Tapping and Rubbing: Exploring New Dimensions of Tactile Feedback with Voice Coil Motors

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ABSTRACT

Tactile feedback allows devices to communicate with users when visual and auditory feedback are inappropriate. Unfortunately, current vibrotactile feedback is abstract and not related to the content of the message. This often clashes with the nature of the message, for example, when sending a comforting message.

We propose addressing this by extending the repertoire of haptic notifications. By moving an actuator perpendicular to the user's skin, our prototype device can *tap* the user. Moving the actuator parallel to the user's skin induces *rubbing*. Unlike traditional vibrotactile feedback, tapping and rubbing convey a distinct emotional message, similar to those induced by human-human touch.

To enable these techniques we built a device we call *soundTouch.* It translates audio wave files into lateral motion using a voice coil motor found in computer hard drives. SoundTouch can produce motion from below 1Hz to above 10kHz with high precision and fidelity.

We present the results of two exploratory studies. We found that participants were able to distinguish a range of taps and rubs. Our findings also indicate that tapping and rubbing are perceived as being similar to touch interactions exchanged by humans.

ACM Classification: H5.2 [Information interfaces and presentation]: User Interfaces, Haptic I/O; B 4.2 Input Output devices.

General Terms: Design, Human Factors

Keywords: force feedback, haptics, vibrotactile, user interfaces, voice coil motor.

INTRODUCTION AND MOTIVATION

Vibrotactile feedback has been widely employed for eyes-free communication, which is particularly valuable in mobile scenarios. When auditory feedback is socially inappropriate [12] or used for other cues, vibrotactile feedback can be the best or even the only channel that allows a device to communicate with the user [14].

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However, current implementations of vibrotactile feedback are limited. Vibrotactile feedback can convey a variety of signals, but these are generally perceived as conveying urgency. While this is appropriate for alerting users, it might be less appropriate for notifying users about a non-urgent, enjoyable event, such as the receipt of a text message from a close friend. It seems particularly inappropriate if the tactile ring *is* the message, such as when trying to communicate "I am thinking of you" over a messaging system.

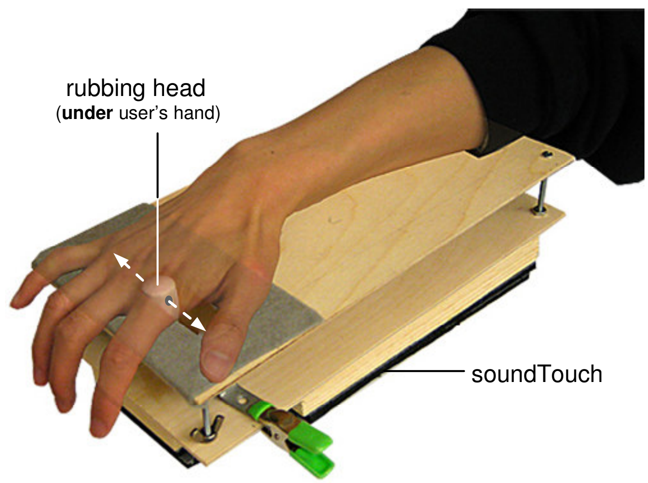

Figure 1. Rubbing interaction implemented using our soundTouch prototype.

We propose extending the haptic vocabulary of notification and messaging devices with tactile messages inspired by human-human communication. We make two contributions:

1. We introduce two new types of haptic feedback, *tapping* and *rubbing*. These are modeled after their human-human counterparts and designed to convey attention and comfort, rather than urgency.
2. We report the results of a user study demonstrating (a) that users indeed perceive the above modalities as tapping and rubbing as experienced in human interaction and (b) that users can distinguish a wide range of tapping and rubbing frequencies and amplitudes.

The proposed techniques cannot be implemented with traditional vibrotactile method, because these methods cannot produce sufficiently low frequencies. Below 20Hz, the offset (eccentric) DC motors used in these devices can no longer produce noticeable displacements. To implement rubbing and tapping we therefore developed a haptic device that we call *soundTouch*. *SoundTouch* uses a voice coil motor from a computer hard drive to sidestep the mechanical limitations of traditional vibrotactile devices. As a result, soundTouch supports a large space of tactile designs inaccessible with traditional vibrotactile methods.

In the following, we give an overview of the related work, introduce soundTouch, and describe how we implemented tapping and rubbing. We then present two exploratory studies on the quantitative and qualitative expressiveness of tapping and rubbing. We close with a discussion of our findings.

RELATED WORK

We draw on three areas of related work: force feedback, haptics in HCI and applications of hard drive actuator technology.

Force feedback

Force feedback offers a large range of tactile sensations with the goal of mimicking real world experience, and is often used in virtual reality environments. One approach commonly used in haptic gloves is to use an auxiliary system of actuators with pulleys and cables to provide force feedback [1]. Pneumatics have been proposed to reduce the size of the pulleys but still require a wearable device [4]. Salisbury's *Phantom* uses a similar approach to create visual haptics whereby a user can feel a space by holding a stylus connected to a rig of actuators [20]. Sensors detect the orientation of the user's finger and the rig generates the appropriate force feedback. These approaches can be effective for desktop scenarios, but require users to hold the stylus to get the feedback.

Haptics in HCI

Our work is guided by a large body of work in psychophysics. Studies on locus have found fingers and hands to be more sensitive than thighs and arms [10]. Cutaneous sensitivity is generally accepted to be logarithmic in nature, both for the detection of pressure as well as the resolution of frequency [3].

Hayward and MacLean present a good introduction to haptics [13]. The following projects highlight some of the technologies being used to create haptic interfaces.

The most widespread technology is the offset motor used to generate vibrotactile feedback in mobile phones and game controllers. Despite the aforementioned limitations of the technology, researchers have been able to generate a variety of uses for vibrotactile feedback. Li developed a technique similar to pulse-width modulation that generates on the order of 10 different amplitudes of vibration [17].

The *C2 Tactor* uses an alternative approach, generating vibration by moving a small contactor via a voice coil actuator [2]. Brown and Brewster have done a significant amount of work with the C2 Tactor showing how a variety of haptic icons can be generated by modulating waveform and location [5,6,7]. Chang uses a similar approach with *Multifunction Transducers* that allows a single actuator to be used for vibration and audio [8].

Haptics has also been proposed as a way of allowing users to communicate with one another. *HandJive* explored how users would communicate with a haptic input/output device using force-feedback [11] while Chang's *ComTouch* explored how users would communicate with one-another using vibration [9]. Both employed an unstructured approach that resulted in an arbitrary abstract language

Poupyrouv's *AmbientTouch* uses layers of piezoelectric to generate vibrotactile feedback in PDAs [23]. Luk implemented an array of piezoelectric tabs to generate lateral skin stretch, allowing different waveforms to be felt under the thumb [18]. Lee's *Haptic Pen* used a solenoid to mimic the feeling of pressing down with a stylus [15].

Rubbing and tapping have been proposed as input mechanisms for interacting with touch screens [22] and with synthesized surfaces[21], but not as forms of feedback.

Applications of hard drive actuator technology

Hard drive actuators are attractive for their low cost, small size, and resilience. They have been used in biomedical telerobots to provide combined actuation and force sensing [19]. In subsequent work, hard drive technologies were used in multi-fingertip haptic displays for detecting surface variation in virtual and telepresence environments [26]. A similar multifinger display has been studied for its information transmission characteristics, employing three-dimensional taps and vibrations [24]. In a very different direction, hard drive motors were used to create a force feedback controller for steering and experiencing music [25].

SOUNDTOUCH

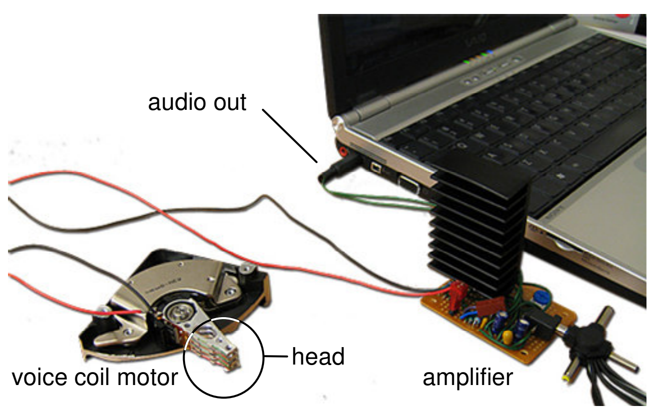

Figure 2. Our *soundTouch* prototype translates sound signals into tactile feedback.

Figure 2 shows our soundTouch prototype—it forms the basis for a series of tactile interfaces we have created. The prototype consists of a voice coil motor extracted from a disk drive. It is connected to the audio out jack of a notebook computer. The notebook computer delivers a sound signal that soundTouch converts to motion similar to the way a speaker converts an electrical signal into audible sound. Between the audio out and the voice coil motor is a custom amplifier circuit board that amplifies the 150mVPP of the audio-out jack to the 12V required by the motor (based on *Analog Devices AD815AYS;* see APPENDIX A for more details).

The key element is the voice coil motor that we extracted from a regular hard disk drive (a 3.5inch *Western Digital*). Figure 3a shows a close-up of the voice coil motor. Applying a voltage to the device actuates the coils, which rotates the arm. When creating tactile interfaces based on soundTouch, we attach covers with different tactile qualities to the head of the drive to create different tactile effects when it comes in contact with the skin (Figure 6).

Features

By feeding it a sound file, soundTouch can be manipulated freely, i.e., it can play back an arbitrary signal rather than, say, just a signal of a single frequency. In particular, it allows us to perform very coarse as well as very fine motions and any combination thereof. SoundTouch can produce actuations orders of magnitude below the audible range, i.e., << 20Hz. Additionally, soundTouch can move the head to a particular location at configurable speed.

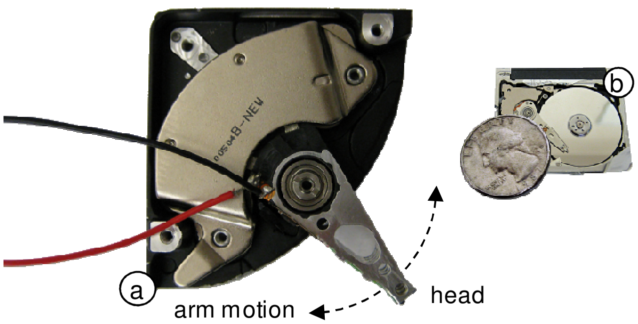

Figure 3. (a) Close-up of the voice coal motor in soundTouch (b) micro drive next to a US quarter.

At the same time soundTouch can perform fast and delicate motions when fed a high frequency signal. For the sake of illustration, we have developed a demo application that makes soundTouch play back audio files, including wave and mp3 music files. SoundTouch can reproduce frequencies considerably outside the range relevant for tactile feedback (15 kHz and potentially higher). If the played signal contains frequencies in the audible range, then the device will vibrate audibly, basically functioning as a speaker.

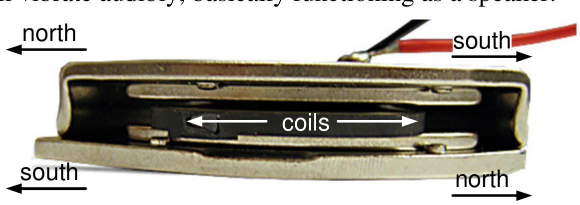

Figure 4. Side view of a voice coil motor

Unlike the voice-coil-like motors used in the C2 Tactor [2], the hard drive motor in soundTouch moves the coils instead of the magnet. Because the coils are lighter than the magnet, soundTouch can generate greater acceleration of the armature with less voltage. The hard drive motor in soundTouch uses a sandwich of two bipolar magnets (Figure 4), further increasing force.

The voice coil motor in our current prototype measures 5.5cm x 3.6cm. Future versions may achieve form factors suitable for mobile applications by using the mechanics from a smaller hard drive, such as an IBM micro drive (Figure 3b). Customized designs can generate even higher forces [16].

TAPPING AND RUBBING

We have built two tactile interfaces based on soundTouch. Both interfaces are designed to emulate common human-human touch gestures, namely *tapping* and *rubbing*.

Tapping

Figure 5 shows our *tapping* prototype. We created it by attaching a wooden "hammer" to the head of our soundTouch prototype. By driving the device with signals in the range around 1Hz, the device produces a tapping motion.

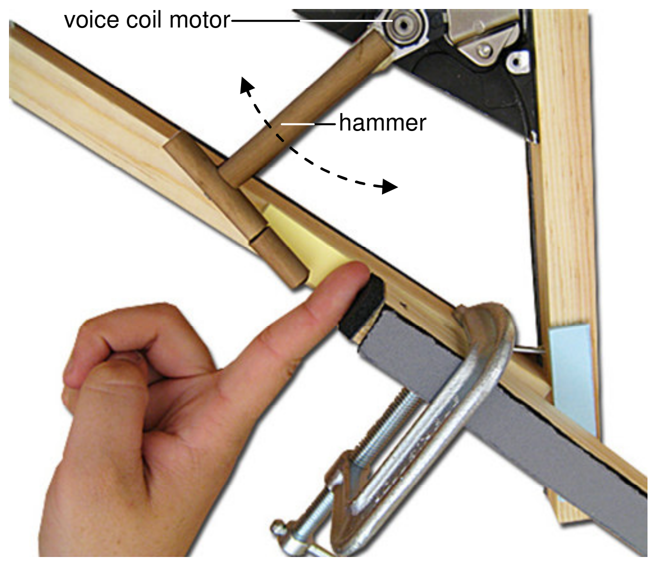

Figure 5. Tapping prototype: a hammer attached to the head of the soundTouch prototype taps on the user's finger.

The arm is 8.1cm long and has an angular displacement of 30°, resulting in a linear displacement of 3.4cm. A layer of foam at the bottom of the device reduces noise and structural vibrations.

We explored a number of materials for the hammer head including: a rubber eraser, a trackpointer tip, rubber cement, a toothbrush, glue, a paper clip, cotton, styrofoam, epoxy, wax, a sponge, a rubber band, and a foam earplug. Figure 6 shows some of them. The main factor impacting the experience was whether the material was deforming (cotton, foam) or non-deforming (rubber, epoxy), with little subjective difference within each of the two classes. Since the experience with deforming materials changed over time, eventually degrading to feeling like a non-deforming material, we ended up using a non-deformable head and chose the most durable one of them: an epoxy glue dot.

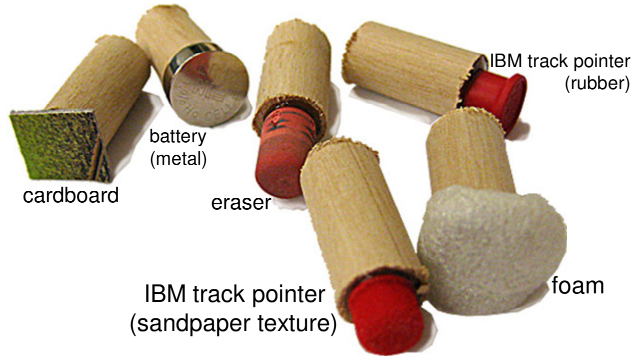

Figure 6. Some of the materials we have used as hammer heads

To quantify the range of forces generated by the tapping prototype, we mounted a force sensor (a *Measurement Specialities FC22*) perpendicular to the motion of the contact head and measured static force generated for voltages at 0.5V increments in the range 0V-12V. The force generated by the voice coil motor we used is characterized (r^2 = 0.977) by a linear regression: F=0.101V – 0.83, where F is force in Newton and V is voltage in Volts.

Rubbing

Figure 1 shows our rubbing interface. As shown in Figure 7, rubbing is achieved by moving the head tangential to the user's hand, so this interface is literally "orthogonal" to the tapping interface.

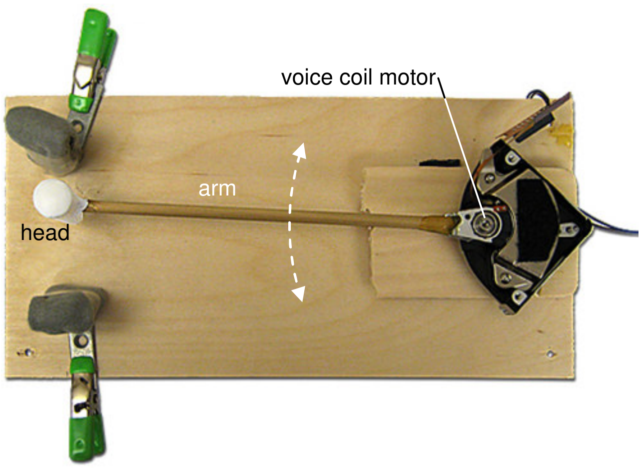

Figure 7. Rubbing prototype (cover removed).

During piloting, the head occasionally got caught on the edges of the user's hand. To address this, we used a window limiting the contact area to the participant's hand size (Figure 8). Two clamps and repelling magnets on the sidewalls of the window limited lateral motion. These two fixes eliminated the problem.

An initial prototype used a shorter arm (8cm) as shown in Figure 8b. We eventually replaced it with the longer arm shown in Figure 7 (21cm) to obtain a longer rubbing motion (6.5cm). By mounting the head perpendicular to the plane of motion, we obtained a very even rubbing motion. Repelling permanent magnets at the bottom of the contact head and underneath the device keep the head suspended and provide the desired pressure against the user's hand. The magnets effectively eliminate vertical torque forces on the soundTouch device.

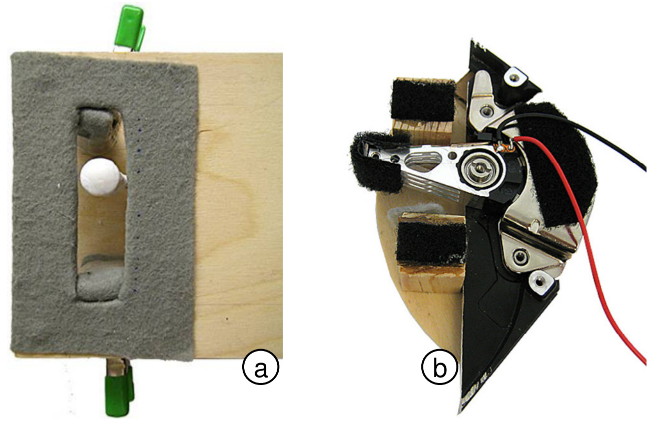

Figure 8: (a) Rubbing prototype with cover; only the head shows through (b) earlier prototype.

For rubbing we explored a similar set of materials as with the tapping prototype. Unlike with the tapping prototype, the texture of the material used for the contact head significantly changed the rubbing experience. Many of the materials created a rough sensation that was uncomfortable or dragged on the skin too much. Smoother materials such as the glue dot felt too slick to elicit a rubbing experience. We ended up blending the two approaches by covering a smooth round surface with Teflon tape. This created a smoother surface than many of the materials we had tried earlier, and had an almost skin-like quality (Figure 9b).

Figure 9. (a) Bare head and (b) covered in Teflon tape.

SCENARIOS

The primary motivation that inspired rubbing and tapping is to allow devices to extend the tactile vocabulary of devices. This is especially relevant when exchanging simple messages with close associates or family members. The use of a richer tactile vocabulary allows sending simple self-contained tactile messages, rather than requiring the combination of a generic vibration alert and a textual message.

For example, a haptic message could update others about common daily events (e.g. "I am leaving for home"), information that could be useful to communicate but not sufficiently important to merit a phone call.

Rubbing and tapping bear inherent associations with physical touch. This makes them particularly suited for messages that match the underlying connotations, such as reminders (tapping) and expressions of care and comfort (rubbing).

For the same reasons, the more expressive haptic vocabulary created by tapping and rubbing is well-suited for personal tactile ringtones for close friends and family members. Beyond this main scenario, we feel that a richer tactile vocabulary could be useful for the following situations.

Truly silent alerts. Vibrotactile alerts are intended to be unobtrusive, yet people in close proximity can often hear other people's phone vibrating. A phone left on a desk can make a loud noise when vibrating. Rubbing, in contrast, is *silent* and can therefore be used for truly unobtrusive alerts. Notifications could be administered by a mobile device or, in a office setting, through the user's chair.

Alerts guaranteed to be noticed. When users are on the move or in a noisy environment there audible ringtones might not be heard, vibrations not be felt. Escalating alerts via harder taps provides a means to deliver crucial alerts.

Game controllers. Many popular game controllers use Immersion's vibrotactile technology in their rumble packs to augment the gaming experience [1]. Vibration is a good representation for some events, such as the user driving off the road or being shot at. For positive events, such as when picking up a health pack, a rubbing sensation might be better suited.

In-car navigation. Car navigation systems use speech output to inform drivers where and when to turn, which can interfere with conversations with other passengers. Vibration alerts are easily missed, because cars tend to vibrate due to road irregularities. This limitation can be avoided by communicating turn directions or traffic events using tapping and rubbing, administered through actuators in the steering wheel or in the seat.

USER STUDIES

We conducted two exploratory studies. Their purpose was to investigate how users perceptive taps and rubs and how well users can distinguish different types of these signals. This would allow application designers to create messages out of sequences of taps and rubs.

STUDY 1: USER PERCEPTIONS OF TAPPING

The first study investigated participants' perception of tapping. We varied *amplitude* and *frequency/number* of taps. We investigated whether users could *distinguish* and *identify* different amplitude and frequency levels.

Apparatus

The tapping device shown in Figure 5 was used to present taps to the participants' fingertips. For each stimulus condition, a stop guard was calibrated to each participant's index finger. Sound waveforms were generated using a C++/C# program with DirectSound on a 2.0 GHz PC running Windows Vista.

Independent variables

In the *Amplitude* condition, participants were presented taps of differing amplitudes. In the *Frequency* condition, participants were presented taps at differing frequencies (taps per second).

Tasks 1: Distinguish

When performing the *Distinguish* task, participants experienced a stimulus pair twice on each trial before making a forced-choice decision about which one felt stronger (*Amplitude* condition) or faster (*Frequency* condition). The interval between pair members was 1.0s and the interval between pairs was 2.0s.

The cues users can use to distinguish tap sequences depend on whether frequency or duration is kept constant. Varying tapping frequency leads to a different number of taps if duration is kept constant. As a pilot participant pointed out, this allowed participants to differentiate between the "slow ones" and the "really slow ones" by counting taps. Keeping the number of taps constant, in contrast, led to sequences of different lengths.

We explored both aspects. In the *Frequency* condition, half of the participants were presented stimuli of constant duration (*ConstantDuration*) while the other half of the subjects were presented with a constant number (*ConstantNumber*). Tap sequences were 3 taps long. The design was within subjects for *Amplitude* and between subjects for *Frequency*.

All participants experienced the same sequences of stimuli. The order of stimuli presentation was pre-randomized. This allowed us to compare per trial performance across participants. For the *Distinguish* task, there were 3 blocks of 22 trials. Each block consisted of all pairs of stimuli differing by 1 or 2 levels over the 1-7 level range, as shown in Table 1. We considered pairs of stimuli differing by more than 2 levels, but pilot studies suggested these were fairly easy to differentiate and so we did not examine them in the formal study. Participants were given a 5 minute break between blocks.

We used 7 different amplitude levels evenly spaced from 0N to 1.0N and 7 different frequencies from 5Hz to 29Hz.

	1	2	3	4	5	6	7
1		x	x				
2	x		x	x			
3	x	x		x	x		
4		x	x		x	x	
5			x	x		x	x
6				x	x		x
7					x	x	

Table 1: Stimulus pairs differed by one or two levels. The resulting pairs are marked with an x. Entries shaded in gray represent pairs that differed by two levels. Columns and rows denote level of first and second tap.

We measured error rate. For the distinguish task, a trial was considered an error if the participant identified the wrong stimulus as stronger.

Task 2: Identify

When performing the *Identify* task, participants were presented with the same stimulus twice, again with an 0.5s interval in between, and asked to rate them on a 7-item Likert scale (1 = slow/soft ; 7 = fast/hard). The same 7 levels of amplitude and frequency used in Task 1 were used in Task 2.

One pre-randomized block of 49 trials was presented to participants. To avoid sequencing effects, the block consisted of a sequence of values such that both orderings of every pair of numbers from 1-7 appeared in the block.

For *Amplitude*, the contact head was placed 9° from the participant's fingertip, resulting in an arclength of 1.0cm. For *Frequency*, the contact head was positioned 4° from the participant's finger tip resulting in an arclength of 0.45cm. These distances were chosen based on pilot studies. The stimulus was generated using a 250ms square wave. Although the bandpass characteristics of the soundcard dampen the signal, a consistent tapping sensation can still be generated (a plot of the output signal can be found in APPENDIX B). The presentation of the *Frequency* and *Amplitude* conditions was counterbalanced across participants.

The *Distinguish* task was always completed before the *Identify* task. This was done to give users an idea of the range of taps and rubs generated by the device, before asking them to rate taps on an absolute scale. Both tasks were completed for one stimulus condition before performing the other.

Questionnaire

For each condition, participants answered the questions "How would you describe the tactile sensations you just experienced to someone who has not experienced them?" and "Which aspects of the experience felt natural and which aspects did not?" Because we wanted to elicit how users naturally describe the tactile sensations they experienced during the study, the experimenters were careful not to mention the word "tapping" or other suggestive terms.

Participants

16 volunteers (8 female) ranging in age from 18-22 years (median 19) were recruited from within our institution. Participants received an American Express gift card as a gratuity for their time.

Two participants were left handed. Participants wore headphones playing pink noise from an MP3 player to eliminate ambient noise. Each participant took approximately 1 hour to complete the experiment.

Results: Distinguish Task

For the *Distinguish* task, error percentages were aggregated over all participants for each ordered pair of stimuli for the *Amplitude*, *ConstantDuration* and *ConstantNumber* conditions (Tables 2, 3, and 4). A row/column pair represents the ordered pairs of levels for the stimuli presented.

	1	2	3	4	5	6	7
1		2	2				
2	0		10	0			
3	2	6		17	4		
4		6	17		15	6	
5			14	6		29	8
6				4	13		25
7					2	21	

Table 2: Tapping *AmplitudeDistinguish* error in % collapsed across all participants for *Differentiate* task when being presented a stimulus pair of intensity (<row>. <column>).

	1	2	3	4	5	6	7
1		0	4				
2	4		4	0			
3	0	8		3	0		
4		4	17		4	4	
5			4	4		8	4
6				0	0		17
7					8	0	

Table 3. Tapping *ConstantDuration* Distinguish error rate in % collapsed across all participants.

Post hoc multiple means comparisons showed no significant effects for block number on error rates, suggesting no learning effects. We aggregated errors for each participant for each of the stimulus conditions. Surprisingly, participants did not perform significantly different between *Frequency* and *Amplitude* conditions ($t(15) = 0.66$, $p > 0.05$). Since we used the same trial sequences for both *Frequency* conditions, *ConstantDuration* and *ConstantNumber*, we were able to compare error rates between the groups. We aggregated errors for participants in each condition by trial number. Participants made significantly more errors in the *ConstantNumber* condition ($t(65) = 3.338$, $p<0.001$). As expected, participants performed significantly better on the *Distinguish* task for stimulus pairs that differed by 2 levels than those that differed by 1 level for all conditions (*Amplitude* $t(16)=3.777$, $p<0.01$), *ConstantDuration* $t(8)=2.95$, $p<0.05$ and *ConstantNumbers* $t(8)=2.084$, $p<0.05$).

	1	2	3	4	5	6	7
1		0	4				
2	8		15	4			
3	0	0		13	8		
4		0	0		13	13	
5			4	13		46	29
6				8	13		63
7					8	17	

Table 4. Tapping *ConstantNumber* Distinguish Error rate in % collapsed across all participants.

Results: Identify Task

Mean values of user reported levels for the *Identify* task are shown in Figure 10, Figure 11, and Figure 12. Post-hoc multiple means comparisons showed that users were able to identify the appropriate stimulus level for all levels and conditions with the exception of *ConstantNumber* for frequency levels 3 and 4.

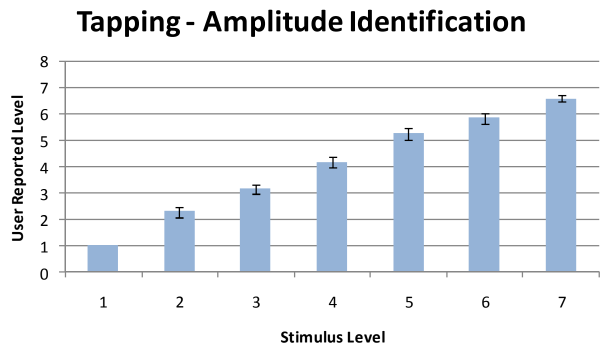

Figure 10. Mean values of user reported levels for the *Identify* task for the *Amplitude* stimulus condition. Error bars show 95% confidence interval.

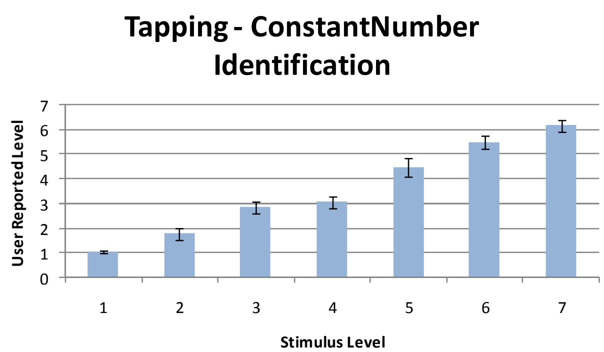

Figure 11. Mean values of user reported levels for the *Identify* task for the *ConstantNumber* condition. Error bars show 95% confidence interval.

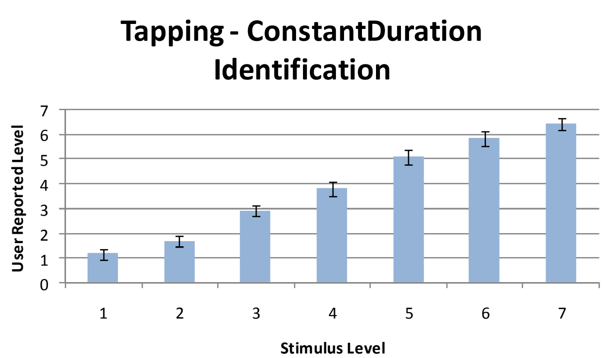

Figure 12. Mean values of user reported levels for the *Identify* task for the *ConstantDuration* condition. Error bars show 95% confidence interval.

Results of the questionnaire

When describing their perceptions, many participants used terminology drawn from human-human interaction. Thirteen of the 16 participants used the word "*tap*" in their descriptions. Additional descriptions included: "getting flicked on the finger", "tickling", "brushing something off", "drumming fingers" and "touch". Twelve participants volunteered that the experience had a human quality to it, often citing that it felt like "getting tapped on the shoulder, but on your finger". Fifteen participants indicated that the faster stimuli felt like vibrations from a mobile phone or game controller. Twelve participants mentioned that the harder taps did not feel "natural" and 5 said that the fast ones did not feel "natural".

When asking participants about in what scenarios they would want to use the respective stimuli, six participants stated that single taps would be good for mobile phone alerts in quiet environments because of their silent nature. Seven participants thought they would be useful in situations in which they could not feel vibrations, as when outside or walking around.

STUDY 2: USER PERCEPTIONS OF RUBBING

The purpose of the second study was to examine user perceptions of stimuli from the *rubbing* prototype.

Task and stimuli corresponded to those in Study 1, except for three differences. First, instead of a series of taps, participants were exposed to a series of rubs. The rubbing prototype shown in Figure 1 was used, adjusted to fit the respective participant's hand size. Second, there was no *Amplitude* condition since our pilots showed that the distance covered did not allow differentiation of differing amplitudes. Third, the *ConstantNumber* condition used 2 rubs instead of 3 taps.

The experiment was a within-subjects design for two *Frequency* conditions, *ConstantDuration* and *ConstantNumber*. Eight volunteers (6 male) from our institution between the ages of 18 and 26 participated in our study. All participants were right-handed.

Results: distinguish task

Post hoc multiple means comparisons showed no significant effects for block number on error rates, again suggesting no learning effects. To compare error rate for the two conditions, errors were aggregated across participants for each trial. Participants made significantly more errors on *ConstantNumber* than on *ConstantDuration* ($t(66)=9.077$, $p<0.01$).

	1	2	3	4	5	6	7
1		0	4				
2	4		0	0			
3	4	0		0	0		
4		0	13		8	0	
5			0	0		8	4
6				0	8		33
7					0	0	

Table 5: Rubbing *ConstantDuration* Distinguish error in % collapsed across all participants.

	1	2	3	4	5	6	7
1		7	4				
2	7		15	22			
3	7	12		22	15		
4		15	22		30	30	
5			15	30		48	33
6				22	15		56
7					15	41	

Table 6: Rubbing *ConstantNumber* Distinguish Error in % collapsed across all participants.

As expected, participants performed significantly better on the *Distinguish* task for trials in which stimulus pairs differed by 2 levels than those that differed by 1 level in both the *ConstantDuration* condition ($t(8)=2.528$, $p<0.05$) and in the *ConstantNumber* condition ($t(8)=2.828$, $p<0.05$).

Results: identify task

Figure 13 and 14 show the results of the *Identify* task.

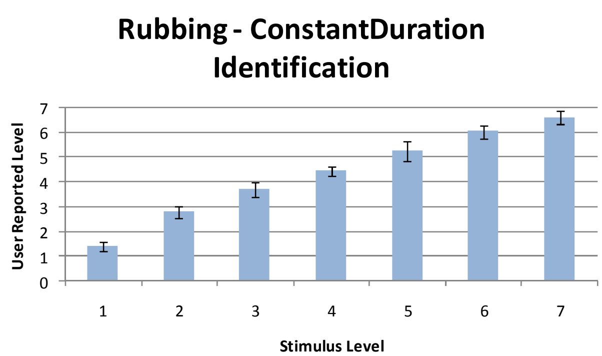

Figure 13. Mean values of user reported levels for the *Identify* task for the *ConstantDuration* condition. Error bars show 95% confidence interval.

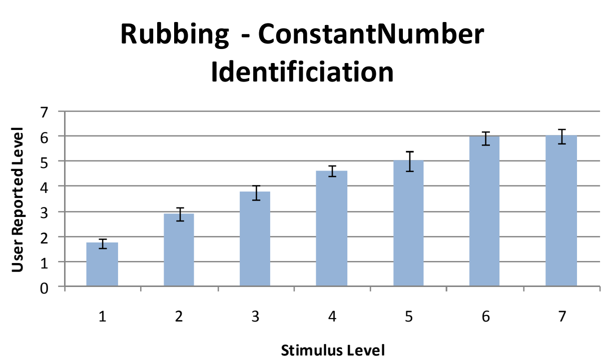

Figure 14. Mean values of user reported levels for the *Identify* task for the *ConstantRubs* condition. Error bars show 95% confidence interval.

Questionnaire results

Three of the eight participants volunteered that the experience felt like "*rubbing"*. Those that did not described it as "*grazing*" or a "*light sweeping*". Four participants volunteered that it had a human-like quality to it as if someone else was touching them. One participant said "*It felt strangely comfortable, almost like the touch of someone else. It was more like a finger touching my skin than an object.*"

Half of the participants felt that the faster rubs felt more natural while the other half thought the slower ones were more natural. Those who cited faster ones being more natural mentioned that it felt more like "sliding your hand across a table" or "dropping a marble through your hands". These participants said that for the slow ones, you could feel the actuator moving against the palm and could tell it was an artificial thing. Participants who said slower was more natural used comments like "I don't come across anything that moves that quickly" to describe their experiences. They also described the sensation as being more like "rubbing your hands together or "running a cotton swap through my hand" or "playing with a rubber eraser".

When asked about usage on a mobile phone, comparisons between rubbing and vibration inevitably came up. Four participants volunteered that they would prefer this to vibration for truly silent scenarios where sound from vibration would be annoying. Four participants suggested it would be better for in-hand tasks because it was less jarring than vibration.

Five participants described the *ConstantNumber* stimuli as feeling like they were rubbing or grazing an object against their hand while the *ConstantDuration* stimuli felt more like touching something that was moving (water, marble, bus handle, etc). One participant said the sensation caused by *ConstantNumber* stimuli "felt more like I'm shaking, whereas [*ConstantDuration*] seemed more like I'm holding onto something that's shaking".

DISCUSSION AND DESIGN IMPLICATIONS

Our experiment provides some initial insight about how people experience stimuli generated by our soundTouch prototype. A few design implications also emerge.

SoundTouch's tapping and rubbing mimic real world

The participants consistently described their experiences with terms like tapping and rubbing and seemed to readily relate the experiences to common human-human interactions.

The softer taps were consistently reported as feeling natural. The naturalness of taps was tested for the hardest and fastest ones. The fastest taps were frequently described as vibrations. This implies that tapping and vibration are perhaps on a frequency continuum, yet perceptually distinct.

The participants split on describing their rubbing experiences as rubbing or lighter grazing. This may be in large part due to the implementation, which could not push hard enough into the participant's palm. This suggests using some kind of force feedback approach with a pressure sensor and an actuator into the contact plane to maintain consistent pressure across an uneven surface. This is in essence combining tapping and rubbing.

Design of Notifications

The qualitative responses we collected indicate how tapping and rubbing cues could be used for mobile phone alerts and feedback. Implicitly, participants compare the tapping and rubbing sensations to vibrotactile feedback commonly found on mobile phones. They also suggested a wide range of scenarios for tapping. On the one hand, strong, single taps were proposed for mobile phone alerts in outdoor environments where audio cannot be heard and vibration can often not be felt. On the other hand, taps were also proposed for use in quiet environments where the audible nature of vibrations makes them inappropriate.

Although most participants thought rubbing would be too subtle for alerts, many proposed that they would be great for feedback for when the device is in-hand, like when sending a text message. Many participants described this as preferable to the current "buzzing" that they get as confirmation, which is "uncomfortable" when the device is in-hand.

Distinguishing and Identifying Taps and Rubs

The accuracy on the *Distinguish* task is high, with a few exceptions. Likewise, results on the *Identify* task show that participants can identify 6-7 levels in the range 0-1N force and 5-29Hz.

This implies that the just-noticeable-differences for these levels are smaller than the intervals we used. While more work is needed to examine this, it is clear that our approach allows a fairly expressive haptic vocabulary. We expect that the higher error rates seen for the *Distinguish* task at higher amplitude and frequency stimuli resulted from decreased sensitive for these stimuli.

For all the stimulus conditions we tested for the *Distinguish* task, participants made significantly more errors in the *ConstantNumber* task than in the *ConstantDuration* task. In other words, the force or frequency of the stimulus was less of a distinguishing factor than the number of taps or rubs. For some applications, the number of taps and rubs may have a pre-learned meaning. Although designers can leverage this to improve the learnability of haptic icons, it also limits the number of viable distinct icons.

Locations for tapping or rubbing apparatus

Several situational and physical contexts elicit special design requirements. According to our participants, walking and driving reduce one's sensitivity to tactile feedback. Likewise, the pocket location on the thigh exhibits lower cutaneous sensitivity than the fingertip, in part due to the clothing and in part due to the reduced concentration of nerve endings. Using our current scale, harder taps should be used in applications to be used in these contexts, or be adapted to requirements of specific contexts.

Rubbing (at least our current version of it) is too subtle for in-the-pocket cues. Modifying it to allow pressing into the contact surface (combination of rubbing and tapping) might mitigate that issue. For in the-hand, lighter tapping is best. Some participants mentioned discomfort with the harder taps and so for use in the hand context applications might employ softer taps. This suggests rubbing will be most effective when applied to in-the-hand scenarios.

CONCLUSIONS AND FUTURE WORK

We presented tapping and rubbing, two tactile feedback techniques based on physical human-human interaction. These techniques are the result of our exploration into low frequency feedback using our soundTouch device, which uses voice coil motors to generate tactile feedback.

We made two contributions. First, we presented two new naturalistic tactile feedback techniques, tapping and rubbing, using the soundTouch technology. Second, our exploratory user studies of these two techniques demonstrated both that users perceive them as the taps and rubs encountered in daily experience, and that they provide a large range of distinguishable cues.

Future work will explore mobile implementations of our tapping and rubbing interfaces, applications to exploit these cues, and design of haptic icons for the mobile application space. One particular interest in this space concerns the pre-learned semantics of tapping and rubbing, and how they could productively guide haptic icon design. Another promising idea is to use multiple tapping actuators to generate perceptually different icons.

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APPENDIX A – SOUNDTOUCH AMPLIFIER CIRCUIT

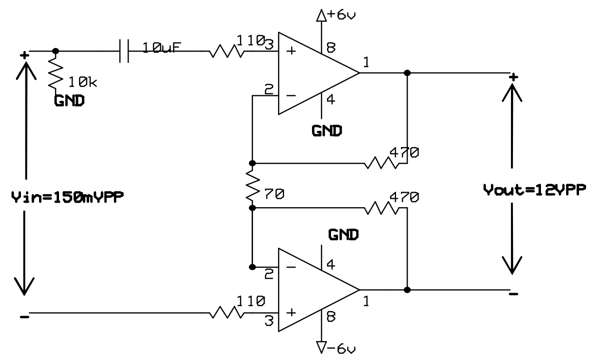

Figure 15. Amplifier component.

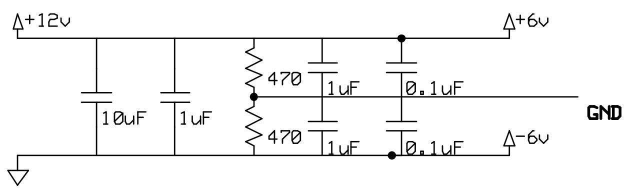

Figure 16. Voltage divider to create +6V and -6V power rails for two amplifiers.

APPENDIX B – WAVEFORM THAT GENERATES TAPPING

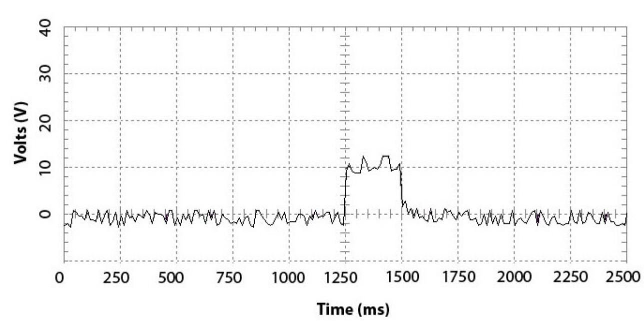

Figure 17. Voltage waveform produced by soundTouch to generate a tap with amplitude of level 7.