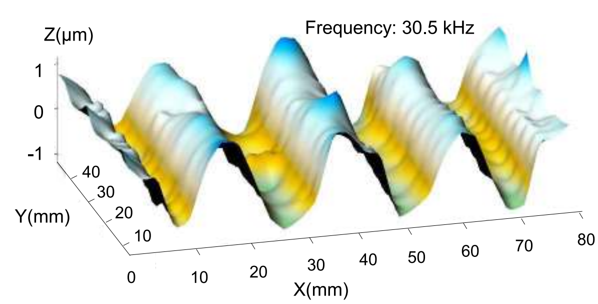

Figure 3: Laser vibrometric measurements of the (x=8; y=0) mode.

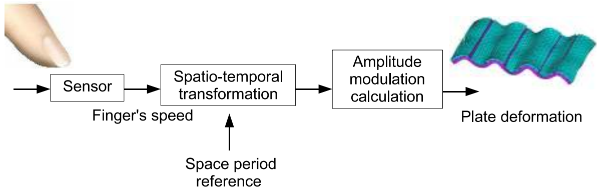

Figure 4: Control of the wave amplitude.

a function of the vibration amplitude [1]. Hence, with this setup, the sensation felt when the finger is moved on the plate is a sliding sensation similar to the one observed with Langevin transducers. This sensation is independent of the relative position of the finger from the nodes and the tops of the wave. To create the texture feeling, the idea is to generate alternatively sliding and blocking sensations, tuning the vibrating wave amplitude.

For that purpose, we propose to modulate the amplitude of the power supply tension with a low frequency signal (Fig. 4). Thus the wave amplitude modulation is controlled according to the finger position.

This signal is said ”low frequency” compared to the vibration frequency of the plate, but it is fully compatible with the mechanoreceptor bandwidth of fingers [3]. This produces a modulation of the vibration amplitude of the stationary wave which creates, in turn, a modulation of the sliding effect. This temporal variation of the sliding property of the device makes the user feel he is touching sliding and braking areas, which is interpreted as touching a surface with gratings (Fig. 5). Yet one can notice that the use of square wave modulation signals to control the slippery feeling does not induce directly the user to perceive a square wave periodic texture. Boundaries conditions between the braking surface and the slippery surface are indeed less spiky or steep than real square textures for instance.

To sum up, this device has the advantage to be much more compact than Watanabe et al.'s device and, like with the Langevin transducer used by Watanabe et al., allows the exploration of the surface without any risk for the user. The device developed is not transparent. It is a first experimental device whose conception has been made with a substratum in CuBe for convenience reasons. In a near future, we will develop the same kind of device with a substratum in glass and ceramics glued at the edges of the surface that will give a transparent surface below which a LCD screen will be placed (see Fig. 1 for the description of such a device).

This kind of device can then be integrated in a touchscreen [23, 10] to add tactile effects. The sensing capability of the screen can be used to measure the position of the finger and update the corresponding friction of the surface. As done by Kaaresoja et al.

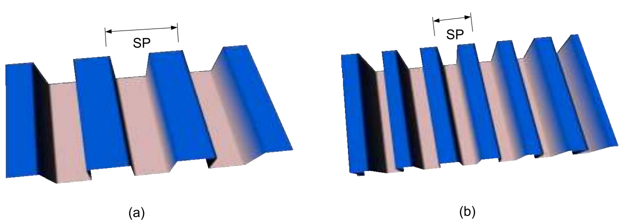

Figure 5: Examples of virtual textured surface that can be simulated on the tactile display. In this case, blue areas are the one with the greater friction coefficient. The spatial period (SP) in (a) is larger than in (b).

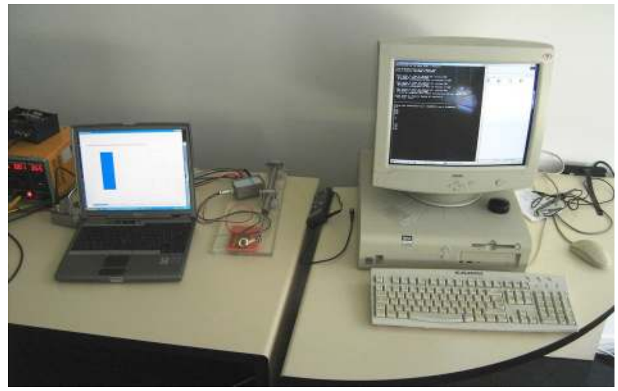

Figure 6: The apparatus is composed of the tactile display and two computers connected on the network. One computer (on the right) reads the position of the linear sensor to update the texture on the tactile display (centered) while the other computer (on the left) controls the parameters of the expriment.

[12], it is then possible to select text, scroll a page or ”drag and drop” objects. In addition, as it is possible to change the coefficient of friction of the surface, it is possible to render finely textured surfaces on the display that can be felt by the user [2, 36]. The question that is left unanswered is the resolution with which it is possible to render these textures.

3.2.2 Other apparatus

All spatial periods were simulated with our tactile device connected to a computer through a PCI SELIAtec PI01 board and custom designed electronic boards. The position of the finger was constrained on the tactile surface by a linear position sensor having a 70 μm resolution. An application running on the computer measured the position of the finger at a frequency of 1000 Hz to update the square wave actuated on the tactile surface (Fig. 6).

Another computer was used to run the experiment and display on the screen the current sample simulated. It was connected to the computer running the tactile device through a network connection.

The tactile display with the position sensor were placed on a table at a distance that participants could reach easily. We decided not to hide the device from participants view, as the surface keeps the same aspect whatever the grating simulated. In this way, participants are also not afraid of touching the surface. Participants were equipped with an headphone to prevent them from earing any potential noise generated by the device. They were also instructed to wash and dry their hands before the beginning of the experiment.

The applications were coded in C++ and OpenGL for the display.

3.3 Task and Stimuli

The task required participants to discriminate between two spatial periods simulated on the tactile device. Two rectangles side to side, marked 1 and 2, were displayed on the computer screen running the experiment to represent the two spatial periods simulated (Fig. 7). One of the sample was the standard spatial period (PS), presented randomly on the left or right, and the other one was the comparison spatial period. The spatial period currently simulated on the tactile display was represented by a filled rectangle while the other one was represented by an empty rectangle. The participant used the left and right arrows on the keyboard to switch back and forth between the two rectangles, which updated at the same time the spatial period simulated on the tactile display.

The participants were instructed to hold the elbow of the dominant arm on the table and insert their index finger in the ring at-

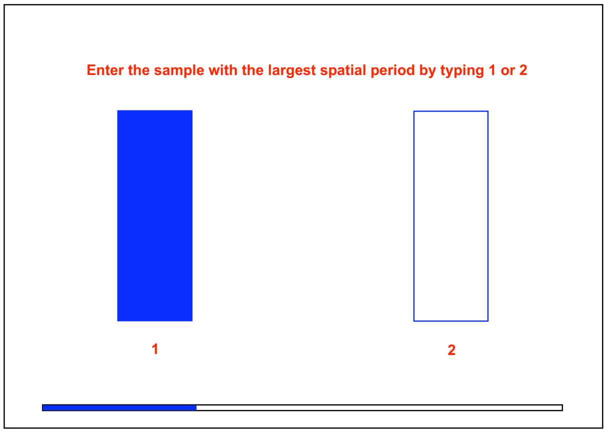

Figure 7: The graphical interface represents the two samples to compare by two rectangles labeled ”1” and ”2”. The current sample simulated is represented by a filled rectangle. Participants can switch between the two samples using the left and right arrows and indicate what they consider to be the largest spatial period by typing ”1” or ”2”.

tached to the linear position sensor. In addition, we asked them to try to keep a 45 degrees angle between the surface and the finger (Fig. 8 b). Participants are then instructed to move their finger forward and backward along the position sensor to feel the simulated gratings. We asked to use a ”light force and medium speed” even though neither the force or speed were controlled during the experiment [13].

Participants used their dominant hand to explore the tactile surface and the non-dominant hand to control the sample to be simulated with the left and right arrows. They were free to switch between the two samples as many times as they wanted and explore each sample as long as they wanted before typing ”1” or ”2” corresponding to the sample that they considered to have the largest spatial period. Then, two new samples to discriminate were then presented and the progress bar presented at the bottom of the display was updated to give an indication of the number of remaining samples. All raw data were logged in a text file for future statistical treatment.

3.4 Design

The four standard spatial periods evaluated had a value of 0.25, 0.35, 0.5 and 1.0 cm. For each standard grating we used eight comparison gratings. Comparison gratings had a spatial-period step ranging from -20% to +20% of the standard in 5% intervals (-20%, -15%, -10%, -5%, +5%, +10%, +15%, and +20%) except for the 0.25 cm spatial period where we used the following comparisons: -25%, -20% -15%, -10%, 10%, 15%, 20% and 25% as done by Nefs et al. [20] who found a differential threshold more important for the de 0.25 cm spatial period. The vibration amplitude of the plate is alternatively equals to 0 μm (perception of high friction) and to 1.15 μm (perception of low friction) (Fig.5).

All combinations of standards and comparison gratings were repeated 16 times, which amounted to 512 (4 standard periods $\times$ 8 comparisons $\times$ 16 repetitions) trials for each participant. The experiment was carried out in eight sessions each consisting of four blocks. A block consisted of 16 (1 standard $\times$ 8 comparisons $\times$ 2 repetitions) trials of the same standard grating. Each standard was used in all sessions. The presentation order of the four spatial periods was randomized as well as the presentation order within a block. A session lasted between 30 and 45 minutes. Sessions were

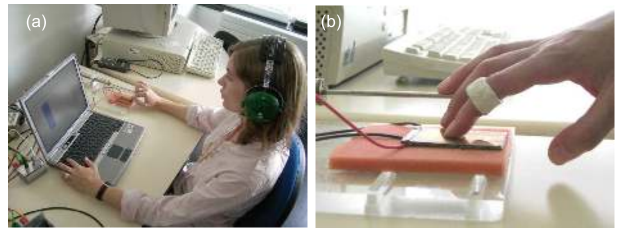

Figure 8: (a) Position of the participant wearing an earphone. (b) Position of the finger on the tactile surface.

separated by at least half a day. In the first session of the experiment, we gave the participants the instructions aloud. We repeated the instructions in abbreviated form in other sessions. They could ask additional questions if they wished.

The experiment started with a training session intended to check whether the procedure was clearly understood and to give the participant an opportunity to familiarize with the stimulus and the task. This training period is composed of four sample pairs that are easy to discriminate and lasted about 2 minutes. We provided correctness feedback for the practice trials, but not for the experimental trials.

In summary, the experimental design was:
8 participants $\times$
8 sessions $\times$
4 blocks (one standard spatial period each)$\times$
8 comparisons $\times$
2 repetitions
= 4,096 total comparisons

4 Results

4.1 Weber fraction

The Weber fraction can be graphically measured from the psychometric function of each spatial period [7]. A more systematic way to do is to run a linear regression on the logit transformation of the data [15].

The analysis reveals that participants have a good regression fitness for all spatial periods (R^2 min = 0.73, R^2 max = 0.96 , R^2 average = 0.88). The Weber fractions for spatial period discrimination are plotted in Fig. 9 as a function of spatial period for all eight participants. The figure shows also the average results for all participants. The overall Weber fraction was approximately 8.96% of the standard spatial period. All participants had approximately the same discriminatory sensitivity, except for participant CC who seemed to be somewhat less sensitive than the other participants. Average Weber fractions were 9.58%, 8.93%, 9.24%, 8.07% for 0.25, 0.35, 0.5 and 1.0 cm, respectively. Thus the actual average differential thresholds ranged from 239 μm for the 0.25 cm spatial period to 807 μm for the 1.0 cm spatial period.

A repeated measures within-subjects design (ANOVA) was used to further analyze the effect of the spatial period on the Weber frac-

Table 1: Mean results of the discrimination test.

Standard spatial period (cm)	JND or Mean threshold (μm)	Mean Weber fraction $\pm$ SD
0.25	242	9.58 $\pm$ 3.82 %
0.35	318	8.93 $\pm$ 2.39%
0.50	473	9.24 $\pm$ 3.47 %
1.00	824	8.07 $\pm$ 4.07%

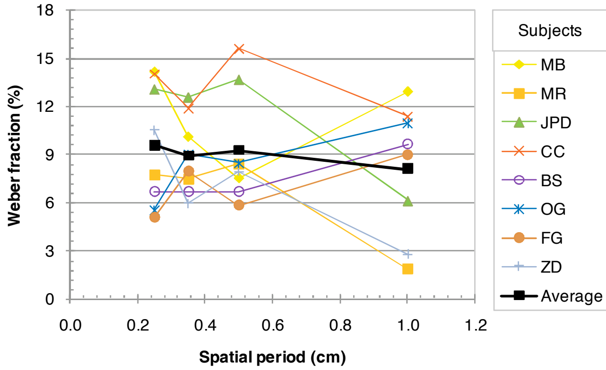

Figure 9: Weber fractions for spatial period discrimination are plotted for each individual participant. The averaged results aver all participants is also represented.

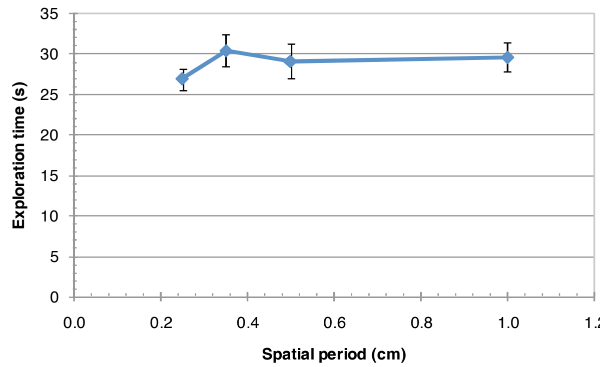

Figure 10: Mean exploration time for each spatial period. Error bars represent 95% confidence interval.

tion. Repeated measures of variance did not show any significant effect of spatial period on the Weber fraction ($F_{3,21} = 0.455$, p = 0.522). Of course, this result is not equivalent to finding that Weber fraction is the same, since one cannot use statistical analysis to prove the null hypothesis. However, this result tends to show that the Weber fraction is kept constant.

4.2 Exploration Time

Participants were free to explore each sample as long as they wanted. Analyzing the time participants spent to explore the samples corresponding to each spatial period is interesting to know if some spatial period are more difficult to analyze than others.

Repeated measures of variance did not show a significant main effect of spatial period on the exploration time ($F_{3,27} = 1.25$, p = 0.3). The mean exploration time ranges from 26.9s for the 0.25 cm spatial period to 30.4 s for the 0.35 cm spatial period with a mean value equal to 29 s (Fig. 10).

5 Discussion

5.1 Spatial Period Discrimination

The experiment we proposed allowed us to determine the differential thresholds for the spatial periods of virtual square gratings. These gratings were simulated with a modification of the surface coefficient of friction in the condition of dynamic touch. We observed that the Weber fractions remained close throughout the range of spatial periods evaluated (the values range from 8.07% to 9.58%). In addition, as the statistical analysis of variance showed no significant difference between the Weber fractions found for each spatial period, we can reasonably conclude that this ratio remains constant at 9% for the four spatial periods considered. This result is important as it shows that the spatial periods are perceived with the same acuity throughout the range of spatial period considered.

5.2 Comparison Between Virtual and Real Gratings

Morley et al. [16] found a Weber fraction of 5% for square gratings with spatial periods of 0.77 and 1.0 mm while Nefs et al. [20] found Weber fractions between 6.4% to 11.8% for sinusoidal gratings with spatial periods between 2.5 and 10 mm.

In Morley et al. experiment, the transition from a groove to a ridge is sharp as the finger is only in contact with ridges. In addition, participants were highly trained before running the experiment. As a result we can consider the Weber fraction of 5% found as a lower bound for real square gratings. The greater Weber fractions found by Nefs et al. for the spatial period of 0.25 cm can be explained by the sinusoidal grating used where the transition between a groove and a ridge is smooth. This phenomenon can explain why we found a Weber fraction equal to 9.58 % for the smallest standard spatial period (0.25 cm) when Nefs et al. found 11.8 % for the sinusoidal grating. Thus, this value can be considered as an upper bound for real square gratings.

These results indicate that we can reasonably consider that the 9% Weber fraction found in our experiment is close to the Weber fraction of equivalent real square gratings but can be improved.

5.3 Design Guidelines

What appears to be important for the simulation of gratings is the transition between grooves and ridges. Our hypothesis is that a sharp transition between a groove and a ridge will reduce the Weber fraction. In that way the Weber fraction found in our experiment appears to be influenced by the shape of the modulation amplitude of the gratings simulated. The transition from the low friction state to the high friction state slows the displacement of the finger, which is perceived as a level transition. However, this transition is different from the sensation of sharp ridges as in Morley et al. experiment, where the grooves could not be touched. As a result the transition from one groove to another was easier to detect in their experiment.

We can consider that the friction coefficient of the device not actuated (i.e. the initial friction of the plate when vibration amplitude equals 0 μm) can also have an influence on the capability of participants to discriminate between different spatial periods. The transition from a surface with a high friction coefficient to a slippery surface is easier to detect compared to the transition from low friction coefficient to a slippery surface. We do not know the roughness of the samples used by Nefs et al. but the low friction coefficient of our device not actuated ($R_a = 0.6\ \mu m$) can be a drawback for the spatial period discrimination.

From these considerations, we can raise the three following points that can help to improve the JND discrimination of friction based tactile devices:

- The average friction of the surface not actuated should be as high as possible to give a straightforward transition between friction areas and slippery areas.
- The maximum vibrating amplitude of the surface has to be high enough to get a good slippery feeling.
- The shape of the vibrating wave modulation can be optimized in order to simulate a very sharp transition between grooves and ridges.

6 CONCLUSION

This study shows that users can effectively discriminate square gratings with a friction based tactile device. The Weber fractions remain constant throughout the virtual gratings evaluated and are close to the Weber fractions of real gratings. This experiment helped us to get a better understanding of friction based tactile devices which leads us to give the guidelines for the design of improved friction based tactile devices.

These results suggest that friction based tactile devices can be used for co-located tactile displays. In addition they appear to be a realistic alternative to pin based arrays. Considering their low bulkiness, they could be easily integrated in laptop to get touchpad with tactile capabilities, as shown in Fig. 1.

7 APPENDIX

The just noticeable difference (JND) gives the smallest difference in a specified modality of sensory input that is detectable by a human being. It is also known as differential threshold.

A JND experiment is constituted of standard samples of the stimulus considered and comparison samples. From the raw data collected during the experiment, the percentage of trials for which the participant decided that the comparison stimulus had the larger spatial period is computing for each standard stimulus. This gives a psychometric function. The differential threshold is computed from the value where 75% of comparison samples are judged to be greater than the standard stimulus. The Weber fraction is the ratio between the differential threshold and the standard stimulus.

A logits[1] transformation can be applied to the psychometric function as the psychometric function is supposed to follow the equation 1, where α is the 50% discrimination threshold and β is empirically determined.

$$p(x) = \frac{1}{1+(\frac{x}{\alpha})^{\beta}} \tag{1}$$

The transformed curve is supposed to be a straight line given by the equation 2 where a and b are empirically determined.

$$logit(p) = aX + b \tag{2}$$

The differential threshold and the Weber fraction can then computed from the logit function and the a and b values.

[1] $logit(p) = ln\left(\frac{p}{1-p}\right)$

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