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Enriching passive touch sensation on flat surfaces using visual feedback

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Abstract

While human computer interaction has evolved around touch interaction a lot in recent years, it's been lacking any haptic feedback from the very beginning. Nowadays, devices using touch interaction all to do on a flat surface, using either a projection of digital contents or a touch screen. Since haptic feedback is an important factor in human surface perception, people have tried various ways to simulate haptic feedback even on completely flat surfaces. One of these ways is electrotacile feedback, which has mostly been used to simulate surface properties on active touch where the user has to move their finger over the surface in order to feel the haptic sensation. Previous research shows that vision is also a very important factor in surface perception and proprioception in general.

We conducted a user study to investigate the influence of visual feedback on passive touch using electrotactile feedback. We concentrated on simulating depth instead of roughness which doesn't word particularly well for passive touch. We found that even though both electrotactile and visual feedback work well for depth or softness if applied individually, as soon as we presented our study subjects a condition with both feedback types, they did not repond to it anymore.

Während sich die Mensch-Computer-Interaktion in den letzten Jahren stark um Touch-Interaktion entwickelt hat, hat dieser Interaktion von Anfang an jegliche Form des haptischen Feedbacks gefehlt. Heutzutage nuten alle touchfähigen Gerate flache Displays oder Projektionen von digitalen Inhalten auf flache Oberflächen. Da haptisches Feedback ein wichtiger Faktor der menschlichen Oberflächenwahrnehmung ist wurden schon viele Wege erforscht um haptisches Feedback auf komplett flachen Oberflächen zu simulieren. Eine dieser Wege ist elektrotaktiles Feedback was bisher hauptsächlich benutzt wurde um Oberflächeneigenschaften bei aktiver Berührung zu simulieren, also bei einem sich bewegenden Finger auf der Oberfläche. Vorige Studien zeigen auch, dass Visuelle Reize ein wichtiger Faktor bei der Oberflächenwahrnehmung sind und sogar die Wahrnehmung im Generellen dominieren.

Wir haben eine Benutzerstudie durchgeführt um den Einfluss von visuellem Feedback auf passive Berührungen mit elektrotaktilem Feedback zu bestimmen. Wir haben und auf die Simulaton von Tiefe statt Rauhheit konzentriert, was schlecht mit passiven Berührungen funktioniert. Unsere Studie hat gezeigt dass obwohl das elektrotaktile und das visuelle Feedback alleine gut funktionieren um Weichheit oder Tiefe zu simulieren, beide Feedbackarten zusammen keine signifikanten Unterschiede erzielen.

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1 Introduction

Touch interaction has gained a lot of attention in recent years and nowadays more and more devices can be controlled using touch input, from mobile phones over laptops and public displays to train ticket machines. People today are fairly used to touch input techniques and using different gestures for different purposes, but the surfaces are always flat or just slightly curved.
This has been the case mostly for practical reasons since projecting an image onto a non-flat surface is hard or impossible and rough and/or non-flat surfaces or touchscreens can only be used for a very specific purpose since the roughness and form of the display does not adapt to the displayed contents.

In order to overcome this problem and create a surface that adapts to different displayed contents and their desired surface properties, multiple different approaches have been researched and implemented. Those that can be categorized as delivering “electrotactile feedback” all use electric current and electrodes attached to the user in order to deliver a haptic sensation that cannot be otherwise experienced on a flat surface. The most well-known example is the TeslaTouch[BPIH10] from Disney Research which tries to deliver different forms of roughness to the user’s fingers on active touch, i.e. the finger has to be moved in order to feel the sensation. It uses instrumented objects (i.e. the power source is mounted to the object) instead of intrumented users, which is what the Revel[BP12] does – instrumented users enable higher grades of flexibility since only one user has to be instrumented and not multiple objects. However, both TeslaTouch and Revel only deliver a sensation to a moving finger. As soon as the user stops moving their finger on the surface, they stop getting any kind of haptic sensation from those devices.

Older devices used to deliver electrotactile feedback using dense arrays of electrodes. They were capable of delivering different sensations for different parts of the touched surface (i.e. one voltage and/or frequency pattern per electrode), but made it impossible to instrument existing objects or users. They also make it impossible to deliver a visual sensation at the same time since mounting dense arrays of non-translucent electrodes on a touchscreen would make it impossible to see the screen and projecting onto such a dense electrode array requires the electrodes to be white or at least very bright. This makes the dense electrode arrays impossible to use for a large number of use cases since delivering haptic feedback alone is not something a lot of devices require.

However, existing research regarding electrotactile feedback on flat surfaces concentrates on *active touch* where users have to move their fingers over a surface in order to feel the sensation delivered by the electrotactile feedback device. This is useful for a variance of surfaces, applications and surface properties. In our case however, we wanted to research the effects of electrotactile feedback on passive touch where the users don't have to move their fingers. Passive touch is not usable for most sensations generated by active touch, e.g. roughness is something people only feel when moving their fingers over a surface, but when only touching it, roughness is not a dominant sensation. On the other hand, passive touch is perfect for sensations like softness or depth.

We took an existing TENS device which is normally used in medical environments to treat pain and combined it with a pico projector to additionally deliver a fitting visual representation of the pressure applied to our surface, as well as a visual representation of a surface material. We implemented the visual pressure representation by deforming the texture in a way that makes it look like it's pressed into the surface. This deformation was applied in real-time using the pressure data delivered by the pressure sensor we mounted directly below our projection surface. To reduce the delay between the user pressing the surface and the PC rendering the image as small as possible, we used an OpenGL application to render the deformed texture in a performant way.
To coordinate all data, we used an Arduino UNO, which received the pressure data from the pressure sensor and sent it to a PC over a serial connection. The Arduino was also used to adjust the TENS device's output frequency to a rectangular pattern. The TENS device does not need the finger to move in order to deliver electrotactile feedback which makes it suitable for this use case.

We conducted a user study using our apparatus. We collected images of ten different materials (cardboard, cloth, corkboard, fur, grass, jam, leaf, sponge, styrofoam, wood) in order to cover ten surface properties (softness, stretchability, smoothness, thickness, density, dampness, solidness, viscosity, stickiness, formability) we found to be interesting for the sensation of electrotactile feedback on passive touch.
We let each participant of our study press the surface of our apparatus five times per condition. We had four different conditions with ten different textures per condition, resulting in 200 touches per study participant. After pressing the surface five times, each participant filled in a questionnaire about their haptic perception of the surface, which consisted of seven-point Likert scales for each surface property, resulting in 400 data points per participant. We were able to recruit 16 participants from the local university campus to take part in the study.

Our hypothesis was that haptic electrotactile feedback and visual feedback would work together well and generally produce a sensation even better than each of the feedback types on their own. This was based on previous research showing that vision is a very dominant factor when it comes to surface perception or even dominating proprioception entirely. Similarly, delivering a haptic sensation using electrotactile feedback from a TENS device has been proven to significantly alter the subjects' perception of certain material properties[Die], .

However, the results of our user study show that while both haptic and visual feedback individually result in measurable differences of the subjects' surface perception, no statistically significant difference can be measured when both are enabled simultaneously. Both haptic and visual feedback individually lead to stronger perceptoin of “soft” surface properties (softness, stretchability, bendability) and to weaker perception of “hard” surface properties (thickness, solidness, hardness) when enabled. We could not measure any statistically significant differences in the remaining surface properties density, dampness, viscosity and formability.

2 Related Work

Electrovibration was discovered by Mallinckrodt et al. in 1954 [MHSJ53]. They reported that a smooth metal surface covered with a thin insulating layer and connected to a 110V power line caused the surface to feel less smooth, the generated feeling was also described as “resiny”.

Previous work tried to deliver haptic feedback using electrovibration through opaque electrode patterns[ST70] [TB98], instrumented conductive surfaces[BPIH10] or instrumented users [BP12] – but basically all research concentrated on active touch perception and roughness modulation whereas passive touch was completely neglected.

2.1 Electrotactile Feedback

Using opaque patterns of electrodes makes it possible to deliver multiple different sensations at the same time but makes integration into existing objects hard or impossible. The work of Strong et al.[ST70] used a dense array of electrodes, each roughly 1.7mm in diameter. Multiple different experiments were conducted and the participants reported two distinct types of sensations: one of which felt like the sensation appears deep in the finger, concentrated at the joints. This sensation was reported to be unpleasant and to not carry much relevant information about the presentation. The second sensation was reported by test subjects with dry fingers, i.e. high skin resistance. If the participant moved their finger lightly, a texture could be felt.

An instrumented user makes using existing objects easy. Since the user themself carries the source of electricity, every conducting surface can be used to deliver haptic feedback. This technique is also known as *reverse electrovibration*[BP12]. If the user then slides their finger over a surface, they feel a distinctive tactile texture additionally to the object’s normal material properties. Since not the object itself but the user gets instrumented with an electronic device and the electrical signal can be injected anywhere on the user’s body, there’s no need for them to wear any kind of glove or anything else that would restrain them from interacting naturally with their environment. Another important drawback is that no haptic feedback can be deliverd using this method if the user is not moving their finger (i.e. only on *active touch*).

Using electrovibration on flat surfaces has been done in the past using instrumented objects and conductive surfaces[BPIH10]. This is especially interesting using traditional touch screens since it makes it easy to deliver visual feedback alongside the haptic feedback. The work of

Bau et al. compared multiple different interaction techniques for existing user interfaces but also explored applications unique to electrovibration, even utilizing the fact that still fingers remain unactuated – which is also the system's biggest weakness. The executed experiment exposed participants to different frequencies and voltages with four combinations in total.

Yoshimoto et al. used electrotactile surface feedback to alter the roughness perception of materials[YU]. They conducted a user study where each participant explored four different materials augmented with the electrotactile feedback system. For each trial, the participant wore headphones and electrodes on their right index finger. They explored the material and were later asked to to rate the perceived fine and macro roughness by comparing them with reference materials. The electrotactile feedback used in the study causes both pressure and vibrotactile sensation to happen at the same time. The study's results indicated that a stimulus with modulation gain greater than 20 causes various fine- and macro-roughness perception alterations. Especially the fusion between real tactile feedback and the augmented electrotactile feedback has been reported by the participants. However, the used way of delivering electrotactile feedback made it impossible to test high pulse densities since participants could not discriminate them because of sensory adaption[Kac00].

2.2 Multisensory Surface Perception

Generally, simulating haptic feedback such as friction or stiffness without an actual haptic interface is referred to as *pseudo-haptic feedback*[Léc09]. Most if not all the previous work with this technique used visual cues although pseudo-haptic feedback is not necessarily restricted to vision.

It's also been proven that visual perception is strong enough for users to be able to identifty holes and bumps in pseudo-haptic textures[LBE04]. This experiment manipulated the user's visual perception of a supposedly flat texture only by altering the Control/Display ratio of the user's mouse cursor. Using only this visual queue, participants in user study were able to identify both holes and bumps and draw their profile on a sheet of paper. Similar work includes the perception of texture, resistance and spatial depth[WY08].

In 2008, Bibin et al. implemented a medical simulator with visual and pseudo-haptic feedback[BLB$^+$08]. In this case, the user had to "feel" the inner organs when pressing the skin of the patient he wanted to anesthetize. The pseudo-haptic feedback was implemented without any haptic device using only a standard computer and mouse. Instead, pseudo-haptic textures[LBE04] were used which make it possible to feel the relief of a picture using only visual feedback and an input device.

It's been shown that vision dominates during conflicts between haptic and visual feedback[SL95] when simulating stiffness, but also at the perception of friction and texture[Léc09]. Vision is even considered to generally dominate proprioception[WW86], which makes it the ideal candidate to enrich other sensations. Visual feedback has thus far often been used to simulate haptic feedback[LBE04] [BLB$^+$08][WY08] but although Bau et al. used real haptic (electrotactile) feedback and used it on visual applications using a common touch screen, they did not try to enhance the touch sensation of specific materials such as cotton or leather.

The strong connection between the human mind and the human perception of texture can also be seen in studies investigating the relation between psychophysical affective factors of texture perception[NOY]. Nagano et al. created a semantically multi-layered structure of tactile textures using psychophysical, affective and preferential layers. They conducted an experiment in which every participant touched different (real) materials and evaluated the causalities using different adjective pairs for the three layers, e.g. rough/smooth for the psychophysical layer, comfortable/uncomfortable for the affective layer and rich/poor for the preferential layer. The result is a three-layered map of all the adjectives used and the influential relationship between them.

When trying to make touch interaction with flat surfaces more realistic, even latency can play a great role. Kaaroseja et al. executed an experiment that showed that delaying the tactile feedback of a common touchscreen can indicate heavier buttons to the user[KAH11]. The experiment compared number and text input of a touch screen device augmented with piezo-based tactile feedback that was delayed by different amounts of time. They compared both performance (i.e. speed of input and number of errors) and user expierience (i.e. subjective satisfaction) of all the latencies. The surprising outcome was that performance does not suffer significantly when increasing the delay between interaction and tactile feedback. However, the users were less satisfied with higher latencies. Participants of the study also often described the buttons with longer latency as “heavier” and and used more force when pressing them.

The results regarding tactile feedback latency were confirmed by a second experiment also carried out by Kaaresoja et al.[KHA11] where the latency was even changed between different keypresses. The variable latency keyboard was again considered to take more force to press the buttons and users even commented that there is something seriously wrong with the keypad and that it was horrible to use. In the questionnarie each participant filled out, the keyboard with the largest delay variation clearly scored the worst satisfaction. The results indicate that users can tolerate a tactile feedback latency variation between 0 ms and 20.0 ms, but wider delay variations worsen user performance significantly. In this study, the users were also directly asked for a weight rating for different buttons so the user comments from the authors' earlier work[KHA11] can be confirmed. Even though earlier research regarding weight has been known to indicate that vision dominates[MEBR99][MK02], these findings can be used to manipulate the user's perception regarding weight of certain interface elements on traditional touchscreen devices.

Certain research also tries to influence touch behavior and/or perception using sound. An example is Foobar et al. who let participands touch a flat surface and played a sound which got distorted based on the applied pressure to the table. Their study suggests that sound can significantly alter the perceived temperature as well as the type of texture. When certain sonuds were played to the participants during the study, they reported the surface to be colder, or more paper-like.

2.3 Related Psychological Phenomena

When grasping objects, texture can have siginificant effect on the force applied to the object[WMBT]. Bergmann Tiest et al. designed an experiment in which the participants grasped cubes covered with different textures. They used pressure sensors glued to the side of the cubes to messure the grip strength for each participant. The sensors were individually adjusted for each participant to compensate for differences in strength. The results showed that the cube's texture influences the applied force even in the very early stages of grasping (the first 10ms).

Another application of pseudo-haptic textures are the Elastic Images from Argelaguet et al.[AJML13] that used a common computer screeen and a mouse as input device. The pseudo-haptic feedback was implemented in form of texture deformation to simulate elasticity which was then (also) paired with different ways of changing the mouse cursor color and shape. The deformed textures were generated from their respective undeformed base textures and augmented with procedural shadows to simulate creases.

Botvinick et al. showed that humans can feel touch on their body by only seeing another limb getting touched[$\text{BC}^{+}98$]. They executed an experiment where each test subject involved sat at a table with their left hand hidden behind a standing screen. A life-sized rubber replica of a human left hand was placed on a table right in front of them and the subject fixed their eyes on that hand during the experiment. Now both the rubber hand and the real hand were both simultaneously touched with a small paintbrush. To strengthen the illusion, the strokes on both hands were synchronized as closely as possible. After being exposed to the sensation for 10 minutes, all participants filled out a questionnaire. The completed questionnaires indicated that participants feeled the paintbrush's sensation not like their hidden hand did, but more like the rubber hand right in front of them had felt the touch.

2.4 Paper Overview

Reference	**Technology**	**Stimulus**	**Input Technique**	**Findings**	**Relevance**
Semantically Layered Structure of tactile textures [NOY]	-	Touch	Direkt physical touch	Multi-layered graph of different material properties and their influences	Low
The influence of material cues on early grapsing force [WMBT]	Pressure sensors	Touch	Direct physical touch	Texture influences very early grasping force (first 10ms)	Low
Roughness Modulation of Real Materials using Electrotactile Augmentation [YU]	Electrotactile Feedback	Touch	Direkt material touch + electrotactile augmentation	electroctactile feedback can be effectively fused with real sensation	High
Analysis of haptic perception of materials by multidimensional scaling and physical measurements of roughness and compressibility [BTK06]	Material samples glued to uniform wood squares	Touch	Direct physical touch	2D-diagram of similarities between materials	Low
The effect of tactile feedback latency in touchscreen interaction [KAH11]	Common touch screens augmented with piezo-based tactile feedback	Touch	Piezo-based tactile feedback	Longer latencies do not affect performance, but subjective satisfaction	Low

Reference	Technology	Stimulus	Input Technique	Findings	Relevance
Playing with tactile feedback latency in touchscreen interaction: two approaches [KHA11]	Common touch screens	Touch/ Sound	Piezo-based tactile feedback and its generated sound	Longer latencies do not affect performance, but subjective satisfaction + users tolerate latency as long as it's constant	Low
An Electrotactile Display[ST70]	Array of small electrodes	Touch		Subjects reported two different touch sensations (with dry and wet fingers)	High
Using Sound in Multi-Touch Interfaces to Change Materiality and Touch Behavior [sou]	Dymanic sound modification/ Piezo-based pressure detection	Sound/ Touch	Participants touch a table, emitted sounds gets modified based on the applied pressure	Auditory feedback significantly affects the perceived coldness and likness judgements of paper and sandpaper	High
VisualHaptics: Generating Haptic Sensation Using Only Visual Cues [WY08]	Common PC	Vision	Mouse Input	By changing the shape, movement and size of a common mouse cursor, a broad range of people was able to experience different haptic sensations using only visual cues	Medium

Table 2.1: Overview of related work, showing the used technology, the stimulus that was manipulated, the input technique, the findings and the relevance of each paper to this thesis. Notice the missing research regarding passive touch sensation.

2.5 Summary

A lot of research has been done regarding electrotactile feedback, both for enhancing/altering and generating texture perception. There are various ways of generating haptic electrotactil efeedback, from dense arrays of electrodes over instrumented users and instrumendet objects. Basically all the current research is about *active* touch and passive touch remains mostly unexplored.

Most of the related work of psychological nature shows either that visual feedback is important for texture perception, that texture perception gets more realistic with multiple senses or that senses that seem unrelated to tetxure perception like vision or sound can in fact influence it.

3 Method

To evalutate the proposed method of delivering visual feedback alongside electrotactile feedback, we conducted a study to investigate the effect of visual feedback on passive touch augmented with electrotactile haptic feedback.

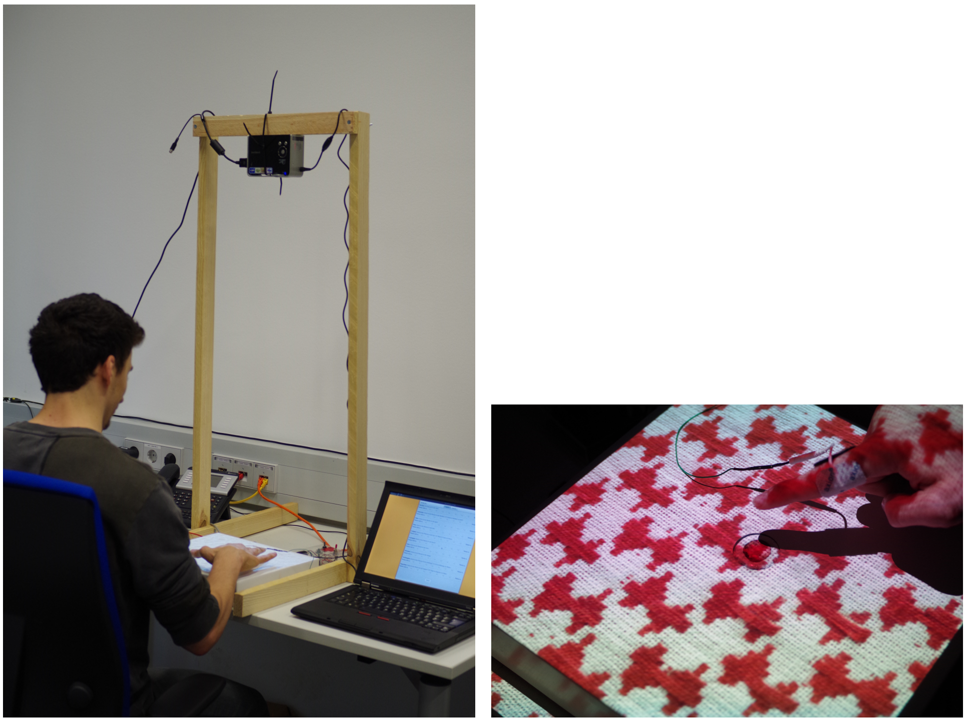

Figure 3.1: The study setting.
Left shows the projector mounted above the projection surface as well as Laptop2 (see Figure 3.2) running the questionnaire software.
Right shows the jam texture projected on the projection surface, as well as the electrode on the subject's right index finger. The circle in the center of the surface is the copper plate used as the second electrode.

3.1 Participants

16 unpaid volunteer participants from the local university campus (4 female) at the age between 20 and 43 (mean 25.8, SD 5.75) participated in the experiment. 2 of them were left-handed.

4 of the 16 participants reported to regularly do some activity that causes callused skin on their hands. None of them had any prior injuries on the index finger of their right hand.

All the demographic data has been collected using a short questionnaire each participant filled out right before they started with the actual experiment.

3.2 Task

We told each participant to press the surface for one second. We indicated the end of a one-second press using a short beep sound and did not tell the participants how hard to press.

3.3 Procedure

The experiment was performed in a shaded room. All participants first answered a questionnaire of three questions regarding their demographic background and

We then attached an electrode to the index finger of each participant's right hand and adjusted the voltage to a level that is neither hurtful nor uncomfortable to them but still generates a distinctive haptic sensation. We did this by settings the voltage to the lowest possible level ($9\,\mathrm{V}$) and slowly increasing it until the participant feld a slight sensation on their index finger. We then proceeded and increased the voltage slightly more.

Every participant pressed their index finger on the cloth for one second, five times per texture. Although the texture deforms according to the pressure applied and the pressure sensor only measures a maximum of about $20\,\mathrm{N}$, and only detects pressures greather than $0.2\,\mathrm{N}$. During the procedure, all participants were instructed to wear headphones to suppress the buzzing sound coming from the TENS device. To not disturb the user too much, we did not give them any visual indicator as to how long or how often they have been touching the surface. Instead, we played a beep sound after every one-second touch and a different one after the user completed the five touches of one texture, to indicate that they are now done with this texture and that we will switch to the next texture.

We used a second laptop for the participants to fill out the questionnarie, which made it easy for us to work with the results but also protected the participants from fatigue effects since they all used their right index finger to use the laptop's trackpad.

3.4 Apparatus

We mounted the pico projector $110\,\mathrm{cm}$ above a table, pointing down on a $30 \times 30cm$ piece of white iron sheet where we projected the texture onto. The projector has a resolution of $1024 \times 768\,\mathrm{px}$ and a brightness of $25\,\mathrm{Lumen}$which together with the white iron sheet and the shaded room is enough to generate a clear picture of the texture. The tables were $150\,\mathrm{cm}$ above the ground and height of the chair we used was configurable as to not block the view of any participant with the projector.

The TENS device was connected to a $230\,\mathrm{V}$ power plug and to the Arduino Uno, which was in turn connected to a ThinkPad T410s laptop and the pressure sensor. The laptop ran the custom software that logged pressure data and displayed the texture on the projector, which was also connected to it.

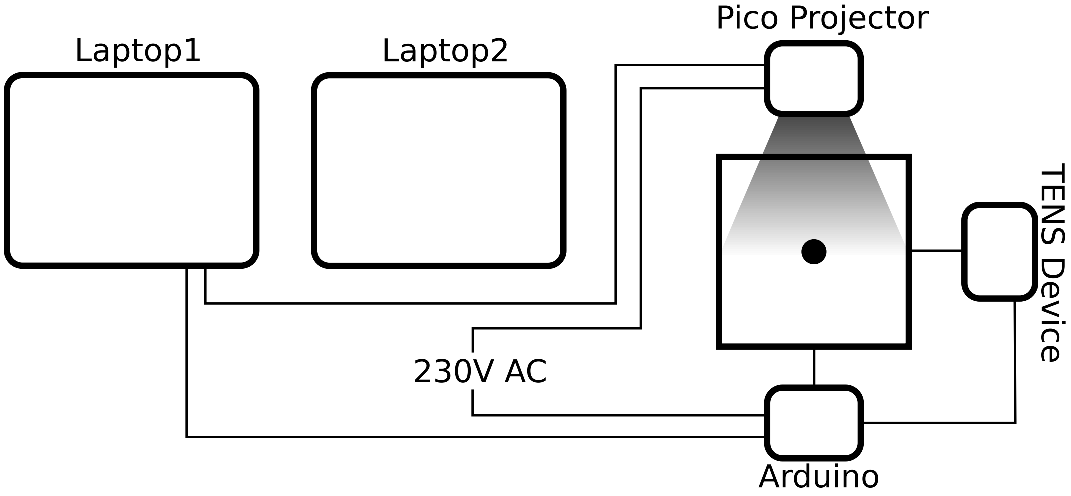

Figure 3.2: Overview of the experimental setup including all the devices used.

3.4.1 Hardware

During the user study, we used 2 laptops of type Thinkpad T410s, called Laptop1 and Laptop2 in Figure 3.2. Laptop2 was used to display an application which let the user answer a set of questions regarding their haptic perception of the presented texture and feedback combination.

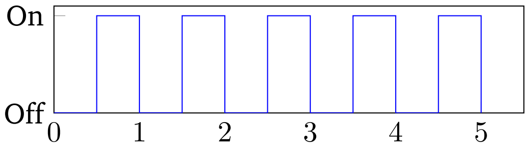

Figure 3.3: Five second sample of the used frequency pattern “f1stim05pause05”. The time-based on/off switching of the stimulus was performed on an Arduino UNO while the stimulus itself was generated by a TENS device.

Laptop1 was used to run an OpenGL application to deform the texture and was also connected to our prico projector in order to deliver the visual feedback accordingly.

To display the texture on a surface, we used a *Samsung Pocket-Imager*, mounted roughly 1.1 m above the table, hooked up to Laptop1. This produces an image roughly 30 × 30 cm in size, which roughly covers the entire are of our projection surface. The projector is hooked up to both a 230 V AC power source and to Laptop1 via a VGA plug, providing it with a 1024 × 768 px video input. It features a contrast of 1000:1 and a brightness of 25 Lumen. To keep the entire apparatus dismountable and light (for better transportation), we used wood latches and thumbscrews.

We used an Arduino UNO[1] to generate the frequency for the TENS device. It is hooked up to a 230 V AC power supply to get the required energy for the up to 80 V needed in order to generate the haptic sensation. It also reads the data from the pressure sensor and sends it to Laptop1 over a serial USB connection. The accuracy of Microsoft Windows’ timer caused us to lose a slight bit of the pressure data since it only reports one timestamp per 10 ms.

We used a 30 × 30 cm white iron sheet panel with a thickness of 0.6 mm. We placed a copper plate of 2 cm diameter in the center of it, which acted as the second electrode and was connected to the TENS device in order to create the haptic feedback. Directly below the copper plate, we placed a pressure sensor which reports pressure data back to the Arduino. Additionally, the surface is 3 cm above the ground to placee the arduino beneath it and give some space for us to arrange the pressure sensor.

To generate the haptic feedback, we use a TENS (*transcutaneous electrical nerve stimulation*) device, which is normally used in medical environments to treat pain. It gets the frequency to use from the Arduino, where we can also disable the frequency completely, but not the applied voltage. We used a rectangular frequency pattern we call *f1stim05pause05*, i.e. we used a frequency of 1 Hz, which we activate/deactivate for intervals of 0.5 s. Figure 3.3 shows a small example timeline. This has previously proven to cause significant differences in some of the surface properties we used in our questionnaire[Die]. The TENS device we used features a

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[1] http://www.arduino.cc

potentiometer on top of it which we used in the study to dynamically adjust the output voltage to every participant.

The pressure the user applies to the surface is used to dynamically deform the texture. To measure it, we used an Interlink Electronics FSR 406 [2] pressure sensor. It has an active area of about $4 \times 4\,\mathrm{cm}$ and measures forces between $0.2\,\mathrm{N}$ and $20.0\,\mathrm{N}$. The Arduino receives the pressure information and maps it into a signed byte range of $[0, 127]$ and sends it to the Laptop1 over a serial connection. Since the pressure sensor is very sensitive at low pressure ranges, we used a threshold to detect if the user is really pressing on the sensor. Visually, this made no difference to our subjects, but it made it possible for us to keep the study data correct (i.e. we did not wrongly detect a very small pressure value as an actual press from one of the participants).

3.4.2 Software

The PC is running the software that displays and deforms a texture. It uses OpenGL[3] to render the texture. It's written in Java and uses LWJGL[4] to access OpenGL. The texture is rendered in 3D-Space and displays it on a grid of 50×50 vertices. Each of these vertices gets transformed according to its distance to the texture center using to a function that describes this deformation. We used a deformation function $def(x, p, r)$ where x is the distance of a point to the texture center (which was also the coordinate system's base point), r is the radius of the deformation/hole in the texture and p is the maximum depth of the deformation. Since we are using a cosin function, we also constrain the deformation to the radius defined by r. The software applied te deformation on-the-fly using a vertex shader. See Figure 3.4 for an example of the `def` function and Figure 3.5 for an example of the function applied to a texture. For the user study, we tried a handful of different values for p and finally decided that $p = 1.2$ is the most interesting one that still shows a visible texture deformation without being completely unrealistic.

$$def(x, p, r) = \begin{cases} \frac{p}{2} \cdot cos\left(\frac{1}{r} x\pi\right) + \frac{p}{2} & x \leq r \\ 0 & \text{else} \end{cases} \tag{3.1}$$

The texture spans over a quad of the size 2×2, the hole (i.e. the deformation) has a size of 0.15×0.15 and is located in the center of the texture. The final projection of the texture was

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[2] `http://www.interlinkelectronics.com/FSR406.php`

[3] `http://www.opengl.org`

[4] `http://www.lwjgl.org`

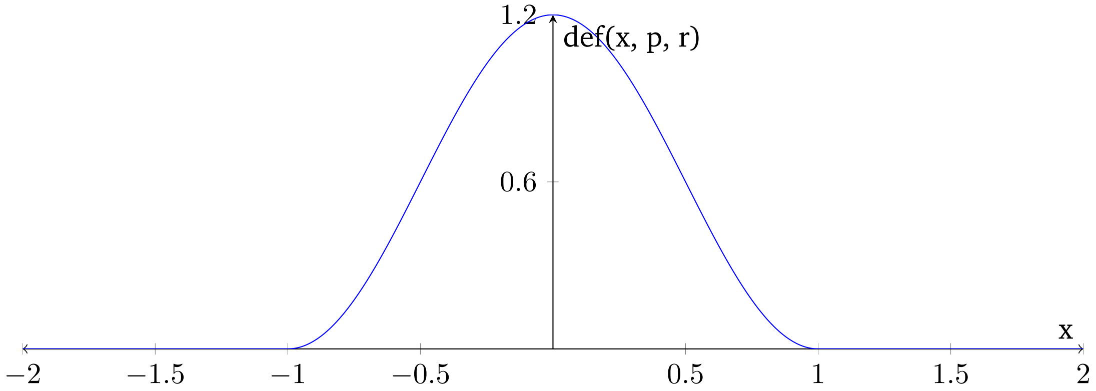
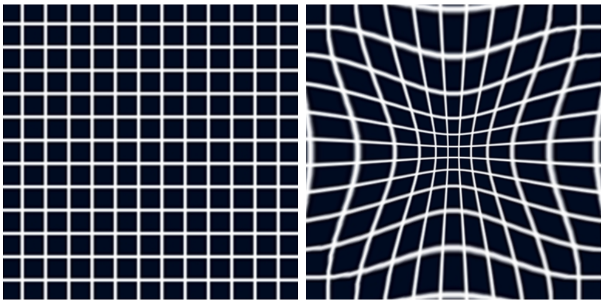


Figure 3.4: Plot of equation 3.1 with $p = 1.2$ as well as $r = 1.0$, i.e. $def(x, 0.6, 1.0)$. Note how the function value is 0 before -1 and after 1 (which is the value of r) even though we are using a cos function. This allows us to generate a smooth deformation without showing a repeating pattern.

adjusted so it was about $30cm \times 30cm$ on the surface it was projected onto – this was achieved by mounting the projector $1.1\,\text{m}$ above the surface.

Since the output should be squared but the pico projector features a $1024 \times 768\,\text{px}$ output, the software restricts the output to (horizontally) centered $768 \times 768\,\text{px}$ viewport. All 20 textures were in png format and had a resolution of $768 \times 768\,\text{px}$, as to fill the entire viewport. When applied however, we slightly scaled them up so a very small part of the texture remained outside of the viewport. When the textute deformation gets applied and the subject presses the pressure sensor strong enough, the texture deformation algorithm stretches the material far enough for those previously invisible parts to be visible. This effect can be seen in Figure 3.5, at the right texture.



(a) Normal **(b)** Distorted ($p = 1.2$)

Figure 3.5: Example of the applied texture distortion, with the two values that were used in the user study (0.0 and 1.2). The grid texture is only used to illustrate the deformation and was not present during the user study.

Additionally to the depth deformation, we simulated a darkening effect on the texture when pressed (and only for $p \geq 0$). The darkening effect is implemented in the fragment shader in order to apply the effect to every pixel of our texture. Since the window behind the texture gets filled with black, we didn't change the pixel's color but simply its alpha value to be more translucent towards the center of the texture, thus getting darker. Equation 3.2 shows how the alpha value of each of our texture's pixels gets manipulated. We use a vector $c = (0.5, 0.5)$ as a shorthand for the texture's center. Since the alpha distortion also depends on the current value the pressure sensor measures, we define a variable m to reflect that. Unlike def, am does not use a point's distance to the center, but the point directly (due to technical reasons). We use a two-dimensional vector k to represent the current point.

$$am(m,k) = \begin{cases} 1 - ((1 - \|k - c\|)) * m + 0.5 & m \geq 0 \\ 0 & \text{else} \end{cases} \tag{3.2}$$

Every time the instructor manually moves on to the next texture using a key combination, the texture software sends a network request to Laptop2 containing the name of the texture that was just being used, its unique ID, its name, the participant number and the value for r. Laptop2 is running a GTK+[5] application providing an easy way for participants to answer the questionnaire regarding their haptic perception of the presented texture. The questionnaire software saves the participant's data in a .csv file for later use.

3.5 Measurements

The dependent variables were measured using a questionnaire each participant filled out after every stimulus. We used seven-points Likert scales to measure the participant's haptic perception. We provide a table (3.1) explaining each measured material property including one or more examples for materials with a high score in the corresponding property.

We used the questionnaire software to ask all participants about their haptic perception of the surface (see Figure 3.2). This made it possible to properly randomize the texture and deformation order without lots of trouble, since the questionnaire software always knew what participant, texture and deformation factor we currently measured.

We directly logged the information reported from the pressure sensor to a file. This gave us the opportunity to later examine it again and gather some statistical data like the maximum amount of pressure applied during a stimulus.

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[5] `http://www.gtk.org`

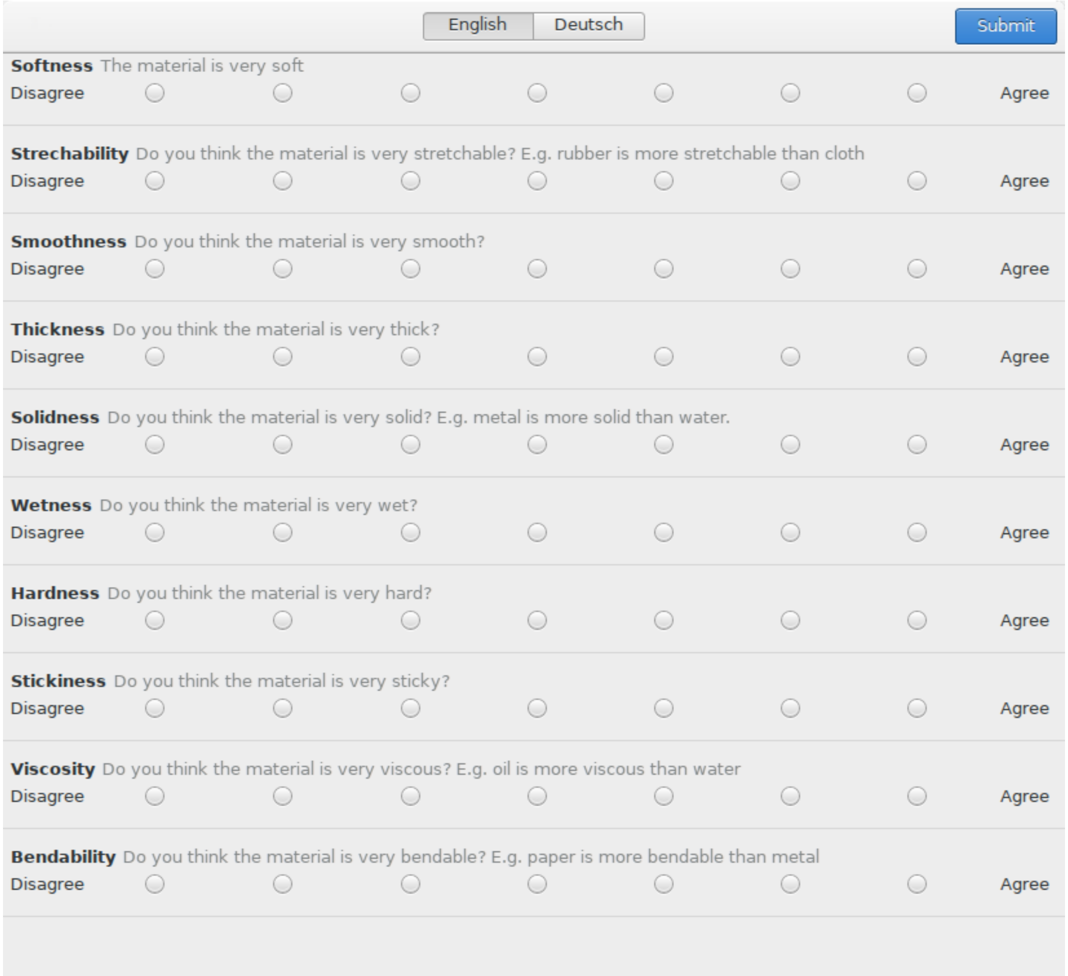
Material Property	**Description**
Softness	The material is easy to press, not hard or firm *Example: cloth*
Stretchability	A material is stretchable if it easily increases in size when pulled. *Example: rubber*
Smoothness	Flat, even, not rough surface *Example: glass*
Thickness	The feeling of having a long distance between the top and the bottom of a surface; the opposite of thinness.
Density	The sense of close distribution of the texture; something that is solid, not fluid
Dampness	The sense of wetness, something that is not dry *Example: wet sponge*
Solidness	Also hardness, something that is difficult to bend or move *Example: metal*
Viscosity	The feeling of a fluid that does not flow easily. *Examples: oil, paint*
Stickiness	The feeling of something adhesive, or having glue to it that easily attaches to anything touching it. *Example: glue, tape*
Formability	The sense of something that is able to bend easily *Example: wire*

Table 3.1: All measured material properties, their description and examples.

3.5.1 Texture Overview

We tried to find 10 textures to cover all the material properties we asked our participants to rate the different sensations by, i.e. softness, stretchability, smoothness, thickness, density, dampness, solidness, viscosity, stickiness and formability (See also Table 3.1). The goal for the material selection was to cover each of these properties with at least one material. Table 3.2 contains an overview over the textures used and explains which material properties each texture covers.

We presented all textures with two different values for r in Equation 3.1, 0.0 and 1.2, totalling in 20 different texture/deformation combinations.



Softness The material is very soft
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Strechability Do you think the material is very stretchable? E.g. rubber is more stretchable than cloth
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Smoothness Do you think the material is very smooth?
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Thickness Do you think the material is very thick?
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Solidness Do you think the material is very solid? E.g. metal is more solid than water.
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Wetness Do you think the material is very wet?
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Hardness Do you think the material is very hard?
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Stickiness Do you think the material is very sticky?
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Viscosity Do you think the material is very viscous? E.g. oil is more viscous than water
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Bendability Do you think the material is very bendable? E.g. paper is more bendable than metal
Disagree ○ ○ ○ ○ ○ ○ ○ Agree

Figure 3.6: Screenshot of the questionnaire interface. Since the experiment was conducted in Germany but some participants did not speak German, we included an English variant of every question.

3.6 Design

We used a within-subjects design with three independent variables:

- Electrotactile feedback (on/off)
- Projected texture (10 different)
- Texture deformation (on/off)

Texture	Covered Material Properties
Cardboard	Thickness, Smoothness, Dampness
Cloth	Thickness, Formability, Softness
Corkboard	Formability,
Fur	Softness, Formability, Smoothness
Grass	Formability, Smoothness
Jam	Wetness, Viscosity, Stickiness
Leaf	Thickness, Smoothness
Sponge	Formability, Density, Softness, Stretchability,
Styrofoam	Dampness, Thickness, Formability
Wood	Stiffness, Dampness

Table 3.2: Overview of the textures used during the user study and what material properties they cover.

Considering the great impact of visual information on perception in general, we expect the results to show that the visual feedback enhances and supports the haptic feedback to an even greater degree.

(a) Cardboard **(b)** Cloth **(c)** Corkboard **(d)** Fur

(e) Grass **(f)** Jam **(g)** Leaf **(h)** Sponge

(i) Styrofoam **(j)** Wood

Figure 3.7: Overview of all the textures presented to each participant during the user study. Every participant saw all of these texture in four different variations.

4 Results

We gave the test situations short names in the scheme of `H0D0sof` where...

- `H0` indicates the state of the haptic electrotactile feedback during the test situation, where `H0` indicates that the haptic feedback was disabled during the test and `H1` indicates that it was enabled.
- `D0` indicates the state of the texture deformation. In the `D0` case, the texture did not distort when the subjects pressed the surface. `D12` indicates a value of $p = 1.2$ in our def function from Section 3.4.2. For a visual example of the difference, see Figure 3.5.
- `sof` indicates the tested material property out of the 10 listed in Table 3.1. We shortened the names to use only the first three letters of each property which is still enough to uniquely distringuish them. In that sense, the available values would be `sof`, `str`, `smo`, `thi`, `den`, `dam`, `sol`, `vis`, `sti`, `for`.

We took the average of all ten textures to get a value for each test situation, totalling in 40 different values. Using these names, we used a Friedmann tst to find out what material properties are significantly affected by each test situation. Post-hoc analysis using Wilcoxon signed-rank was conducted.

4.1 Perceived Texture Properties

The Friedmann test showed significant differences in texture perception for softness, stretchability, thickness, solidness, hardness and bendability. They all showed differences for missing haptic feedback (`H0`) and missing texture deformation (`D0`).

Softness: For missing haptic feedback (`H0`), the texture deformation significantly strengthened the subject's perception of softness (comparison `H0D0sof` – `H0D12sof`: $Z = -3.517, p < 0.001$). Similarly, for missing texture deformation (`D0`), the addition of haptic feedback also significantly strengthened the subject's perception of softness (comparison `H1D0sof` – `H0D0sof`: $Z = -3.517, p < 0.001$).

Stretchability: For missing haptic feedback (`H0`), the texture deformation significantly strengthened the subject's perception of stretchability (comparison `H0D0str` – `H0D12str`: $Z = -3.517, p < 0.001$).

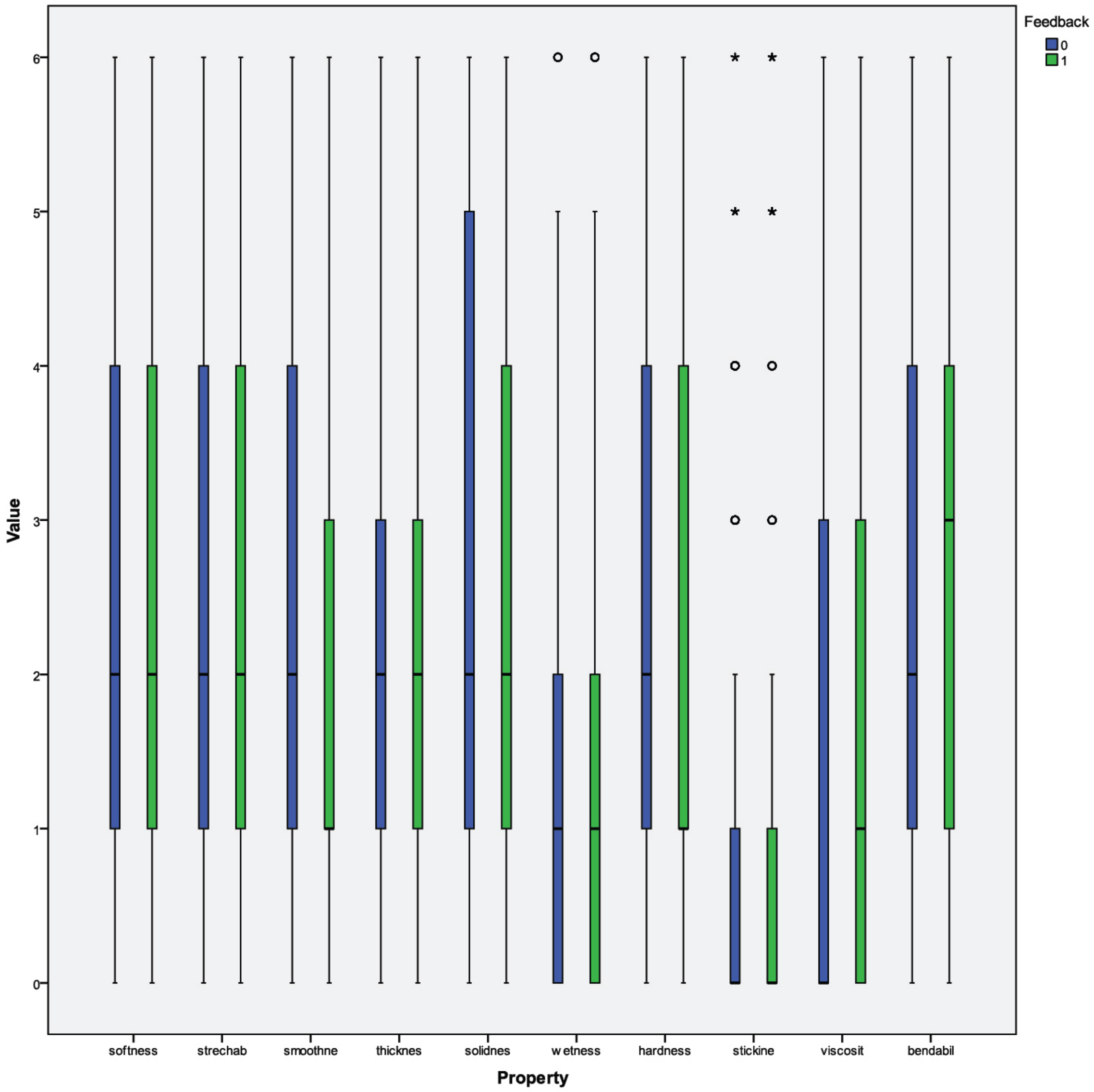


Figure 4.1: Subject test data for results for missing texture deformation. The bars show values for both enabled and disabled haptic feedback.

Similarly, for missing texture deformation (`D0`), the addition of haptic feedback also significantly strengthened the subject's perception of stretchability (comparison `H1D0str` – `H0D0str`: $Z = -3.414, p = 0.001$).

Bendability: For missing haptic feedback (`H0`), the texture deformation significantly strengthened the subject's perception of bendability (comparison `H0D0ben` – `H0D12ben`: $Z = -3.181, p = 0.001$).

For missing texture deformation (`D0`), the addition of haptic feedback significantly strengthened the subject's perception of bendability (comparison `H1D0ben` – `H0D0ben`: $Z = -3.258, p = 0.001$).

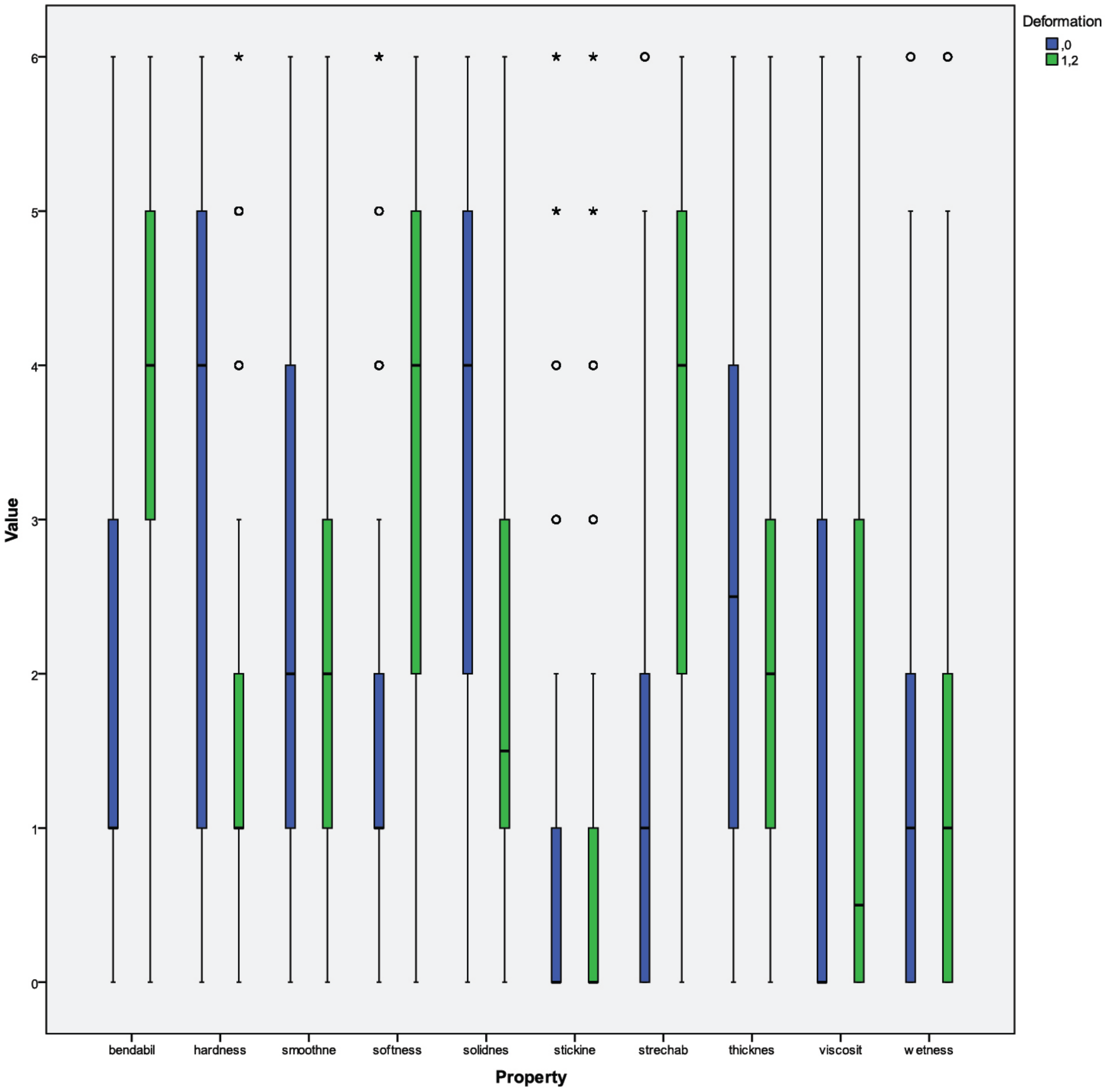


Figure 4.2: Subject test results for missing haptic feedback. The bars show values for both enabled and disabled texture deformation.

<u>Thickness</u>: For missing haptic feedback (`H0`), the texture deformation significantly *weakened* the subject's perception of thickness (comparison `H0D0thi` – `H0D12thi`: $Z = -2.138, p = 0.033$). For missing texture deformation (`D0`), the addition of haptic feedback significantly *weakened*

the subject's perception of thickness (comparison `H1D0thi` – `H0D0thi`: $Z = -2.106, p = 0.035$).

Solidness: For missing haptic feedback (`H0`), the texture deformation significantly *weakened* the subject's perception of solidness (comparison `H0D0sol` – `H0D12sol`: $Z = -3,266, p = 0.001$). For missing texture deformation (`D0`), the addition of haptic feedback significantly *weakened* the subject's perception of solidness(comparison `H1D0sol` – `H0D0sol`: $Z = -3,209, p = 0.001$).

Hardness: For missing haptic feedback (`H0`), the texture deformation significantly *weakened* the subject's perception of hardness (comparison `H0D0har` – `H0D12har`: $Z = -3,238, p = 0.001$). For missing texture deformation (`D0`), the addition of haptic feedback significantly *weakened* the subject's perception of hardness (comparison `H1D0har` – `H0D0har`: $Z = -3,238, p = 0.001$).

4.2 Observation

During the user study with the 16 participants, quite a few of them commented on the various aspects of it, such as the texture representation, but we could also see some differences in the particiants' behavior.

4.2.1 Texture representation

One of the participants suggested that the rather non-fitting test situations like non-bendable jam cause them to think not about touching jam, but about something that looks like jam but makes it *not* react to their touches. One of the subjects said that especially the unbendable jam (i.e. the `D0` situation) makes them think that the jam is distributed on a hard surface, causing them to think about that harder surface rather than the jam itself. Another subject suggested something similar but he was imagining the jam being covered by a hard glass surface, making it look like jam but feel like glass. Also, other non-fitting situations such as bendable wood (`D12`) confused participants but they did not seem think about another material in that case.

4.2.2 Fatigue

Participants generally reacted very differently to the electrotactile feedback regarding fatigue. Some participants did not need us to recalibrate the output voltage at all while some of them did not seem to feel any feedback anymore several times after a few minutes of using it. This seemed to be related to the usual activities people do with their hands as well as the callused skin (which is something we asked the participants about in a questionnaire).

4.2.3 Touch behavior

The addition of haptic feedback and texture deformation caused some general observations:

- The more "interesting" (where the `H1` and `D12` situations are more interesting than their `0` counterparts) the test situation got, the longer the participants seemed to press the surface.
- When switching from the test surface to the laptop running the questionnaire application, most participants looked back at the test surface and the projected texture for a while before answering the questions. This seemed to be more often the case with more "interesting" (see above) conditions.
- Although we did not tell the participants in what way to press the surface (except very rudimentary instructions), only very few participants "played" with the texture deformation when it was enabled. The rest of the participants pressed the surface only in a single monotonic motion.
- Lots of participants told us that viscosity did not fit to any of the test conditions.

5 Discussion

As mentioned in chapter 3.6, our hypothesis was that both haptic and visual feedback would increase the subject's perception of the material properties and that the effect would increase even further if they are both enabled simultaneously. This is a hypthesis largely based on the fact that visual feedback is known as dominating proprioception[WW86], but also on studies showing that vison dominates even during conflicts between haptic and visual feedback[SL95]. To support the hypthesis even further, it's been shown that vison dominates the perception of friction and texture[Léc09].

However, the results from chapter 4.1 don't support our initial hypothesis.

Most interesting is the fact that the conditions with electrotactile *and* visual feedback enabled did not yield any kind of statistically significant difference in the subjects' perception.

On the one hand are *softness*, *stretchability* and *bendability*. They are all positively affected by the deformed texture if the haptic feedback is missing and positively affected by haptic feedback if the texture feedback is missing. Both haptic and electrotactile feedback together don't make a statistically significant difference. So in this case, both electrotactile and haptic feedback strengthened the subject's perception of all four material properties, but if both haptic and electrotactile feedback are enabled at the same time, they seemed to neutralize each other.

On the other hand are *thickness*, *solidness* and *hardness*. Just like in the first case, the `H1D12` conditions did not yield significant differences in the subject's haptic perception of our flat test surface. For the other conditions, the results for these three material properties are the the opposite of those from our first case. For disabled haptic feedback, the addition of our visual real-time texture deformation *weakened* the subject's perception of all three material properties. The same happened with disabled texture deformation and the addition of haptic feedback – the data shows significant *weaker* values for thickness, solidness and hardness once we enabled the haptic feedback.

To summarize, we have two property categories which are affected by haptic feedback *or* visual feedback, but never both at the same time. The first category is that of "soft" material properties, namely softness, stretchability and bendability. For this category, both visual and haptic feedback strengthened our subjects' perception of the respective properties.
The second category is that of "hard" material properties, namely thickness, solidness and hardness. In this category, the subjects reported the highest values for disabled haptic and

disabled visual feedback. Enabling either haptic *or* visual feedback weakened the subject's perception of the respective material properties. Again, enabling both types of feedback did not yield any significant differences. We could not measure any significant difference for the remaining four surface properties density, dampness, viscosity and formability.

The fact that our texture deformation did not cause the subjects to perceive the surface as harder, thicker or more solid is of no surprise. The texture deformation is suppoed to deliver depth or softness and those properties don't work very well for delivering sensation of hardness. More interesting is that the electrotactile feedback seems to fail to strengthen our subject's perception of hardness. On the contrary, it seems to strengthen the perception of "soft" material properties as shown by our results for *softness*, *stretchability* and *bendability*. To summarize, both the electrotacile haptic feedback and the visual feedback seem to weaken hard surface properties and strengthen the subjects' perception of soft surface properties, making both the ideal candidates to simulate soft surfaces.

But even though both our haptic and visual feedback strenghtened our subject's perception of softness, both of them together did not show any statistically significant difference, neither in weakening hardness nor strengthening softness. There's no obvious explanation for this phenomenon since the previous literature suggests that the two sensations should work well together. However, all previous literature only covers active touch. Thus, our results could show an important difference in the surface perception between active (moving finger) and passive (non-moving finger) touch sensation.

We an imagine some causes for this phenomenon. For example, since the electrotactile feedback was an unknown sensation to all of our study participants, many of them reacted in an unpredictable way to the senstaion. Chapter 4.2 lists some of the obvservations we found to be interesting. It could be possible that the unkonown, new and interesting sensation of electrotactile feedback on the subjects' finger caused them to answer the questionnaire not about how it *really* felt to them, but about how they thought it *should* feel. Some participants have, in fact, asked us during the study what they are answering the questionnaire about. They usually asked us if they should answer the questionnaire about what they see *or* what they feel. We wanted to keep the participants as unbiased as possible, so our initial instructions to them didn't specify what they are answering about. When we answered their question, we kept he reply vague. So, if most participants really didn't use both their visual and haptic perception to answer the questionnaire, it could very well be possible that some of them (even if just subconciously) chose one of the senses and completely neglected the other. That way, the combination of both visual and electrotactile feedback would not make a difference over the conditions without haptic feedback.

However, when both types of feedback were enabled, we did not even measure a significant difference to the conditions with no feedback enabled at all. It seems like visual and haptic feedback just did not fit together well, since they worked as expected when used alone. The combination of both feedback types seems to cancel each other out however. Another explanation for this phenomenon is that the haptic feedback only fits to hard, non-bending surfaces, in which case it makes it feel slightly softer. Soft material, however, often have a very smooth surface. Some participants even mentioned during the study that the texture deformation reminds them of rubber which has usually a very flat surface and no haptic feedback that would be similar to our generated electrotactile haptic feedback.

Another explanation of the results can be found at the texture level. We selected the textures (see figure 3.7) to they would cover each of our ten surface properties (see table 3.1). While this has worked out quite well, we did not select textures that would also fit the sensation participants get on their finger when the electrotactile feedback is enabled. Since we did not compute the results for all texures individually, differences in texture perception and textures that fit to only one of our feedback types could be the cause for the phenomenon we're seeing in our end results. For example, lots of people found the grass texture to be very fitting for the haptic feedback, but of course grass does not bend in the real world in the way we deformed the texture. This would be a case of fitting haptic feedback but completely out-of-place visual feedback. Another example is the jam texture which a lot of subjects found to be the most "interesting" one. Here, so they said, the visual deformation of the texture was very fitting and realistic. However, when slightly pressing into the contents of a glass of jam, the haptic sensation on one's finger is only minimal and nothing like the electrotactile feedback coming from the TENS device we used. Although not specifically selected for this purpose, we expected the cloth, styrofoam and sponge textures to be fitting for both electrotactile and visual feedback applied, but none of the participants found them interesting in any way.

6 Conclusion

In this paper we have developed a texture deformation and shading application. We selected ten different textures to represent ten surface properties important for the haptic perception, namely softness, stretchability, smoothness, thickness, density, dampness, solidness, viscosity, stickiness and formability. We selected the textures so each surface property is covered by at least one of them. To measure the pressure applied by each participant, we built an apparatus consisting of a round copper plate and a surrounding surface made of iron sheet to project a texture onto. We used a pressure sensor right below the copper plate in order to measure each participant's pressure feedback. The pressure sensor was connected to an Arduino UNO which received the pressure data and sent it to a PC over a serial connectoin. We used the pressure data in order to deform and shade the preseted texture in real time. The visual feedback was provided by a pico projector mounted orthogonal to the projection surface. We used one electrode on each participant's right index finger and the copper plate as second electrode in order to deliver haptic feedback in form of electrotactile feedback generated by a TENS device. Additionally to the texture deformation application, we developed a questionnaire application that was used by each participant after completing a texture – we asked them about all ten of our texture properties using seven-point Likert scales. We conducted a user study with 16 participants and found that although both visual and electrotactile feedback resulted in measurable differences regarding some of our surface properties, both types of feedback together did not yield the expected effect.

Even though the combination of our two feedback types did not lead to significant differences in any of the surface properties we measured, the results of both types of feedback individually are promising. Usage of our texture deformation algorithm to simulate softness or depth touchscreens is more than possible, easy to implement and cheap because it's doable with todays hardware. The electrotactile feedback is harder to apply to current use cases since the user has to be intrumented but use cases are imaginable. For example, the electrode could be hidden inside a glove for the user to wear, or in the chair the user sits on. The only requirement is direct skin contact and the user can feel the sensation on their finger(s). This is only problem with higher-than-usual voltages which have shown to cause a sanstaion on both electrodes.

The possibilities for extending both the apparatus and the user study are manifold. For future work, the texture deformation could be varied more in order to find an ideal deformation for certain textures or materials. For example, the current deformation algorithm does not work very well for "stretchable" materials such as rubber, where crinkles in the material should be simulated, similar to the pseudo-haptic textures by Ferran et al[AJML13]. Similarly, we can

imagine deformations that concentrate on stickiness rather than softness – the texture could only deform after a certain pressure threshold and when the subject releases their finger, the texture could stick to the finger. Similarly, after releasing the finger, the texture could swing for a bit in order to simulate viscosity, which in our study a lot of participants found to be out of place. On the hardware side, the realism of the texture projection could be improved. It's currently limited by the fact that the subject's hand covers part of the surface when interacting with it. We can imagine a similar test setting with a semi-translucent replacement for our copper plate and a projection from below the surface.
Also, the user study could be extended to check differences in the subjects' perception of various other surface properties.

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All links were last followed on March 17, 2008.

Declaration

I hereby declare that the work presented in this thesis is entirely my own and that I did not use any other sources and references than the listed ones. I have marked all direct or indirect statements from other sources contained therein as quotations. Neither this work nor significant parts of it were part of another examination procedure. I have not published this work in whole or in part before. The electronic copy is consistent with all submitted copies.

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