Generating Haptic Textures with a Vibrotactile Actuator

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ABSTRACT

Vibrotactile actuation is typically used to deliver buzzing sensations. But if vibrotactile actuation is tightly coupled to users' actions, it can be used to create much richer haptic experiences. It is not well understood, however, how this coupling should be done or which vibrotactile parameters create which experiences. To investigate how actuation parameters relate to haptic experiences, we built a physical slider with minimal native friction, a vibrotactile actuator and an integrated position sensor. By vibrating the slider as it is moved, we create an experience of texture between the sliding element and its track. We conducted a magnitude estimation experiment to map how granularity, amplitude and timbre relate to the experiences of roughness, adhesiveness, sharpness and bumpiness. We found that amplitude influences the strength of the perceived texture, while variations in granularity and timbre create distinct experiences. Our study underlines the importance of action in haptic perception and suggests strategies for deploying such tightly coupled feedback in everyday devices.

Author Keywords

Texture Perception; Haptic Feedback; Magnitude Estimation

ACM Classification Keywords

H.5.2 User Interfaces: Haptic I/O, Interaction Styles

INTRODUCTION

Active exploration is required if one wishes to understand the texture of an object: When resting a finger on a material, we perceive the material's basic features, such as cues related to shape and temperature. To understand the texture, we also need to know what it feels like to move one's finger over it. The relative motion of the fingertip and the surface create vibrations [21] and these vibrations activate sensory receptors in our fingertips [2]. Through them the material comes alive in our hands [4].

In HCI it is becoming more common to apply this insight in the design of vibrotactile feedback, leading to systems that tightly couple vibration to human motion. Such feedback has been used to change the perceived compliance of materials [16,34], emulate mechanically complex systems [41], and simulate contact with different surfaces through a proxy tool [6,31].

While a haptic experience of texture is caused by our body moving relative to a surface or material, it is not clear what characteristics of a material make us experience its texture in a particular way. Consequently it is not clear how to manipulate vibrotactile feedback if one wishes to generate a specific haptic experience. Previous explorations have either used discrete mappings between pulse-trains and motion or pressure [16,34], or attempted to recreate the original sensation as closely as possible by recording the vibrotactile signature of a surface and playing it back [6,31]. However, the first approach is difficult to generalize, as we do not understand how the experience would change if the mapping is changed, while the second approach does not contribute to an understanding of why different types of vibrotactile actuation are experienced in certain ways.

To better understand how the experience of texture can be manipulated by varying parameters of vibrotactile feedback, we conducted a magnitude estimation experiment [33]. The experiment uses haptic feedback that is tightly coupled to user input. To achieve this, we created a slider consisting of a glide-bearing that moves over an anodized aluminum rod. This bearing is augmented with a vibrotactile actuator and a position sensor with high spatial and temporal resolution. As a user moves the slider over the rod, we provide haptic pulses synchronized to the user's motion. This is experienced as a texture between the slider and its track. In the experiment, we adjusted the parameters with which we generated the vibrotactile feedback, while asking participants to rate their experience of the texture.

We found that bumpiness, roughness, adhesiveness and sharpness all had unique *granularity* and *timbre* profiles, which suggests that these parameters can be used to generate qualitatively distinct sensations. The response curve of *amplitude* displayed different slopes, suggesting that sensations such as bumpiness or roughness benefit from high amplitude vibration more so than adhesion or sharpness. The results also suggest that pulse frequency might play a less important role than expected and that timbre should be further investigated for a better understanding of haptic experience.

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RELATED WORK

Our work is about haptic experiences, in particular, the experience of texture. A host of work exists on classifying and mapping such experiences (e.g., [39]). The vocabulary we will use is based on Okamoto et al. [25], who presented a synthesis of dimensions of haptic perception from 18 studies. Okamoto et al. identified three major perceptual dimensions: hard/soft, cold/warm and a texture dimension of rough/smooth. They also suggested that the roughness dimension has micro and macro sub dimensions, and that sticky/slippery could be another possible dimension [25]. We use *roughness* and *bumpiness* as more colloquial terms for micro and macro roughness, while we use *adhesiveness* to capture the sticky/slippery dimension. *Sharpness* was added based on user feedback during a four person pilot study.

We first discuss the role of vibration in setting about such experiences. Then we survey techniques for creating vibrotactile feedback and show how coupling them to user movements help create experiences of haptic textures.

The Role of Vibration in Experiencing Surfaces

To fully experience the haptic qualities of a material, touch alone is insufficient. Resting one's hand on a material may evoke an impression of temperature or reveal shape features if they are prominent enough to distort the skin, but to feel how hard a material is, one needs to actively press against it; to experience its texture, one must move ones finger relative to the object one is touching [7,18]. When one moves a finger over a surface, the texture of the fingertip in combination with the texture of the surface produce vibrations [2,21]. These vibrations are used to infer information about the material we are touching [4,19].

In *The World of Touch,* Katz [7] differentiated between the sensation of vibration and that of pressure. He argued that either can occur without the other: When touching an object without moving it, we perceive pressure, but not friction. When letting a pen loosely glide over a piece of canvas we feel the vibration induced by the motion, but not pressure. This vibration is sufficient for us to experience the texture that the pen is gliding over.

This idea is supported by the modern understanding of the physiology of tactile perception: There are four main types of nervous receptors in the skin. Ruffini's Cylinders and Merkel's Disks are related to skin deformation and pressure perception. Meissner's Corpuscles respond to vibration from ~30Hz to ~80Hz while Pacinian Corpuscles react to vibration from ~250Hz to ~350Hz. A large body of studies suggests that perception of textures is linked to vibration at frequencies sensed by the Pacinian system [2,3,18,19,43]. This suggests that we can create an experience of texture using solely vibrotactile actuation.

Vibrotactile Feedback Technologies

As vibrations are key to the experience of texture, we review technologies for generating vibrotactile feedback. The most common way of doing so is using eccentric rotating mass (ERM) vibration motors. Rumble packs for game controllers were early uses of ERM motors [27]. ERM motors fit into a mobile device but are typically limited to alerting, shaking, and pulsating. In research they appear to be the go-to solution for quick experimentation (e.g., [32]), though the limitations created by the slow speed up times and a coupling of intensity and frequency of the ERM stimulation are well understood [44]: the amplitude and frequency of their actuation cannot be controlled independently.

Piezo actuators have been used to overcome this limitation. While piezo elements are often used for friction reduction in haptic interfaces (e.g., [1,37]), they can also provide traditional vibration at lower frequencies as well as clicking sensations. Various methods have been suggested for using this to augment displays of mobile devices with additional haptic cues [20,28,29]. While piezo elements have high temporal precision, they have relatively small actuation range, and therefore low achievable amplitude.

Vibrotactile feedback can also be created using solenoid-style actuators (also known as voice-coils, tactors, or haptuators). Such actuators work as audio-speakers do: A magnetic core is constrained within a copper coil. The magnet moves proportionally to the amplitude and direction of the electrical signal applied to the coil. Using audio speakers for haptic feedback was first described in 1926 to enable deaf people to 'feel' speech [8]. Since then, devices have been improved to minimize sound generation [42]. These devices can be controlled with an audio signal, achieve a higher velocity than piezo actuators, and achieve high temporal precision. Therefore, they have become a popular tool for exploring haptic feedback within the HCI community, for example in papers by Israr and Zhao [44–46], Strohmeier [34] and others [10,12,41].

Coupling User Action and Vibrotactile Feedback

As argued above, texture is experienced through movement. Therefore, there has been a growing interest in coupling movements and vibrotactile feedback to create experiences of roughness, compliance, and other dimensions of haptic experiences. Nara et al. [23] demonstrated a 'slider' consisting of steel balls on a variable friction surface. Using a friction reduction approach, Nara et al. were able to provide distinct haptic sensations by adjusting the frequency at which they provided bursts of low friction relative to the motion of the user's finger.

Tactile texture discrimination in robotic applications is typically achieved by moving a probe over a surface and analyzing the frequency and spectral response of the signal [40]. This approach of measuring textures with a moving probe was adopted by Romano and Kuchenbecker who coupled such a recording device to a playback device. The playback device is held by the users and, as it is moved over a flat and smooth surface, provides them with the sensation of moving the device over one of the pre-recorded materials [6,31].

This link between user action and haptic feedback need not be limited to motion. Kildal [16] explored coupling pulse speeds to pressure exerted on a surface, providing users an experience of compliance. Yao and Hayward [41] coupled pulse speed to the angle at which a rod is tilted, providing an experience of an internal rolling stone. Strohmeier et al. [34] presented a flexible device which couples pulse frequency to changes in the amount by which the device is bent, resulting in an experience of changing material composition.

All work listed above is based upon a common principle: When coupling vibrotactile feedback with user motion, vibration and motion are perceptually combined, leading to a new experience. The vibration is no longer attributed to a vibrating actuator, but rather is felt to be a property of a dynamic system that does not vibrate [23]. Therefore, if one wishes to find parameters of vibrotactile feedback that lead to an experience of texture, these parameters must also be adapted to user motion.

Open Questions

The literature suggests that coupling vibrotactile feedback with user motion is promising. However, previous work has either not systematically varied the parameters with which the feedback is generated [34,41], or presented only anecdotal results regarding the mapping of feedback parameters to experiences of texture [23,24]. Kildal conducted a qualitative study of two levels of four parameters (granularity, amplitude, grain-distribution and regularity), demonstrating that they could create a variety of sensations [16]. However his analysis was not designed to link variations in feedback parameters to variations in experience of texture. Kildal stipulates that “Future controlled studies will focus on answering this question.” [16, p.7].

We next describe a simple haptic interface that we use to conduct such an experiment.

IMPLEMENTATION OF HAPTIC FEEDBACK DEVICE

We envision vibrotactile feedback coupled to human action to be used for augmenting tangible interfaces with additional dynamic material properties – similarly to how projection is used to augment the appearance of tangible tokens. Ideally we would like to explore such feedback in unconstrained space, using 3D motion tracking. However, for the sake of a controlled experiment and to maximize spatial and temporal sensing resolution, we constrain interaction to moving an object along a straight path.

Mechanics

We created a custom slider using a linear glide bearing (length 80mm) with a Frelon GOLD® lining and a anodized aluminum rod (⌀ 20 mm, length 500mm) as seen in Figure 1. We opted for glide bearings, because they create only negligible vibrations when moved.

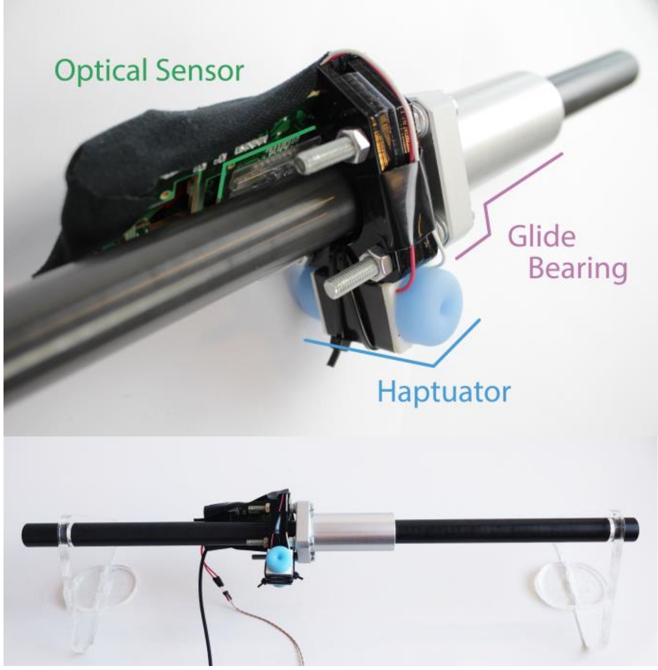

Figure 1 – Slider used for experiment. Participants interact with slider by moving the silver glide bearing. The optical sensor measures the movement and the Haptuator vibrates the device relative to the speed at which the slider is moved.

Sensing

We used an optical sensor, harvested from a Logitech M500 mouse. The sensor was placed on the gliding element, so it would move a computer’s cursor as the slider was moved. The update rate of the sensor was measured to be 125Hz and the step resolution was measured to be 0.032mm (note that we disabled mouse acceleration).

Signal Flow & Vibrotactile Actuation

We used a BM3C Haptuator by TactileLabs[1]. The haptic feedback was generated as an audio signal based on cursor position, which was sampled at 200Hz using Max/MSP. The audio signal was played back using an external soundcard (UR44 by Steinberg) and a low power, generic audio amplifier connected to the haptic actuator. The delay between onset of motion and haptic actuation was estimated to be around 20ms (4.5ms from the soundcard, 2ms for registering movement, 8ms for updating cursor position from the mouse, and 5ms from Max/MSP operating in overdrive mode).

Parameters of Vibrotactile Actuation

Sound is typically produced by a vibrating object that causes longitudinal waves in the air, which we then hear. Because what we hear is directly linked to the vibration of such an object, we can use existing vocabulary that describes sound for describing the vibrations that cause the sound, such as *amplitude* (loudness), *frequency* (pitch), and

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[1] http://tactilelabs.com/wp-content/uploads/2016/06/Haptuator-BMXC-series-v1.1.pdf

timbre (the quality of a sound, or color – consider the difference in sound between the vowels in 'eek' and 'oh').

While *amplitude* and *timbre* can directly be applied to haptic feedback, frequency cannot be a feedback parameter, as we vary frequency with user input speed. Instead we use *granularity* as a constant that, multiplied with the motion of the user, results in frequency.

We generate haptic feedback as a series of 64 sample pulses. The frequency with which they occur is based on the user's action and granularity of the virtual texture:

$$f = Granularity * User\ Motion$$

User motion is defined as the speed with which the slider is moved. It is measured in cm per second:

$$User\ Motion = \frac{cm}{seconds}$$

Granularity represents the number of features on a surface. We defined it as pulses per cm (p/cm):

$$Granularity = \frac{pulses}{cm}$$

The pulse frequency can therefore be expressed both by granularity multiplied by user motion, or for the implementation, as pulses per second:

$$f = \frac{pulses}{cm} * \frac{cm}{seconds} = \frac{pulses}{seconds}$$

Finally we pass the signal through a bandpass filter to modulate its timbre, allowing us to create sensations which are qualitatively distinct while sharing the same granularity and amplitude.

EXPERIMENT

Having established the feedback parameters, we are now interested to investigate how these can be used to create different texture experiences. There are a number of established psychophysical research methods that are used to "derive an understanding of the relation between changes in the physical stimulus and the associates sensation" [15, p.11]. Of those, we chose to use magnitude estimation, in which users estimate the strength of individual stimuli by assigning numbers to them [9,33]. Because this method does not set a predefined maximum or minimum, we felt that it was best suited for an experiment in which the presence of the target experience is not known. The result of this experiment will allow us to create response curves that show how a change in the vibrotactile feedback influences the experience of texture.

To make basic comparisons between the effects of individual parameters and to validate the magnitude estimation experiment we decided to add a second task. Participants were asked to produce the texture experience that they previously evaluated, using the same parameters as in the magnitude estimation task.

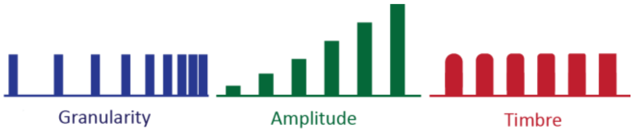

Figure 2 – Naïve visualization of vibrotactile parameters.

As we were interested in potential interaction effects of the haptic feedback parameters, we opted for a factorial design. Based on a pilot study, we chose to compare the effects of 5 levels of granularity, 3 levels of amplitude and 4 levels of timbre on participants' experience of roughness, bumpiness, adhesiveness and sharpness.

Experimental Apparatus

We used the linear slider described in the implementation section. The experimental flow and data-logging were done in Processing. Communication between Processing and Max/MSP was handled by OSC [38].

To ensure that participants base their responses solely on their haptic experience, participants were asked to wear headphones during both tasks of the experiment. The headphones were playing white noise to mask any external sound.

Independent Variables

When reasoning about the effects of different feedback parameters, and for choosing appropriate levels, we think of them as shown in the naïve model above (Figure 2).

Granularity

We imagined granularity to correspond to individual surface features. When impulses can be distinguished from each other, we expected them to be described as bumps. At higher granularity levels, for which individual pulses cannot be clearly distinguished, we expected users to report an experience of roughness. We expected to find a point at which pulses are generated so rapidly that they cannot be distinguished from each other at all, leading to smooth experiences, potentially influencing the perceived adhesiveness.

The granularity levels we chose were 312.5, 19.53, 4.88, 2.44, 1.22 pulses per cm. The choice was constrained by the sensing resolution of the optical flow sensor used (0.032mm per step). Our particular software implementation also required us to use values sharing a common denominator. Based on the sensing resolution, the highest achievable granularity was 312.5. The other values were chosen based on a geometric series, while still having a distribution that naively felt equidistant to the experimenters. We chose to pick geometric series as these reflect our acoustic understanding of frequencies: octaves form a geometric series (e.g., A3 = 220Hz, A4 = 440Hz, A5 = 880Hz).

Amplitude

We expected amplitude to modify the intensity of a given experience, while not having any influence on the type of experience.

Amplitude levels chosen were set in Max/MSP to -9.8db, -6.8db and -3.8db relative to line level. If the amplitude approached line level any closer, there were some timbre and granularity combinations which could make the experimental apparatus vibrate to the extent that the optical flow sensor could detect the vibration. This would lead to a feedback loop causing continuous vibration. The lowest value was chosen so that all combinations would still be clearly perceivable. The medium value was selected halfway between these two (in regards to sound, the perceived amplitude doubles every 6db).

The output from max was set to default, as was the internal volume regulation of the UR44. The output of the UR44 was set to 75% and connected to a 4.5V, 1W preamp set to maximum volume.

Timbre

We believed that timbre would have an influence on how clearly impulses can be felt, interacting with how granularity is experienced. We also expected timbre with a high frequency peak to feel sharper than timbre that peaks at low frequencies.

We adjusted the timbre of the pulse train using a band-pass filter. The filter was implemented using the state variable filter object (svf~) of Max/MSP with the Q set to default. We chose to center the filter on 40, 80, 160 and 320Hz (in the rest of the paper, when we speak of ‘high’ or ‘low’ timbre, we are referring to the center frequency of this filter). These values were chosen as they encompass both the typical response frequencies of Meissner’s Corpuscles (~30 to ~80Hz) as well as the Pacinian system (~250 to 350Hz) and because they are a geometric series.

Experimental Measures

The dependent variables were the participant’s estimation of roughness, bumpiness, sharpness and adhesiveness. To ensure that we had a shared understanding of the words chosen to describe these experiences, we discussed them using example objects (Figure 3).

We described *adhesion* as a measure of stickiness which is highest when the slider felt most sticky and is lowest when the slider did not feel sticky or felt slippery. We demonstrated this by the difference felt when moving a finger over the smooth area of a stone, compared to the silicone surface of a bicycle light. We intend it to capture the sticky/slippery dimension described by Okamoto [26].

We described *roughness* as a sensation relating to how coarse a texture is. Roughness is lowest when structures are very close together, as if the slider was moving over very fine sandpaper and higher when structures are larger and further apart, as if moving over coarse sandpaper. We discussed this using the broken edge of the stone in Figure 2 and the smooth side of the stone as examples. Roughness is used to capture the micro-roughness dimension [26].

Figure 3 - Objects used to discuss texture experiences.

We described *bumpiness* as the experience that there are distinct shape features on the object, which could be distinguished from others. Low bumpiness is when the slider feels as if it is moving over a flat surface, high bumpiness is when there are a large number of shape features. We again used the stone which had several bumpy features as an example. The comb seen in Figure 3 was used to discuss that as bumps move closer together, they might no longer be experienced as discrete bumps. Bumpiness is expected to capture macro-roughness [26].

We described *sharpness* relating to bumps as an estimate of how pointy a bump is. For experiences of roughness, we described sharpness as ‘the potential of the texture to scratch you’. We used the pointy and blunt sides of the comb as well as sandpaper and canvas as examples. Sharpness was added based on feedback from participants in a pilot study.

Task 1: Magnitude Estimation

In this task we investigate how the perception of textures changes when the stimulus changes (e.g., “Does roughness increase with granularity?” or “How does changing the timbre influence how adhesive something is perceived to be?”).

To do so we conducted a fully factorial magnitude estimation experiment based on the design suggested by Stevens [33] as described by Gescheider [9]. For each trial we varied levels of frequency, amplitude or timbre. The measures were the user’s estimation of adhesiveness, roughness bumpiness or sharpness. The measures were blocked and the blocks were counterbalanced between participants. The feedback parameters were randomized for each block.

Participants were read the following text (adapted from Gescheider [9]) and given a written copy, which the experimenter discussed with them sentence by sentence.

“As you move this slider, we will provide you with varying haptic stimuli. Your task is to tell us how strongly you experience (adhesion/roughness/bumpiness/sharpness) by assigning a number to the sensation. Call the first sensation

Figure 4 – Participants during the magnitude estimation task.

any number that seems appropriate to you. Then assign successive numbers in such a way that they reflect your subjective impression. There is no limit to the range of numbers you may use. You may use whole numbers, decimals or fraction. Try to make each number match the intensity with which you perceive the sensation."

Participants were told not to set a maximum or minimum value before they started the experiment and were instructed to report their initial judgements without dwelling too long on any particular trial.

Task 2: Haptic Texture Production

This task investigates how the perception of textures compare to each other (e.g., "Is a high frequency timbre component more important for the experience of sharpness than for the experience of roughness?" or "Does amplitude play an equal role for all experiences investigated?").

Participants were presented with a digital interface with 3 sliders: A 5-point slider for frequency, a 3-point slider for amplitude and a 4-point slider for timbre, corresponding to the levels of the stimuli experienced in task one. The sliders were not labelled and the participants received no instructions on the effect of moving the sliders. Participants were asked to create the sensation they felt best represented roughness, bumpiness, sharpness or adhesiveness to them. They were not given a time limit. The discrete scales were chosen, so participants would not be able to create experiences of texture which they were not presented with during the magnitude estimation task.

Experimental Procedure

Upon signing of consent forms the experimenter discussed the dependent variables with participants as outlined above. Once participants and experimenter felt they had a shared understanding of the experimental measures, the experimental procedure was explained. When the participants felt that they understood the instructions, they conducted a practice experiment with 7 combinations of levels for each measure. This was done to familiarize participants with the device and prevent learning effects.

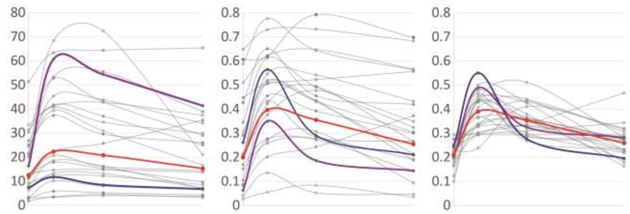

Figure 5 - Data processing steps: means of raw data (left), normalized geometric means (center) and visual response scales (right). Each line represents the data of one participant. The geometric mean of all participants is indicated in red. Two participants are highlighted to highlight how the transformations influence individual response curves.

Task one and two were interwoven. After participants completed a block of task one, they proceeded to create the corresponding experience for task two. Each participant spent approximately 75 minutes on the entire procedure (Figure 4).

Participants

We recruited 24 participants of which 10 were female. Participants were between 22 and 79 years old (M 35.8, SD 13.6).

Data Analysis

The raw measures (Figure 5, left) of task one (magnitude estimation) were normalized per participant, by dividing each participants data by their highest response (Figure 5, center), as discussed by Jones et al. [15]. A repeated measures multivariate ANOVA was conducted on this normalized data. For descriptive statistics we took the geometric mean for each level of each parameter, as suggested by Gescheider [9, p.239]. For creating visualizations of the data, we translated the individual response scales, based on the difference of participant average from the grand mean average (Figure 5, right), as suggested by Han et al. [11]. For the exact calculation please refer to the spreadsheet provided with the supplementary material, or see Han et al. [11]. Note that we cannot make any claims in terms of magnitude between the responses of individual participants or between the strength of the experiences. What the response curves do show is if and how a change in our haptic feedback parameter (x-axis) led to a change in how participants experienced the texture (y-axis).

The data for task two required no further normalization. We analyzed it using a within-subjects multivariate ANOVA.

All reported statistics use Greenhouse-Geisser correction if the assumption of sphericity is violated. If the Greenhouse-Geisser estimate of sphericity is > 0.75, Huynh-Feldt correction was used. Post-hoc tests were Bonferroni corrected.

RESULTS – MAGNITUDE ESTIMATION

Based on the multivariate ANOVA, we found that manipulating haptic feedback parameters did indeed lead to changes in the experience of texture. We found significant main effects for timbre ($F_{12, 204} = 8.100$, $p < .001$) amplitude

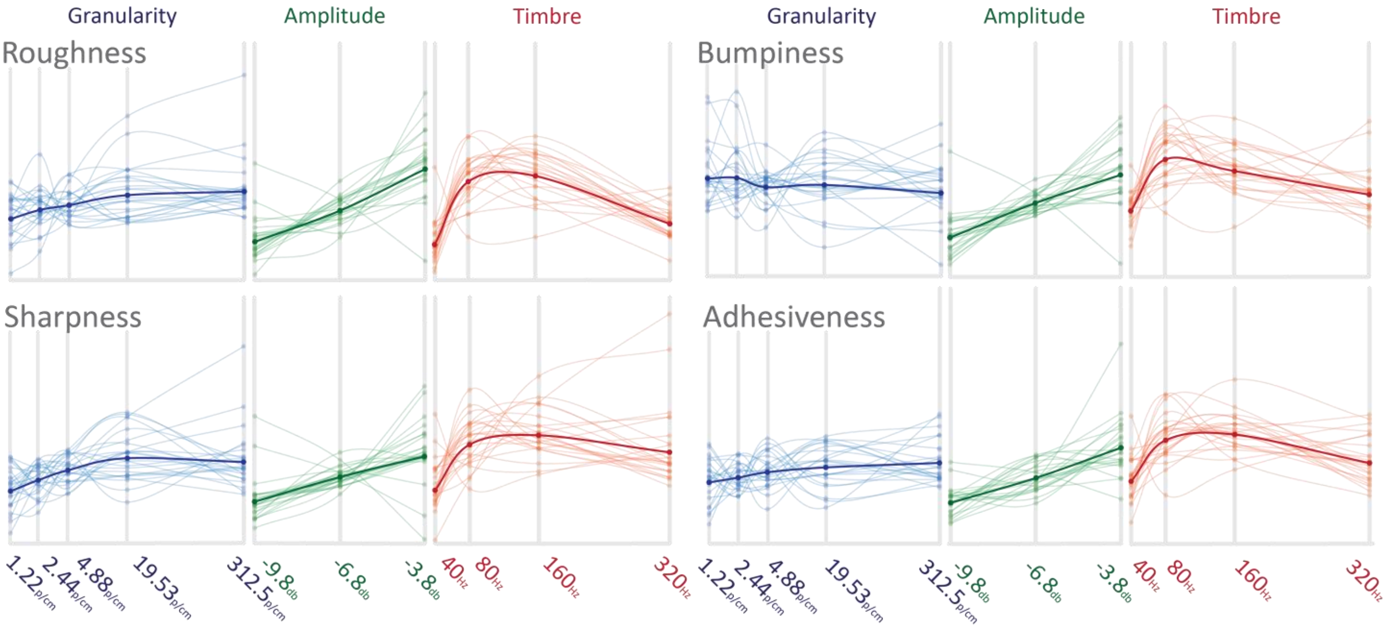

Figure 6 - Response curves. Each line represents the geometric mean of how strongly a participant experienced roughness, bumpiness, sharpness or adhesiveness at the indicated level of the feedback parameter. The bold lines represents the geometric mean of all participants.

($F_{8, 88} = 6.647$, $p < .001$) and granularity ($F_{16, 368} = 2.942$, $p < .001$). The way the experience of texture is influenced, differs for each feedback parameter: granularity does not exhibit a clear trend, which is reflected in its low effect size ($\eta_p^2 = .113$) while timbre had a larger effect ($\eta_p^2 = .323$) that appeared quadratic. Amplitude appeared linear and had the strongest effect size ($\eta_p^2 = .377$). We did not find any interaction effects.

To better understand the experiences of texture, we next look at the individual univariate results. Because our main focus is to better understand the experiences of texture, we will report the rest of the results grouped by experience type as visualized in Figure 6.

Roughness

In Figure 6 (top left) we see that perceived roughness increased with increasing *granularity* ($F_{1.905, 43,819} = 6.170$, $p < .005$). While overall this effect is not particularly strong ($\eta_p^2 = .212$), for the lower range of granularity it was experienced much stronger than for higher levels. Below 4.88p/cm the average rating increase per p/cm is 3.46% of the grand mean, while above 4.88p/cm it only increases by 0.04%. This effect is somewhat hidden by the logarithmic scale: please note that the granularity values double with each step on the x-axis.

We expected that as granularity increased, it would eventually be experienced as smooth and that we would see a dip in our response curve (blue, left). While this did indeed happen for some participants, the mean actually slightly increased. We also did not find a significant difference between a granularity of 19.53p/cm and 312.5p/cm. This could mean that we did not test a wide enough range of granularities, or that the timbre levels that were experienced as rough masked the effect of the decreased granularity.

Looking at *amplitude*, we can see that there is a strong linear effect on perceived roughness ($F_{1.216, 27.976} = 49.357$, $p < .001$, $\eta_p^2 = .682$). Post hoc analysis revealed that all levels were significantly different from each other ($p < .005$).

Finally we can see that *timbre* has a steep rising slope between 40Hz and 80Hz. While for 8 participants the experience of roughness peaked at 80Hz, the grand mean continued to rise by an additional 5.45%, peaking at 160Hz, after which the experience of roughness declines. Timbre had a significant effect ($F_{2.554, 58.743} = 49.063$, $p < .001$, $\eta_p^2 = .681$) and post hoc analysis revealed that 40Hz and 320Hz were different from 80Hz and 160Hz ($p < .005$). A contrast confirmed the quadratic nature of the response curve.

Bumpiness

While *granularity* did not have a significant effect on bumpiness (Figure 6, top right), we can see a negative trend. Bumpiness is strongest for granularities below 4.88p/cm. The effect of granularity appears non-linear. It drops between 2.44p/cm and 4.88p/cm but otherwise the negative trend appears negligible.

We consider bumpiness to be equivalent to macro-roughness, and as such expected bumpiness to increase where roughness decreases. The response curve of granularity indeed shows an opposite trend to roughness (Pearson's $r = - 0.84$).

Amplitude had a significant effect on perceived bumpiness ($F_{1.185,\ 27.479} = 41.567$, $p < .001$) though the effect size was somewhat lower than for roughness ($\eta_p^2 = .644$).

The response curve for *timbre* peaks at 80Hz and then directly starts to decline. The effect of timbre was significant ($F_{2.235,\ 51.410} = 25.006$, $p < .001$, $\eta_p^2 = .521$) and had a quadratic response curve. *Timbre* at 80Hz and 160Hz was different from 40Hz and 320Hz ($p < .005$).

Sharpness

Sharpness (Figure 6, bottom left) appears superficially similar to roughness, but there are slight differences which will become more prominent in task two. Low *granularity* was typically not experienced as sharp; there appears to be a significant positive trend ($F_{2.49,\ 57.259} = 7.913$, $p < .001$ $\eta_p^2 = .256$). Beyond 19.53p/cm this effect is weaker, though for 11 participants the experience of sharpness continued to increase at 312.5p/cm.

Amplitude had a significant effect on sharpness ($F_{1.110,\ 25,522} = 17.86$, $p < .001$) but the effect size is much lower than for roughness and bumpiness ($\eta_p^2 = .426$).

The response curves for *timbre* show that the experience of sharpness declined relatively little between 160Hz and 320Hz (for sharpness the decline is 18% of the grand mean, while for adhesiveness it is 24, for bumpiness it is 32% and for roughness it is 46%). In fact, for 9 participants the experience of sharpness increased between these two values. This suggests that high frequency timbre is most likely to lead to sharp sensations. The overall effect of timbre on sharpness was also significant ($F_{2.164,\ 49.772} = 11.903$, $p < .001$, $\eta_p^2 = .341$). Sharpness again lead to a quadratic response curve, however, it was the only experience for which the *timbre* level of 320Hz was not significantly different from 80Hz and 160Hz.

Adhesiveness

Looking at all response curves for adhesiveness, there appears to be high agreement. However, many participants reported that they had difficulty rating adhesiveness. Because of this, we suspect that the lower amount of variance simply means that there were very few moments at which users felt adhesiveness strongly enough to give it a confidently high rating (Figure 6, bottom right). We found statistically significant effects of *granularity* ($F_{4,\ 92} = 4.770$, $p < .005$, $\eta_p^2 = .172$), *amplitude* ($F_{2,\ 46} = 32.212$, $p < .001$, $\eta_p^2 = .583$) and *timbre* ($F_{3,\ 69} = 15.841$, $p < .001$, $\eta_p^2 = .408$).

RESULTS – TEXTURE PRODUCTION

In task two the activity of the participants is inversed. The experiences of texture, which so far have been the dependent measures, have now become a single independent variable, and the feedback parameters which previously were independent variables now become the dependent measures. As expected, we found that experience type had a significant effect on how participants used *granularity* ($F_{3,\ 69} = 2.87$, $p < .05$), *amplitude* ($F_{2.15,\ 61.808} = 7.618$, $p < .005$) and *timbre* ($F_{3,\ 69} = 4.892$, $p < .05$).

Figure 7 shows the number of participants that chose a particular level of a parameter. Note that the peak for high amplitude may appear exaggerated compared to other scales as participants have less options to select from. In

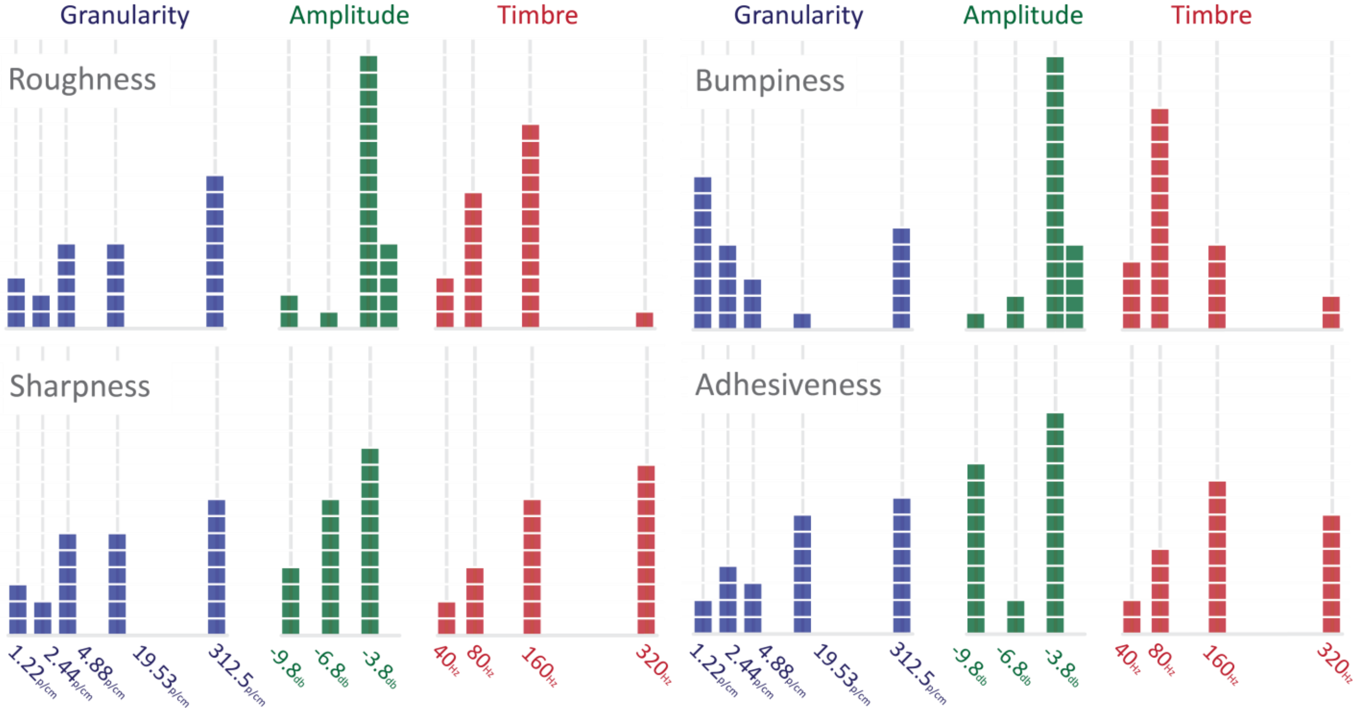

Figure 7 – Each square represents a participants' choice of a parameter when generating a haptic experience.

general, the results from task two agree with the results of task one.

As expected for **roughness** (Figure 7, top left), few participants chose low *granularity* levels. The high number of people who chose 312.4p/cm is also in agreement with our results from task one, but contradicts what we expected. *Amplitude* confirms the previously observed strong effect, while for *timbre* most people chose 160Hz (compare to Figure 6, top left).

Bumpiness (Figure 7, top right) shows that most participants favored the low *granularity* levels, though surprisingly 6 participants chose 312.5p/cm. *Amplitude* again confirms the previously observed effect, and for *timbre* most people also chose 80hz, as expected (compare to Figure 6, top right).

For **Sharpness** (Figure 7, bottom left) more people preferred high *granularity*. We clearly see that *amplitude* is less important, as participants distributed their choice comparatively evenly. Most participants chose the highest *timbre* value, which was expected based on task one (compare to Figure 6, bottom left).

The stand out feature for **Adhesion** (Figure 7, bottom right) is that participants had split opinions on *amplitude*. Almost half felt that lower amplitude lead to a stronger experience of adhesion. *Granularity* and *timbre* were used somewhat as expected, with participants trending towards higher levels (compare to Figure 6, bottom right).

DISCUSSION

The aim of this study was to investigate how actuation parameters relate to haptic experiences. In particular, we have focused on the experiences that can be created from coupling actuation parameters to movement. Next we discuss the main findings on this coupling.

Actuation parameters and haptic experiences

We found that amplitude had a very strong effect, but that it was not equally important for all experiences of texture. Contrary to our expectations, we found a much weaker effect of granularity; however, it does appear to play an important role in distinguishing between micro and macro textures. Finally, we introduce the concept of timbre, which has received very little attention in the context of vibrotactile feedback so far. We found that it had a relatively strong effect and that, within the constraints of the sampling points we collected, it had a quadratic response curve. Our data also indicates some interactions between timbre and granularity which were not intuitively obvious to us. We found that the 312.5p/cm level of granularity had surprisingly high levels for roughness and bumpiness in both tasks. We believe that this was caused by timbre overriding the effect of granularity: while neither roughness nor bumpiness had a granularity level which they were uniquely correlated with, bumpiness was clearly associated with a timbre of 80Hz and roughness was clearly associated with 160Hz. We believe that participants who optimized for timbre in the texture production task chose the highest granularity level as this maximizes the effect of timbre. Conversely, when participants experienced texture with high frequencies, the effect of timbre overrode the effect of granularity.

Timbre can also be used to stimulate a participant at a fixed frequency without the experience of vibration: while an object that receives pulses at 160Hz is experienced as vibrating, an object that receives pulses relative to its motion $(f = Granularity * User\ Motion)$ while resonating at 160Hz is not perceived as vibrating. This may provide interesting opportunities for future studies on haptic perception.

The strong effect that timbre had also suggests that there is value in haptic impulses that do not map linearly to user motion. Recent research on haptic perception also suggests that our haptic experience is not linearly related to how fast we move relative to an object [5]. We expect future work to explore alternatives to the linear mappings that have been used so far.

Methodology and Limitations

Like other magnitude estimation studies on haptic perception [2,4,13,17], the number of levels of independent variables greatly affect the results that can be obtained. As we were interested in capturing interaction effects, we further constrained our number of levels by choosing a factorial design. As we do not anticipate any of the mappings between feedback parameter and experience of texture to be linear, this provides a clear limitation. The precision of our results for granularity and especially for timbre could have benefitted from more levels.

The combination of magnitude estimation and texture production proved interesting, despite each participant merely producing a single texture per experience. Constraining the participant's options to the same levels for both tasks allowed us to easily compare them. Using a continuous scale instead would have allowed us to find the true peaks of the different sensations, which we would like to explore in future work. Magnitude production appears particular appealing for exploring the coupling of actuation parameters and movement, because of the extent to which the sensation is produced by the participants themselves.

Using the Results

While the experiment contributes directly to an understanding of haptic experiences and action-coupled vibrotactile feedback, there are also a number of potential immediate applications of our results. For example, Valve recently released its SteamVR Tracking Hardware Development Kit (HDK) [14]. This HDK enables augmenting virtual reality experiences with custom objects and controllers, which can be augmented with feedback as we describe it. For example, in a virtual kitchen, you could feel the difference between cutting on wood and cutting on stone. While playing virtual golf, you might feel the texture of sand or grass as your golf club touches the ground.

The haptic feedback device that we use is similar to those used in high-end mobile devices [47]. When navigating a foreign city, the methods described in this paper could provide directions by subtly changing the ‘feel’ of directions, for example, making moving north feel smoother than moving east or west.

We see this type of haptic feedback as adding to the repertoire of methods available for the design of Tangible Interfaces. From their inception Tangible Interfaces have been augmented with additional modalities, be it projection [35], shape change [30] or dynamic material properties [22]. Our exploration adds a micro-dimension of digital material surface features, with the intent to move the future of HCI one step further away from ‘pictures under glass’ [36].

CONCLUSION

We presented a method of generating vibrotactile feedback relative to the user’s motion. We demonstrated that this method is able to convey the experience of texture when manipulating a tangible object. Our data suggests that roughness and bumpiness can be separated by granularity while sharpness and adhesiveness appear to be experienced when timbre levels are higher. Roughness is also associated with lower timbre than bumpiness, and both roughness and bumpiness are more dependent on amplitude than sharpness and adhesiveness are. This relation between haptic textures and vibrotactile feedback was demonstrated to be consistent both when participants perceived a texture and had to evaluate it, as well as when participants were asked to create a texture. The findings in this paper can be applied in applications using commodity hardware, as tracking technologies and high-end devices with the necessary haptic actuators are becoming more common.

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REFERENCES

1. Michel Amberg, Frédéric Giraud, Betty Semail, Paolo Olivo, Géry Casiez, and Nicolas Roussel. 2011. STIMTAC: A Tactile Input Device with Programmable Friction. *Proceedings of the 24th Annual ACM Symposium Adjunct on User Interface Software and Technology*: 7–8. http://doi.org/10.1145/2046396.2046401
2. Sliman Bensmaïa and Mark Hollins. 2005. Pacinian representations of fine surface texture. *Perception & psychophysics* 67, 5: 842–854. http://doi.org/10.3758/BF03193537
3. Sliman Bensmaïa, Mark Hollins, and Jeffrey Yau. 2005. Vibrotactile intensity and frequency information in the pacinian system: a psychophysical model. *Perception & psychophysics* 67, 5: 828–841. http://doi.org/10.3758/BF03193536
4. Sliman J. BensmaIa and Mark Hollins. 2003. The vibrations of texture. *Somatosensory & motor research* 20, 1: 33–43. http://doi.org/10.1080/0899022031000083825
5. Daniel J. Brewer, David J Meyer, Michael A Peshkin, and J Edward Colgate. 2016. Viscous Textures: Velocity Dependence in Fingertip-Surface Scanning Interaction. *Haptics Symposium, 2016 IEEE*: 0–5. http://doi.org/10.1109/HAPTICS.2016.7463188
6. Heather Culbertson, Juliette Unwin, Benjamin E. Goodman, and Katherine J. Kuchenbecker. 2013. Generating haptic texture models from unconstrained tool-surface interactions. *2013 World Haptics Conference, WHC 2013*: 295–300. http://doi.org/10.1109/WHC.2013.6548424
7. David Katz. 1989. *The World of Touch*. Lawrence Erlbaum Associates, New Jersey.
8. Robert H. Gault. 1926. Touch as a Substitute for Hearing in the Interpretation and Control of Speech.
9. George A. Gescheider. 1988. Psychophysical Schaling. *Ann. Rev. Psychol* 39: 169–200.
10. Marcello Giordano, Stephen Sinclair, and Marcelo M. Wanderley. 2012. *Bowing a vibration-enhanced force feedback device*. University of Michigan.
11. Sung H. Han, Maengkee Song, and Jiyoung Kwahk. 1999. A systematic method for analyzing magnitude estimation data. *International Journal of Industrial Ergonomics* 23, 5: 513–524. http://doi.org/10.1016/S0169-8141(98)00017-1
12. Ali Israr and Ivan Poupyrev. 2011. Control space of apparent haptic motion. *2011 IEEE World Haptics Conference*: 457–462. http://doi.org/10.1109/WHC.2011.5945529
13. I. Darian-Smith J.W. Morley, A.W. Goodwin. 1981. Tactile Discrimination of Gratings. *Experimental Brain Research* 9: 146–158.
14. Programmer Joe. 2016. SteamVR Tracking HDK. *SteamVR Tracking HDK > General Discussions*. Retrieved September 21, 2016 from http://steamcommunity.com/app/507090/discussions/0/360671247404603033/
15. Lynette A. Jones and Hong Z. Tan. 2013. Application of psychophysical techniques to haptic research. *IEEE Transactions on Haptics* 6, 3: 268–284. http://doi.org/10.1109/TOH.2012.74

16. Johan Kildal. 2010. 3D-press: haptic illusion of compliance when pressing on a rigid surface. *International Conference on Multimodal Interfaces and the Workshop on Machine Learning for Multimodal Interaction on - ICMI-MLMI '10*, ACM Press. http://doi.org/10.1145/1891903.1891931

17. Ryo Kitada, Toshihiro Hashimoto, Takanori Kochiyama, et al. 2005. Tactile estimation of the roughness of gratings yields a graded response in the human brain: An fMRI study. *NeuroImage* 25, 1: 90–100. http://doi.org/10.1016/j.neuroimage.2004.11.026

18. Roberta L. Klatzky, Dianne Pawluk, and Angelika Peer. 2013. Haptic perception of material properties and implications for applications. *Proceedings of the IEEE* 101, 9: 2081–2092. http://doi.org/10.1109/JPROC.2013.2248691

19. Susan Lederman. 1989. Tactile roughness of grooved surfaces: The touching process and effects of macro and microsurface structure. *Perceptual Psychology* 15: 45–57.

20. Vincent Lévesque, Louise Oram, Karon MacLean, J. Edward Colgate, and Michael a. Peshkin. 2011. Restoring physicality to touch interaction with programmable friction. *Digest of Technical Papers - IEEE International Conference on Consumer Electronics*: 61–62. http://doi.org/10.1109/ICCE.2011.5722773

21. G. E. Loeb and J. A. Fishel. The Role of Fingerprints in Vibrotactile Discrimination. *White paper for DoD Physics of Biology* https://researchgate.net/publication/266874623_The_Role_of_Fingerprints_in_Vibrotactile_Discrimination

22. Ken Nakagaki, Luke Vink, Jared Counts, et al. 2016. Materiable: Rendering Dynamic Material Properties in Response to Direct Physical Touch with Shape Changing Interfaces. *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, 2764–2772. http://doi.org/10.1145/2858036.2858104

23. Takaaki Nara, Takasaki Masaya, Tachi Susumu, and Higuchi Toshiro. 2000. An Application of SAW to a Tactile Display in Virtual Reality. *IEEE Ultrasonics Symposium*: 1–4.

24. Takaaki Nara, Masaya Tkasaki, Taro Maeda, Toshiro Higuchi, Shigeru Ando, and Susumu Tachi. 2001. Surface Acoustice Wave (SAW) Tactile Display Based on Proporties of Mehanoreceptors. *Proceedings of the Virtual Realtiy Conference*.

25. Shogo Okamoto, Hikaru Nagano, and Yoji Yamada. 2013. Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics* 6, 1: 81–93. http://doi.org/10.1109/ToH.2012.32

26. Shogo Okamoto, Hikaru Nagano, and Yoji Yamada. 2013. Psychophysical dimensions of tactile perception of textures. *IEEE Transactions on Haptics 6*, 81–93. http://doi.org/10.1109/ToH.2012.32

27. Daniel Pargman and Peter Jakobsson. 2007. Five perspectives on computer game history. *interactions* 14, 6: 26. http://doi.org/10.1145/1300655.1300674

28. Ivan Poupyrev, Shigeaki Maruyama, and Jun Rekimoto. Ambient Touch: Designing Tactile Interfaces for Handheld Devices. Retrieved July 12, 2016 from http://www.csl.sony.co.jp/IL

29. Ivan Poupyrev, Makoto Okabe, and Shigeaki Maruyama. 2004. Haptic feedback for pen computing: directions and strategies. *Screen*: 1309–1312. http://doi.org/10.1145/985921.986051

30. Majken K. Rasmussen and Esben W Pedersen. 2012. Shape-changing interfaces: a review of the design space and open research questions. *CHI*: 735–744. Retrieved May 16, 2014 from http://dl.acm.org/citation.cfm?id=2207781

31. Joseph M. Romano and Katherine J. Kuchenbecker. 2012. Creating realistic virtual textures from contact acceleration data. *IEEE Transactions on Haptics* 5, 2: 109–119. http://doi.org/10.1109/TOH.2011.38

32. Brandon Shrewsbury. 2011. Providing Haptic Feedback Using the Kinect. *Journal of Rehabilitation Research*: 321–322. http://doi.org/10.1145/2049536.2049628

33. S. S. Stevens. 1955. The Measurement of Loudness. *The Journal of the Acoustical Society of America* 27, 5: 815.

34. Paul Strohmeier, Jesse Burstyn, Juan Pablo Carrascal, Vincent Levesque, and Roel Vertegaal. 2016. ReFlex: A Flexible Smartphone with Active Haptic Feedback for Bend Input. *Proc. TEI '16:*, 185–192. http://doi.org/10.1145/2839462.2839494

35. Brygg Ullmer and Hiroshi Ishii. 1997. The metaDESK: models and prototypes for tangible user interfaces. *Proceedings of the 10th annual ACM symposium on User interface software and technology - UIST '97*: 223–232. http://doi.org/10.1145/263407.263551

36. Bret Victor. 2011. A brief rant on the future of interaction design. *worrydream.com*. Retrieved September 21, 2016 from http://worrydream.com/ABriefRantOnTheFutureOfInteractionDesign/

37. Laura Winfield, John Glassmire, J Edward Colgate, and Michael Peshkin. T-PaD: Tactile Pattern Display through Variable Friction Reduction.

38. Matthew Wright and Adrian Freed. 1997. Open Sound Control: A New Protocol for Communicating with Sound Synthesizers. *Proc. ICMC 1997*, International Computer Music Association, 101–104. Retrieved from

http://cnmat.berkeley.edu/publication/open_sound_control_new_protocol_communicating_sound_synthesizers

39. Juan Wu, Na Li, Wei Liu, Guangming Song, and Jun Zhang. 2015. Experimental Study on the Perception Characteristics of Haptic Texture by Multidimensional Scaling. *IEEE Transactions on Haptics* 8, 4: 410–420. http://doi.org/10.1109/TOH.2015.2438866
40. Danfei Xu, Gerald E. Loeb, and Jeremy A Fishel. 2013. Tactile identification of objects using Bayesian exploration. *IEEE International Conference on Robotics and Automation (ICRA)*.
41. Hsin-yun H.-Y. Yao and Vincent Hayward. 2006. An Experiment on Length Perception with a Virtual Rolling Stone. *Proc. EuroHaptics Int. Conf.*: 275–278.
42. Hsin-Yun Yao and Vincent Hayward. 2010. Design and analysis of a recoil-type vibrotactile transducer. *The Journal of the Acoustical Society of America* 128, 2: 619–27. http://doi.org/10.1121/1.3458852
43. Takashi Yoshioka, James C Craig, Graham C Beck, and Steven S Hsiao. 2011. Perceptual constancy of texture roughness in the tactile system. *J Neurosci* 31, 48: 17603–17611. http://doi.org/10.1523/JNEUROSCI.3907-11.2011
44. Siyan Zhao, Ali Israr, and Roberta Klatzky. 2015. Intermanual apparent tactile motion on handheld tablets. *IEEE World Haptics Conference, WHC 2015*: 241–247. http://doi.org/10.1109/WHC.2015.7177720
45. Siyan Zhao, Oliver Schneider, Roberta L. Klatzky, Jill Lehman, and Ali Israr. 2014. FeelCraft: crafting tactile experiences for media using a feel effect library. *Proceedings of the adjunct publication of the 27th annual ACM symposium on User interface software and technology*, 1: 51–52. http://doi.org/10.1145/2658779.2659109
46. Siyan Zhao, Zachary Schwemler, Adam Fritz, and Ali Israr. Stereo Haptics: Designing Haptic Interactions using Audio Tools Studio-Workshops TEI. http://doi.org/10.1145/2839462.2854120
47. 2015. Apple’s “force touch” and “taptic engine” explained. *www.theguardian.com*. Retrieved September 21, 2016 from https://www.theguardian.com/technology/2015/mar/11/apples-force-touch-taptic-engine-explained-haptic-technology