From Pulse Trains to “Coloring with Vibrations”: Motion Mappings for Mid-Air Haptic Textures

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ABSTRACT

Can we experience haptic textures in mid-air? Typically, the experience of texture is caused by vibration of the fingertip as it moves over the surface of an object. This object’s surface also guides the finger’s movement, creating an implicit motion-to-vibration mapping. If we wish to simulate a texture in mid-air, such guidance does not exist, making the choice of motion-to-vibration mapping non-obvious. We evaluate the experience of moving a pointer with four different motion-to vibration mappings in an interview study. We found that some mappings lead to a perception shift, transforming the experience. When this occurs, the pointer is no longer perceived as vibrating, interactions become more pleasurable, and users have an increased experience of agency and control. We discuss how to leverage this in the design of haptic interfaces.

INTRODUCTION

In our everyday experience, textures are always accompanied by normal force. As we move our finger over a stone wall, we push against it and the wall provides a counter-force. Research has shown, however, that many dimensions of texture experience are caused by vibration, rather than force [19]. As our fingertip moves over the stone wall, the way our fingerprint interacts with the structure of the stones causes vibration in the skin [24]. These vibrations cause Pacinian and Meissner corpuscles to fire, which in turn leads to the experience of texture [3].

It is not sufficient to simply vibrate the fingertip to make us experience the texture of a stone wall. This vibration must correlate with the motion of our finger for the material experience to emerge. We can artificially create the experience of texture, if we generate the vibrotactile feedback with a frequency proportional to the motion with which the texture is explored. This phenomenon has been investigated extensively and various haptics explorations have used this effect to manipulate the material experience of an object or create artificial textures [10,32,37].

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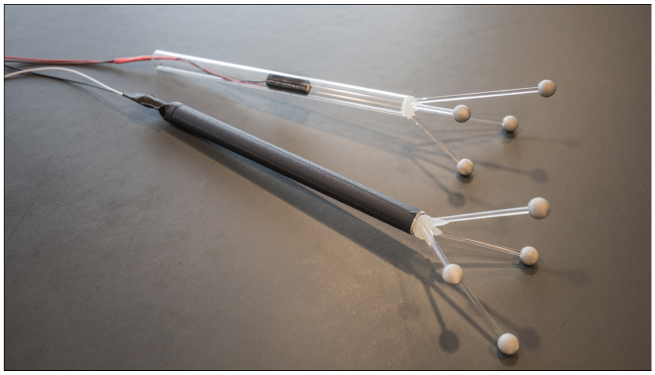

Figure 1 – Haptic feedback device used in our study (front, black) and transparent version with position of haptic actuator visible (back, white/transparent). On right side they terminate in IR markers for the OptiTrack system and on the left in a cable that transports the control signal.

Textures come with an implicit dimensionality: Moving a pencil over paper, we feel the paper’s texture only when the pencil moves along its surface. If we attempt to move the pencil in a third dimension we are either constrained by the normal force when pushing down, or we no longer feel the texture when we lift the pencil. To render a haptic texture, we need to couple the vibrotactile feedback with the user’s movements. If we wish to do so in mid-air, many motion-to-vibration mappings become possible. Choosing such a mapping is non-obvious.

We use a handheld device with a recoil-style haptic actuator [46] (Figure 1) to compare four motion-to-feedback mappings: no mapping (Vibration), mapping to displacement (Translation), mapping to changes in orientation (Rotation) and mapping to a point projected on a plane (Projection). The goal is to understand how motion-to-vibration mappings influence the perception of such motion-coupled vibration. We conducted an interview-based study and observed that for the Translation and Rotation conditions a perception shift occurred: Participants described that the vibrotactile pulse trains we generated transformed into ‘*something more*’, liking the experience to ‘*coloring with vibrations*’ or ‘*moving through a force field*’. When this shift occurred, irritation caused by vibration was reduced and simultaneously the pointing device felt as if was of ‘*higher quality*’ and moving it was ‘*more fun*’. Users reported an increased experience of agency and a heightened sense of their body and their movements.

RELATED WORK

In this paper we discuss the experience of vibrotactile pulse-trains generated by free-form movements. Our work draws on the psychophysics of touch, and is inspired by various haptic-rendering systems. In this section we discuss the physiological and technological foundation on which we build, and highlight how previous evaluations lead us to choose a qualitative, interview based approach.

Texture Perception and Simulation

The perception of texture is caused by the interaction of our fingertip with the material it is touching [24]. This interaction causes vibrations to which the Pacinian system and Meissner Corpuscles are sensitive [18]. The firing of these cells in turn is interpreted as a texture [3].

We can detect the presence of vibration within two relatively narrow frequency bands, ~5 to 50 Hz (Meissner Endings) and ~40 to 400Hz (Pacinian Endings) [18]. While this information is relatively sparse, it is sufficient for a rich set of experience to emerge, including roughness and stickiness [3] as well as compliance [4]. Similarly to how we distinguish between the sound of two musical instruments based on the frequency profile of the tones they emit, we also distinguish textures based on the frequency profile of the vibrations cause by interacting with them [38].

This can be leveraged to create artificial material properties. For example, researchers have simulated a pen moving over a flat surface that is experienced to have the haptic properties of various other materials [10], manipulated the experienced material properties of bending an object [37], or simulated compliance for virtual buttons [20]. These simulations all used a fixed motion-to-texture coupling. We expand this work to mid-air interactions and examine the effects of various mappings on the resulting experience.

Haptic Rendering Systems

The devices used for simulating experiences such as texture or compliance typically follow two approaches. Devices using grounded haptic feedback transmit forces to the user through a kinematic chain of rigid links and joints [9]. In contrast, ungrounded feedback devices provide stimulation of the skin, but no force [8]. Alternative haptic rendering methods include body-grounded devices which provide force relative to the body, inertial approaches that transmit gyroscopic force [25,42], or focused ultrasound [7]. Force can also be simulated by taking advantage of asymmetrical vibration [11]. A further alternative to haptic rendering is physically manipulating texture [15] or compliance [17].

In our study we use a non-grounded system, similar to the approach originally presented by Kuchenbecker [32]. This approach typically uses inertial or force sensing methods [8,10] and detailed modelling of surfaces. In contrast, our system uses a relatively naïve model, but combines that with optical tracking, providing a large volume in which users can interact.

Vibrotactile Actuators

The ungrounded approach used in this paper requires a vibrotactile actuator. Currently eccentric rotating mass vibration motors (ERMs) are the most common solution found in products, dating back to ‘rumble packs’ used in the game-controllers of the early 90’s [27]. While ERMs are easy to implement in prototypes, other devices, such as piezo-actuators (e.g., [23]) are required for more controlled feedback. Solenoid-style actuators including Tactors, Haptuators or voice coils are typically used for texture rendering, as they can independently modulate frequency, amplitude, timbre and velocity. Using solenoid-style setups for haptic-feedback in psychology and psychophysics research is first documented in the early 20th century, using re-appropriated audio speakers [14]. Since then, research has reduced the audible and increased the tactile output of such actuators [46]. They have since found wide usage within the HCI community [37,47–49].

These devices are usually controlled by audio-signals. Their output can be partially audible, sparking explorations of the interactions between haptic and audible feedback, for example using a handheld device that coupled audio and tactile cues based on user motion [1,2]. As our haptic device uses audio signals for control, it exhibits many similarities with these devices. While using similar actuators to previous work [8,10,38], we expand upon this work by exploring new methods of designing the actuation signal.

Evaluations of Haptic Experience

Evaluating and, especially, communicating what good haptic design is, is non-trivial. This is reflected in how researchers chose to evaluate their work. The bulk of evaluations focus on detection thresholds and on studies evaluating if the device does what it is intended to do [7,8,10,16,34,44]. From a human-centered design perspective such information provides limited value. Instead, behavioral studies that investigate how haptic feedback influences task performance are often preferred [11,22,30,37,43]. Such studies, however, do not provide a reader with insight regarding what the haptic experience feels like. In consequence, there are various studies that require participants to report on their impression of a stimulus such as object length [45], compliance [33], or roughness [38], while feedback parameters are adjusted. These studies enable a reader to understand the comparison between parameters of the specific setup, but are often not suitable for comparison to natural objects or other systems.

When research does report on the subjective experience of haptic systems, this is often done in passing [37] or as aggregated questionnaire data [6,21]. A notable exception is an interview study by Obrist et al. [26], which presents in-depth interviews comparing haptic feedback designed to target either Meissner or Pacinian corpuscles. Because we find such research currently underrepresented, this exploration also focuses on the subjective experience. To do so we chose to use an approach inspired by Petitmengin [28,29].

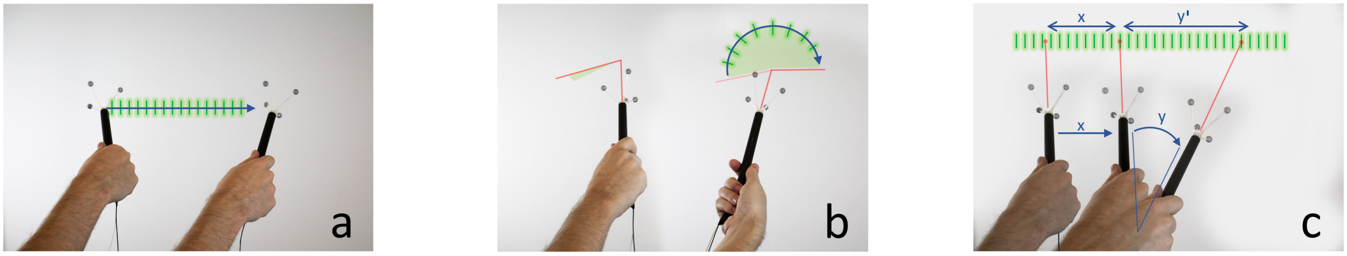

Figure 2: a) Translation condition (vibration is mapped to displacement of the object), b) Rotation condition (vibration is mapped to change in orientation of the object) and c) Projection condition (vibration is mapped to change in position of a virtual point moving over a surface). Textures are green, motion is blue and pointer extensions for clarification are red.

HAPTIC FEEDBACK SETUP

Typically, vibrotactile feedback is generated as a pulse train: a repetitive series of pulses, separated in time by a fixed interval (for example, the Oculus touch controller can currently produce either a 160Hz or a 320Hz pulse train[1]). When the interval used for the pulse train is varied based on user motion, an experience of texture can emerge [10,32,38]. Based on the physiology of texture perception it may be feasible to generate such an experience in mid-air [3]. To implement such a system, one needs to decide which parameters of user motion to use for controlling the pulse interval. We therefore created a pointing device with a tracking system that allows us to implement various of motion-to-feedback mappings:

Pointer

We built a custom pointing device, inspired by the controllers used for VR systems such as the HTC Vive, Occulus Rift or Hololens[2]. We use the Haptuator Mark II[3] by Tactile Labs to generate the vibrotactile feedback. The haptic actuator was placed on the inside of an acrylic pipe, equidistant from both ends. The acrylic pipe had a flexible litz cable on one end, connected to the output of an audio-mixer, and had four markers attached on the other end which were used for tracking its position and orientation (Figure 1).

Tracking

We measured the position of the pointing device using an Optitrack motion capture system. We use 8 cameras which captured the position and orientation of the device at 125fps. After calibration, the average error in positioning is <1.6mm.

Signal Generation

Using Max/MSP, we generate our signal as a pulse train similarly to previous approaches to haptic texture generation [37,38]. Each pulse has a duration of 1.45 milliseconds (64 samples at 44.1KHz sampling frequency). The frequency at which they occur is determined by the motion performed by participants, where a fast movement of the pointing device generates a higher number of pulses and holding it still produces no pulses.

Signal Path

Position information is calculated by the motion tracking software[4] and passed on to a custom C# application that generates movement information, according to the mapping condition. The C# application sends the movement data to a MAX/MSP patch using OSC. The MAX/MSP patch generates the pulse-trains as an audio signal [37,38].

We used the UR44 audio-interface by Steinberg for signal output to an audio mixer. The audio mixer was used to amplify the signal to the necessary levels for driving the Haptuator, as well as for easily switching between textures. The output of the mixer was connected to the haptic actuator embedded in the pointing device. We estimate the system latency to be < 25ms[5].

MOTION-TO-VIBRATION MAPPINGS

Previous studies used motion-to-vibration mappings defined by the properties of the experimental devices, for instance, sliding [38], pushing [20] or bending [37]. In contrast, when moving an object in mid-air, there is no implicit mapping. We therefore designed three different mappings to understand their influence on the perception of motion-coupled pulse trains.

Projection. Rather than a finger moving over a stone wall in front of us, the Projection condition explores the idea of touching a wall that is far away. It is inspired by the light point of a laser-pointer. We generate vibration based on the movement of an imaginary point over a faraway virtual wall. Displacing the pointer (Figure 2c, marked as ‘x’) generates a steady stream of impulses. Rotating the pointer (marked as ‘y’) causes the imaginary ‘light point’ to move increasingly faster, resulting in an accelerating succession of pulses (Figure 2c and Video Figure 1c at 00:59). Projection can be broken down into a translation and a rotation component, which we explore individually:

Translation. This mapping is the one most similar to the movement we make when exploring a physical texture and closest to previous work in this area [10,32,38]. We measure the position of the pointer in 3D space and map the distance

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[1] https://developer.oculus.com/documentation/pcsdk/1.9/concepts/dg-input-touch-haptic/

[2] See also http://engadget.com/2017/08/25/microsoft-hololens-wand-patent/

[3] http://tactilelabs.com/products/haptics/haptuator-mark-ii-v2/

[4] http://optitrack.com/products/motive/

[5] Camera Shutter Speed: 3.9ms, Sampling Rate: 8ms, Networking: 0.85ms, Motive: 0.7ms, Max/MSP: <1.5ms, UR44: 5.12ms, C# 0.5ms (Values based on datasheets where available, otherwise measured or calculated)

between the objects current position and its previous position to pulse frequency (Figure 2a and Video Figure 1a at 00:35).

Rotation. We measure the orientation of the cursor (pitch, yaw and roll, as could be sampled from the inertial sensors of smartphones) and map the change in angle to pulse frequency (Figure 2b and Video Figure 1b at 00:47). This mapping can be implemented using the IMUs of many existing devices.

STUDY DESIGN

Our goal was to better understand how mappings influence the perception of motion-coupled, non-grounded vibrotactile feedback. We chose an interview-based approach to ensure that we cover the breadth of experiences people had when interacting with this type of feedback.

Conditions

We used four study conditions, the first three corresponding to the three mappings explained above: *Translation*, *Rotation*, and *Projection*. In the fourth condition, *Vibration*, the pointer is actuated by a constant pulse-train. For each condition we also presented and discussed the absence of the vibration with the participants (Video Figure 1 at 00:35).

We passed this signal through a bandpass filter with a center frequency of 125Hz and a Q of 250. The low-pass filtering ensured that the vibrations were not audible, and the high-pass filtering made the signal feel crisper. The Vibration condition pulsed at 40Hz. While we could not control for frequency, due to the different mappings, all mappings were designed to feel as similar as possible[6].

There was no visual or acoustic interface. Participants sat in an ergonomic, armrest-free stool, facing a white wall (as seen in Video Figures.) The only information provided to the participants was what they felt in their hands.

Interview Method

Our interview method was inspired by Petitmengin [28,29], with the intent of eliciting descriptions of introspective, subjective experiences. This approach has also been used in a previous study of haptic perception [26] and a study of the 'rubber hand' illusion [40].

We told participants that we research the perception of vibrotactile feedback and that they would be presented with a pointing device that would be vibrated with four patterns. We asked participants to "explore what the pointer feels like by moving it". Participants did not receive explicit instructions on what movements to make. They were asked to maintain the same grip on the pointer for all conditions and, as best as they could, ignore any assumptions they might have about the technological setup and instead focus on their subjective experience.

The interviews were structured by the four conditions which were introduced in rising order of complexity, starting with the Vibration condition (no mapping) and finishing with the Projection condition (non-linear mapping). Translation and Rotation were alternated in order. This allowed participants to slowly build up their own vocabulary, which we then also used when asking questions. Our goal was to explore the breadth and depth of subjective descriptions. Human vocabulary for discussing haptic experiences is limited and initial testing suggested that allowing participants to explore the complexity at their own pace helped them find nuanced ways of expressing themselves.

While conducting the interview we introduced as little information as possible in our questions, using the participants own vocabulary wherever possible. We started the discussion by asking what a vibration pattern felt like and then would follow up by asking participants to expand on their descriptions. If participants made an observation, and inquired if their observation is correct, we always agreed with their observation while asking them to reflect on it further. The following excerpt illustrates a typical exchange:

Exp:	I'm going to bring in this third pattern.
P7:	(Pause) - Oh, now I can feel that it's responding to how I'm moving it. The vibrations.
Exp:	What does that feel like?
P7:	It feels quite exciting, actually. I don't think I've ever felt this before ... it feels as if there is something invisible, [...] some kind of force-field that I cannot see influencing it, which kind of confuses my brain a little bit.

Participants were asked to compare all mappings, and to compare them to the absence of haptic feedback. Participants were also asked to compare their behavior and the precision with which they moved the pointer, with and without haptic feedback. Otherwise the topic and pace of the interview was dictated by the participants—we would merely ask for explanations, clarifications or additional elaboration. If the conversation dried up, we switched to the next mapping condition or to one of the predefined questions. We explicitly told participants that they could ask us to switch back to previous mapping if they needed the experience to better make comparisons. Interviews were audio-recorded.

Participants

We recruited 12 participants, of which 5 were female, through word of mouth and a university e-mail list. Ages ranged from 21 to 65 years (M = 30, SD = 10.7). All but one participant had completed a university degree. Participants received presents as thanks for their participation. The value of the presents corresponded to a typical hourly wage at the location of the experiment. The interviews lasted between 22 (P10) and 72 (P12) minutes (M = 44.8, SD = 13.7). We initially conducted eight interviews and did a preliminary analysis. We then added four more participants. As no new topics emerged, we decided that the number of participants was sufficient.

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[6] Note that this is not true for the video figure, where we aimed at making the differences between conditions as clear as possible

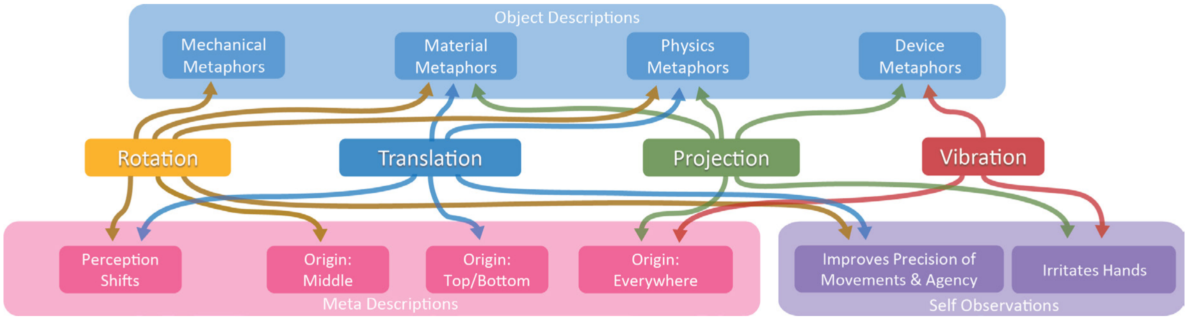


Figure 2: Overview of results. Interview statements were clustered by *Object Descriptions* (top, blue), *Self Observations* (bottom righ, purple) and *Meta Descriptions* (bottom left, pink). The arrows point from condition towards main topics and findings. In blue we see metaphors used, in pink we see which conditions led to perception shifts and where users felt the vibration came from. In purple we see effects the experience had on the users. Rotation and Translation share many topics, but here is no overlap in main topics between them and Vibration. Projection shares properties with all conditions.

Analysis

We transcribed the interviews and manually searched them for relevant sections. We discarded statements by the experimenter (except when required for context), and off-topic discussions. The rest of the documents were split into discrete statements and labelled with the participant ID and condition. The interview transcripts had between 2,000 and 8,500 words, totaling about 50,000 words. For reference, this paper is about 9,500 words.

We clustered the statements 'in vivo'—categories emerged during this process. Data was viewed by all three authors, decisions were made by consensus. We conducted two rounds of clustering. Initially, three major thematic groups emerged. Statements within these groups were then further analyzed and clustered into sub-groups. If a statement fit into more than one sub-group, we created a copy of it, keeping track of duplicates.

The clusters emerged by examining how participants responded to the question 'What does this feel like?'. If they answered by describing the pointer, we placed the response in the *object description* category. If they answered by describing their actions or what they themselves felt like, we placed the response in the *self-observations* category. Responses that made higher level observations such as commenting on the process they went through when experiencing the haptic feedback where grouped as *meta descriptions*. Note that not all topics were covered by all participants. Participants demonstrated very diverse ways of discussing the experiences, evidently drawing from their individual backgrounds.

RESULTS

As can be seen in Figure 2, there were three main clusters. The four mapping conditions lead participants to discuss these in different ways. From *Self Description* we learn which mappings were bothersome and which ones might help perform a task. *Object Descriptions* show us how the experiences of the mappings differ qualitatively from each other and *Meta Descriptions* teach us about how participants explained what they felt and the order in which experiences occurred. The following is a summary of the 12 interviews.

Object Descriptions

When describing what the pointer felt like, participants commonly used metaphors or comparisons to familiar experiences. If these descriptions referred to a material (e.g.: *"...there is a ball in the very old mouse for computers [..] they had this rubbery surface"*, they were grouped as 'material metaphors'. Statements describing forces or using other physics concepts such as *"the resistance increases if I move it quicker"* were labelled 'physics metaphors'. Descriptions of interactions between objects or literal mechanical concepts such as *"like when you ride a bicycle and its going too fast for the gear to keep up"* where labelled 'mechanical metaphors' while descriptions that referred to electronic devices or electronics (e.g.: *"It reminds me of a Geiger counter"*) where labelled as device metaphor.

Plotting the frequency with which these categories occurred (Figure 3) provides an overview of how participants discussed the mappings. During the Translation condition participant's descriptions mainly used physics metaphors. The Rotation condition elicited the most descriptions of materials, but less discussion of physics than the Translation condition. Instead a large portion of these discussions focused on interlocking gears and other mechanical constructions. P8 explained this difference by stating that they both feel very 'familiar', but that the Rotation condition felt more like something they would expect from a man-made device, while Translation felt more like something they could experience in nature. The Vibration condition was most commonly described by referring to electrical devices (electrical toothbrush, smartphone). The Projection condition combined properties of Translation and Vibration.

While participants could clearly distinguish between the Translation and Projection conditions, they grouped them together, often referring to them simulataniously in their descriptions. Participants felt these conditions were more engaging (10 of 12), fun (P1, P5, P11, P12), interesting to move (P6, P7, P8, P9, P10, P11) or pleasurable (P7).

For a less fragmented description of each mapping, the rest of this section is organized by condition, not by metaphor.

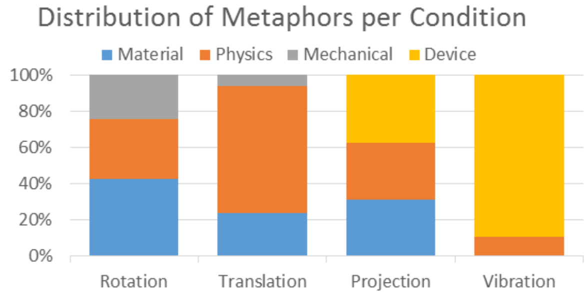


Figure 3 – Frequency with which types of metaphors were used in discussing each mapping condition.

Rotation

Participants enjoyed moving the pointer with the Rotation mapping. P11 said that *"in the beginning [without the feedback] it felt a little boring. [...]. Now it's way more fun"*.

Participants stated they experienced resistance when rotating the pointer (8 of 12). In addition to resistance, participants used terms such as 'higher traction' (P1), and being 'hard to move' (p3) to describe this. The motion also was described as 'grinding' (P11), 'rolling over a rough surface' (P12), and having additional inertia (P11). When asked why this was the case, users explained it by describing the pointer as 'rusty' (P1), 'old' (P1) and 'sticky' (P3). The pointer was also described as feeling heavier (P5, P6, P9).

Rolling the pointer in one's fingers was compared to rolling a hexagonal pencil over a table (P12, P5, P6). P6 made the observation that comparing the Rotation mapping to the absence of haptic feedback was like *"the difference between a high-quality pen and, um, like a plastic pen"*

When asked to describe what the haptic feedback made the pointer itself feel like, all users would describe the material composition of the pointer in some way. The most detailed description was provided by P2 who explained that it felt both heavier and softer *"[as] if this was made of Styrofoam with like an iron rod or something inside it, to make it a little heavier"*. P3 and P12 also experienced a certain level of compliance, associating it with rubber.

The rotation mapping seemed to make the perception of the pointer more complex. This became apparent from the many multi-material and mechanical metaphors used. P1 and P2 both associated the experience with gear-systems in a bicycle and P3 described it as similar to feeling the rubber ball on the inside of an analog computer mouse. This additional complexity however felt familiar, for example P1 stated *"I feel like I've felt this before, but I can't remember where"*.

When we removed the haptic feedback, users felt that the pointer became 'lighter', as if (P1) 'a gear system loses traction'. P2 also reported that the pointer felt 'colder'. While P11 described it as an additional property of the object that is lost *"I can't help but think about it as 'something else' when it's vibrating. It could be 'whatever' in my head. Like a key turning. And then, when the vibrations go away, my imagination fades as well"* (P11). When asked if the pointer felt the same in the absence of haptic feedback as it did at the beginning, before they had experienced a mapped vibration, P11 declined, explaining that *"it feels like I lost something more than I gained something before. If that makes sense ... Like in the beginning* [without vibration] *it was alright just to turn it, but now I ... it feels like its missing something when it's not there"*.

Translation

As with the Rotation condition, participants seemed to enjoy this mapping a lot. P5 and P6 explained that the pointer felt magical or powerful, as if it were a wand from Harry Potter, and P4 immediately exclaimed "*This is a lightsaber*!".

Asked what the Translation mapping felt like, P4 described *"So, to me, it's not a vibration… it becomes something else. ... it just becomes a resistance, you know, to my movement."* Almost all participants (10 of 12) confirmed this experience of resistance. Additionally, P2, P5 and P6 remarked that it felt heavier. P5 specified that *"the movements are causing that I can feel that it's heavier"*. We were somewhat surprised by P3 who felt that the haptic feedback made the pointer feel warmer and by P2 who described the pointer as colder without the haptic feedback.

P4, P5, P7 and P8 described that moving the pointer was as if one was 'moving through a medium'. Examples included 'stirring a pot of dense soup' (P4), 'moving a stick through honey' (P3), and 'swinging a badminton racket' (P2). P12 and P11 experienced such motion as slower, while P3 felt the movement was faster than expected and somehow stickier. P11, P2 and P5 experienced a counter-force when moving it.

Compared to the Vibration condition, the experience during the Translation condition was 'cohesive' (P2) or 'more natural' (P12, P2, P3, P7, P8), *"because it corresponds to my everyday experiences. It corresponds to feeling something when I brush over it, when I am also moving"* (P12).

Removing the haptic feedback presented many of the participants with a feeling of loss, P2 described the pointer, once the vibrations had been removed, as *"colder, deader, and lighter"*. P12 said that "*It's like [the experience] is over, because you've put down the object; because it's dependent on your movements"* P12 contrasted that to the Vibration condition in which the experiences *"gradually fades out"*.

Projection

Many users initially did not experience this as 'natural' in the same way as the two previous mappings. P12 immediately explained that it felt 'artificial' and that what they experienced was 'too complex to correspond with anything natural'. P2 described it as being 'electrical rather than organic'. Similarly to the Vibration condition, participants resorted to metaphors involving machinery. However, this time the vibration that they felt was not a side-effect of the mechanical motion as it was for the Rotation condition, but as output from a digital device—hence we did not consider these in the Mechanical sub-theme. The vibration was describes as feeling like a ‘metal detector’ (P4) or ‘Geiger counter’ (P12).

Exploring the Projection condition was often described as a ‘spatial’ experience (P1, P2, P3, P12). P12 described that it’s *“complex, because it doesn’t correspond to a surface but to the Space around me. When I move it further away or closer to me, with this speed, it kind of corresponds to a spatial experience”.* As participants felt that the vibrations were caused both by their actions and by their surrounding space, the Projection condition was associated with ‘less control’ (P1, P2). Participants again were very conscious of the vibrations, P1 stated that it effected their fingers.

Vibration

Unsurprisingly the Vibration condition was experienced as, well, vibrating. Asked what it felt like, P1, P4, P8, P7 and P12 provided examples of devices that either vibrate themselves (*“It’s the same as when I use my electric toothbrush. It sort of... tickles a bit”* - P1) or objects indirectly vibrated by remote machinery (*“As if I would be sitting in the subway and the seat vibrates.”* - P12). Others (P8, P10, P2) suggested that the vibration felt electric, like *"grabbing an electrical fence that is not very high voltage.”* (P2). Finally, P5 felt said *“well my first thought was, that it was a bit stressful, I guess. Like that I should um, like if you get a notice or an alert or something”* While these results appear rather obvious they provide a useful contrast to the other conditions

Self Observations

When participants answered the question ‘What does it feel like?’ with a description focused around themselves, we placed the description in the *self observations* category. Within this category two groups emerged. One, *holding the pointer* consisted of descriptions of how the haptic feedback influenced their hands. The other, *moving the pointer* was participant’s descriptions of their behavior when interacting with our system.

Holding the pointer

While vibrations can have a positive, relaxing effect (e.g.: [5]), many participants, however, (7 of 12) commented negatively on the experience of holding a vibrating object. Participants remarked that the vibration interacted with their fingers in an unpleasant way (P1, P2) i.e.: *“If I did this for a while it would feel like my hand was a sleep”* (P2) and that this unpleasantness continued even after the vibration was removed *“in my hands it still tickles a bit”* (P3).

Of all people who commented negatively on the vibrations most (5 of 7) pointed out that the unpleasant feeling went away for the mapped vibrations of the Translation and Projection condition. For example, when describing the Translation condition, p3 stated that *“It did not spread out that much. It felt more like that the resistance was in [the tip of the pointer]. It’s not that I didn't feel it. It was just ... my hand is fine now. I can't feel it now. But after [the vibration condition], I could still feel it after it was out, in my fingers. [The vibration condition] kind of left traces.”*

Moving the pointer

Participants stated that they felt the Translation and Rotation condition provided them with a more exact understanding of their movements. While they did not believe that they could move with more accuracy, they felt that they could reproduce a movement with more precision (9 of 12).

Asked to draw an infinity sign and given the option to use any of the conditions, participants typically (9 of 12) chose the Translation condition. P2 explained that *“[If I had to draw] one or two perfect infinity signs, then it probably would not help me so much, but if my life depended on drawing a thousand, then it probably would”.* This heightened sensitivity to their movements also influenced their behavior. Typically, participants moved the pointer slower with haptic feedback present and faster without it. When asked why this was the case, P12 explained that *“It’s because I was paying attention to the impulses before, as they were reacting to my movements. Now, without the impulses only my motion is left without the additional perception I had before”.*

Meta Descriptions

A third way of answering the question ‘What does it feel like?’ were responses that took a broader view and attempted to contextualize the experience, either in time or in relation to others. The two most important themes from this grouping were descriptions of the *origin of the vibration* and descriptions of a *perceptual shift,* from experiencing a pulse-train to a richer material experience.

Origin of the Vibrations

In the *Vibration* condition, participants did not have any specific impression regarding the origin of the vibrations. They just seemed to come from the pointer.

This was different for other mapping conditions. P1 and P3 stated that they felt that for the *Translation* mapping the vibration came from the top of the pointer. P5 felt their perception switch between top and bottom while P2 felt it came from both ends at the same time. This was related to the experience of P8 who felt that the vibration was caused by the environment the pointer was in and P5 and P7 who stated that the vibration felt like it was caused by a medium the pointer passed through. P2 specified further that while the vibration comes from the top or bottom, the pointer is vibrated from its core. P12 also felt that the vibration came from the core of the device.

The origin of the vibration was less clear for the *Rotation* condition. Here participants did not feel that it came from the ends of the pointer. P5 for example felt that it was ‘everywhere’. P12 and P2 felt that the vibration originated from the surface of the pointer. This is contrasted by P11 and P10 who felt that the vibration came from within. P10 stated that the vibrations felt “as if there were an object inside the pointer”.

In the *Projection* condition P12 and P11 felt that the vibration was caused through interaction with the room. P12 felt that the origin of the vibration could be either close or far, depending on the mental images used to think about it.

Perceptual Shifts

One of the most interesting questions was how something that was considered to be an irritating vibrating object could transform into something with new physical properties that participants enjoyed moving. Throughout the interviews we were able to identify clear steps in this process:

(1) Initially participants would focus on the impulses themselves, often unsure what they are experiencing. For example, asked to describe their experience, P8 explained that *"I don't know what the right word for it is, but it, they're sort of discreet pulses"* while P11 was displeased that it was *"just vibrating every time I put it anywhere"*. P7 also disliked her initial experience, stating that *"it kind of feels like it's in pain"*.

(2) Eventually participants learned to understand the mappings and focused their descriptions on them, sharing observations such as *"When I move the stick here, its vibrating and when I stop it stops as well"* (P3) or *"Ahhh so it vibrates faster as I move it faster and it vibrates slower when I move it slower"* (P7).

(3) Understanding the coupling between motion and vibration was not sufficient for creating material experiences. Instead it appears as though at some point, when interacting with the mapped vibration, the perception somehow shifts. For some this happened very fast, others had to move back and forth between couplings for this shift to happen. Sometimes we could tell, based on exclamations, that the shift had occurred. Participants spontaneously exclaimed the following, after having experimented with the mappings: *"Oh, that's neat. It's just so different, it, it, I mean, that reaction, it's totally different"* (P7) or *"Woah. It feels like coloring with vibrations"* (P3) and, possibly inspired by the magic-wand like shape of our pointer, *"I have magic power, I think. (laughs) I don't know. Yeah, magic power"* (P5).

Once the perception-shift occurred, participants no longer described the feedback in terms of impulses or couplings, but in terms of interactive experiences. This perception shift lead to an experience which was both qualitatively different than before as well as novel. For example, P11 described the process of adding a mapped vibration to the pointer that "*It became more*" and that *"the vibrations [] make it feel like something different, like something it's not"*.

We observed an interesting tension because of the way the experience shift lead to an experience that participants were both familiar with from the physical world, while at the same time being very foreign. This is captured in a description by P8: *"I have this, uh, 3D printer that has a little knob that you use to [control a] simple interface, and it kind of clicks like that. So, that was actually what came to mind. But it, it's kind of, it's not something you're used to experiencing"*. The foreignness of the experience was also described by P7 who, when their perception of the Translation condition shifted, explained *"it feels quite exciting actually like this. I don't think I've ever felt this before [...] it feels as if there is something, like there is something invisible, like obviously there isn't but ... but there is some kind of force field that I cannot see, influencing it. Which kind of confuses my brain a little bit"*. The dissonance between what participants experienced and what they thought they should experience is also highlighted by P7 who later expressed her worry: "*I hope you don't think I'm crazy"*.

The perception change was difficult to achieve during the Projection condition due to the complexity of the mapping. Only two participants (P8, P12) were not able to create a mental model that fully explained the mapping. Most others felt that there were external sources influencing the feedback, which introduced a source of uncertainty, preventing the perceptive shift from fully establishing itself.

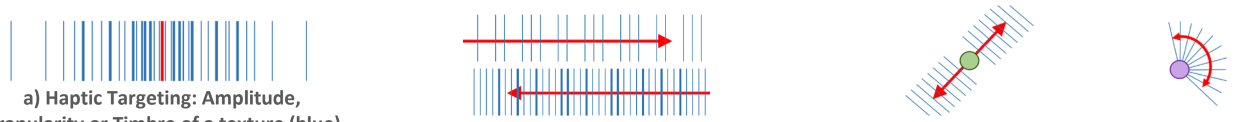
Breakdown Conditions, Limitations

The Translation and Rotation mappings lead to very strong material experiences. However, they required users to move both 'correctly' and very steadily. For example, if a participant changed the position of the pointer in the Translation condition they would almost always also change its orientation. Similarly, it is hard to change the orientation of an object in free space without also slightly changing its position. When the movement and the mapping did not match, participants felt vibration that seemed to react to their movements without synchronizing to what they were doing. In these situations, users commonly considered the pointer as if it was a small creature, with intentions and agency of its own. For example, P3 described this as *"an animal sleeping and just moving a bit around. It's not much, just very little vibrations. So, for example, there is nothing now, but if I move my hand to roll it around, it moved."*

When we touch a physical surface, we can move our hand very steadily, because it is supported by the material we are touching. In midair, such steady motion is difficult. Sometimes user's hands move slightly without the user intending it. This caused impulses which did not match the expected behavior of the pointer. Both these issues of mismatch between motion and mapping, as well as user precision pose a design challenge.

DISCUSSION

There is a perceptual link between movement and vibration. Together, they enable us to experience textures. Various prototypes build on this observation to create virtual textures. As these virtual textures can be created without the normal force of a supporting surface, we can conceivably render textures in mid-air. Mid-air textures do not have a clear motion-to-vibration mapping as in other haptic rendering systems. It is not even clear, what the properties of a 'good' motion-to-vibration mapping should be. Therefore, we set out to explore various motion-to-vibration mappings.



a) Haptic Targeting: Amplitude, Granularity or Timbre of a texture (blue) can be concentrated around a virtual target (red)

b) Directional Haptics: Textures (represented in blue) change based on the direction one moves through them

c) Directional Objects: The green object communicates haptically that it is mapped to linear control, the purple one to rotary control.

d) Dynamic Objects: Based on context the green object might switch functionality from slider to rotary encoder. The granularity can indicate the required precision of the application

e) Augmented Proprioception: When the hand moves through space, the user perceived pulses at fixed intervals. Participants felt that this increased the precision of their movements

Figure 4 – Possible ways of using textures in gestural interfaces, see also Video Figure 2.

Two of the mappings we tested, Rotation and Translation, did indeed have properties that allow us to consider them as 'successful' mappings. Participants experienced additional friction, force and weight when interacting with them. While we do not suggest that these sensations are identical to the texture experience when touching a surface, based on the interviews we find them sufficiently similar to use the same word for both. From now on we will use the word 'texture' in a loose definition that includes mid-air textures.

Benefits of Using Textures

We found that textures had a series of benefits over using regular vibration as haptic feedback:

Less Irritation - Using textures for conveying vibrotactile information does not cause the irritation that is often associated with vibrotactile feedback. Textures are interesting to move through, while regular vibration is considered irritating in a similar way that an electric toothbrush might be.

Added 'Quality' - Adding textures to an object changes its perceived quality, when moving objects through a texture they were perceived as heavier which was experienced as being 'higher quality'.

Providing users with Agency - Using textures provides users with a sense of control. If information is represented as regular vibration, the user has limited control over when or how it is perceived. Using mid-air textures provides the user with a way of anticipating what they should feel if they perform a given action. Information can be encoded to change the 'feel' of that action. The user can then explore this information at a time and pace of their choosing. This provides user with a greater sense of agency over the interactive system.

Improving the Experience of Control - In addition to providing users with a sense of agency, users also feel as though they can be more precise in their movements. The texture acts as an additional feedback channel that helps users observe their own actions. Users felt that textures help them repeat the same gesture multiple times with higher precision. This could be used to provide people with more confidence in using gestural interfaces or improve movement and gesture learning.

Concrete Applications using Textures

Here we present some simple interactions that leverage these textures to different degrees (see Figure 4 and Video Figure 2). The intent of this section is to demonstrate how existing gestural interaction systems can leverage our results.

Haptic Targeting - Haptic systems are often used to convey spatial information. A device might vibrate when pointing toward an interesting location [31] or the pulse frequency or timbre can be modulated based on the distance to a target [12] (See Figure 4a and Video Figure 2a, at 01:25).

We created such a targeting application. We created a texture using the Translation mapping and modulated timbre and amplitude based on the distance to the target. We also implemented a version without the mapping. Anecdotally, users are able to find the target in both versions, but the textures were more pleasant to interact with than vibration.

Directional Haptics - One of the problems with haptic Targeting was described by user P5 who stated, *"I feel like I'm looking through a periscope"*. What they were referring to is true for both textures and vibrations. It is difficult to get the 'big picture', as one can only experience the singular contact point between the pointer and the virtual texture. This makes finding haptic targets a chore that involved carefully scanning through volumetric space. We created an application that provides users with a sense of the direction of the target (see Figure 4b and Video Figure 2b, at 01:37).

By tracking changes in distance, we know if the user is moving towards or away from a target. We can generate a different texture based on the user's movement. The directional haptics appeared to primarily help find the general vicinity of the target. We suggest this approach be combined with *haptic targeting* for finding the precise location.

Directional Objects - The Projection condition, which provided spatial information to users, was both the most confusing and the least enjoyable mapping. This suggests to us that providing spatial information may not be the application that best takes advantage of textures.

Rather than using mid-air textures for indicating locations in space, we can use them to provide objects with additional affordances. By constraining the mapping to a single dimension, or a small number of dimensions, we can give objects 'directionality'. If we map a texture to the 'roll' dimension, a movement in this dimension sticks out relative to other movements. We use this phenomenon to create a series of controllers with prescribed mappings. (See Figure 4c and Video Figure 2c, at 01:49).

We created a slider that could be controlled by movement in a single arbitrary dimension (either x, y, z, pitch, yaw or roll). Upon picking up the controller, one can immediately identify the required motion for adjusting the slider without requiring a visual aid.

Dynamic Objects - Such augmented directionality need not be static. The '*direction'* of the object can be changed when context or tasks switch. In addition to changing the 'direction', the scale (by adjusting granularity, see [38]) can also be modified. This can convey to the user if they should perform a fast or slow gesture (See Figure 4e and Video Figure 2e, at 02:04).

Augmented Proprioception - Users feel that they can move with greater precision when moving the pointer through a texture. The perceived ability to move with greater precision would appear most useful if one's hands were free to manipulate one's surroundings. Moving the vibrotactile actuator from the handheld pointer to a wearable device preserved the experience of precise motion while allowing the user to hold tools or perform gestures unburdened by a tangible pointer (See Figure 4f and Video Figure 2f, at 02:17). While worn on the wrist, the feedback can still provide *dynamic directionality*, suggesting preferred movements to the user.

Key Conceptual Takeaway

For us, one of the most interesting observations was the clear perception-switch from the participants' hands being vibrated *by* the pointer to the participants experiencing textures *through* the pointer.

This switch can be considered a Gestalt phenomenon: Individual pulses are bound together by movement and perceived as a larger *interaction gestalt* [36,39], similarly to how the black shapes of Kanisza's triangle lead us to perceive a white triangle [13]. Like bi-stable images or foreground-background illusions the emerging texture experience is also multi-stable. Users could change what they perceived by 'imagining pictures' or 'changing their intention'.

Another way of thinking about this perceptual shift is one of attention and agency. Participants initially focused on the object and haptic information provided to them through the object. When experiencing a texture, the focus of attention moved beyond the pointing device, the attention was directed at the interaction. The pointer transforms from an object that is being observed, to a tool through which participants actively explored the haptic experience.

The perspective switch changed the way information provided through vibration is interpreted. Before the perception switch, vibrations are experienced as symbols that provide information, for instance, when operating a telerobot, a user might receive a vibration, symbolizing that the robot is being touched [35][7]. In our case, once the perception switch took place, vibrations were no longer considered as symbolic carrier of information. For example, when participants stated that moving the pointer felt heavier, they did not mean that the vibration represented 'heavy', they meant that they experienced increased weight.

Conclusion

So, can we experience haptic textures in mid-air? We found that, based on mapping, experiences very similar to texture can be created. If an object just vibrates without reacting to movement, it is experienced as a device, such as a toothbrush or vibrating smartphone. If an object vibrates based on where it is pointed, it feels more useful, but still like a device – maybe a Geiger counter or metal detector. In our Rotation and Translation condition, however, the way the vibrations were experienced transformed, leading to a material experience related to texture. These textures are more pleasing than 'traditional' vibration and make moving a device more interesting – as if it had higher material quality. Systems using mid-air textures can provide users with a stronger experience of agency and a better sense of control when interacting with them.

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[7] See also Ihde's account of hermeneutic and embodied mediation, as summarized by Verbeek [41].

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