Emulating Human Attention-Getting Practices with Wearable Haptics

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ABSTRACT

Our computers often need to get our attention, but have inadequate means of modulating the intrusiveness with which they do so. Humans commonly use social touch to gain one another's attention. In this paper, we describe an early exploration of how an expressive, wearable or holdable haptic display could emulate human social practices with the goal of evoking comparable responses from users. It spans three iterations of rapid prototyping and user evaluation, beginning with broad-ranging physical brainstorming, before proceeding to higher-fidelity actuated prototypes. User reactions were incorporated along the way, including an assessment of the low-fidelity prototypes' expressiveness. Our observations suggest that, using simple and potentially unintrusive body-situated mechanisms like a bracelet, it is possible to convey a range of socially gradable attention-getting expressions to be useful in real contexts.

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

Keywords: Perception and psychophysics, haptic; tactile rendering; tactile semiotics, design, human factors.

1 INTRODUCTION

Getting our attention is one of the hardest things that today's computational devices and systems have to do, from a user interface standpoint. Humans value and often rely upon this utility, but it is also the source of our computers' most intrusive and annoying behaviour when unwanted or in conflict with a situation [18].

Socially adept people are able to get one another's attention in an *appropriately* intrusive manner. They do so in many ways, including use of visually conveyed body language, gestures and auditory means. Attention-getting can also convey a wealth of subtexts, including urgency, affection, impatience or a reinforcement of the social hierarchy.

Touch is one important and well documented channel of attention-getting practice for both humans and animals. Human touches for this purpose usually involve the hands and arms: a pat on the arm, a poke, a tap on the shoulder, or a squeeze can convey or reinforce this kind of message [15]. Variations in speed, force, duration and location can provide nuance to the gesture, which may be overt or discreet, and in some cases intended to be perceived in a recipient's attentional background. Another important dimension is the gesture's affective content, which may vary from purely utilitarian or impersonal, to explicitly emotional [11]. In a similar vein, the body language of animals can convey a great deal through touch: head-nudges by dogs, and purring and rubbing by cats are examples of behaviour in domestic mammals which we perceive haptically, and generally understand without effort. In the appropriate context, emulating these behaviors could serve to communicate emotional state.

If a haptic device could reproduce the physical sensations associated with these gestures, it should be possible to convey some of the same messages and layers of nuanced meaning. Existing body language, experience and culture could thus be tapped in the service of more socially intelligent computer-human coordination. This approach complements other means of using synthetic haptic signals in service of human-computer communication, including those of symbolic display [2, 17] which seek to expand the information density of a haptic channel through signals that are learned - much as we use printed symbols in order to increase our spoken vocabulary. Here, our goal is to convey a relatively small lexicon of meanings that do not require learning because they are already present in our daily lives.

Tapping into this already-existing language of touch presents several challenges. First, the haptic device must produce a sensation that is similar enough to its biological inspiration that it evokes the same response in the recipient. For example, the biological inspiration might be another human tapping on one's arm. Secondly, the *meanings* of the biological inspirations must be established unambiguously if the device is to use them effectively for communication. A squeeze of the shoulder, if it comes from another human, might mean "pay attention", "well done", "how about that?" or many other things, which may be suggested through a combination of nuance of the actual squeeze, and the immediate circumstances, including cultural environment. Thirdly, it is possible that the recipient's perception of the source of the sensation may affect their interpretation - e.g. a human being may attribute some meaning to that human tap on their arm, whereas the same sensation produced by raindrops striking a coat sleeve might not be interpreted as wilful communication.

1.1 Approach

In this paper, we describe a design sequence aimed at the first of these challenges: simply emulating the sensation of human (or in the broader case, mammalian) touch, with the scope centered on prototypically attention-requesting touches. Given the wide variety of possible sensations and mechanisms that could produce them, we embarked upon a process of "physical brainstorming" with a series of low-fidelity prototypes which afforded the ability to experience, evaluate and refine various options.

The prototypes described herein represent the initial stages of the prototyping process. The first step is an exploration of the types of sensations that can be produced using the simplest possible and most readily available elements and methods; its goal is breadth rather than depth or detail. These so-called "throw-away" (because of the low effort or love invested in them) mockups may be refined through several iterations, determining the effects of changes in material, form and mechanism. Promising candidates are further developed in a second phase, producing low-fidelity actuated prototypes - i.e. still rather simple, but now moving under computer control and beginning to explore issues of technical feasibility in conjunction with haptic experience. It is at this state that the possibilities of sensations become more concrete. These working, ac-

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tuated prototypes also afford the possibility of conducting initial pilot evaluations, giving valuable information for the next round of prototyping and refinement. Producing many low-fidelity, low-cost prototypes early in the design process can quickly reduce the wide range of possible mechanisms to a few practical, effective candidates.

2 RELATED WORK

2.1 How People Get Attention from Other People

Jones and Yarbrough performed a study in which participants recorded touch-based social interactions in their daily lives, along with the contexts of these interactions. The study segmented interpersonal touch into 12 distinct categories of meaning. Attention-getting, for example, involved "spot touches" 84.8% of the time. These were carried out using the initiators hand to contact a non-vulnerable body part (namely the arms, hands or shoulders) of the recipient in 74.2% of cases. The resultant lexicon of physical symbols provides a framework upon which to build haptic signals [15].

Motamedi notes the importance of intersensory mapping in the interpretation of tactile signals [21]. By using a tactile stimulus to evoke related experiences for the other senses, the range and richness of the stimuli can be extended beyond strictly the physical sensation into the realm of memories. This insight is critical, as the establishment of a strong metaphor is crucial if the user is to attribute humanlike characteristics to a mechanical device. A great deal of research into the effects of interpersonal touch is available in nursing literature. One example is provided by Fredriksson: while focused on improving the relationship between caregivers and patients, his study highlights the impact that touch can have on the perception of shared intent, empathy and the direction of attention. Additionally, it lays out the protocol by which the initiator is given permission to enter the personal space of the recipient [9].

2.2 Sensing the User's Environment and State

Understanding the user's attentional and affective state, and the context of his/her immediate environment are topics of intense research effort in a number of fields. While we are not focusing on this problem in the present paper, we mention a few of these ongoing efforts. Horvitz et al. describe inferential models for determining the attentional focus and workload of a user based on sensors, interactions, and contextual information [14]. Cutrell et al. investigated the disruptive effects of interruptions in computing tasks. Their results indicate that the timing of an interruption during task completion can influence the perceived level of disruption incurred [3]. Fogarty et al. proposed a system for inferring the interruptability of programmers performing their tasks by modeling engagement using cues from their workstation software [8]. Dabbish and Kraut examined the attentional effort required for well-timed interruption [4].

A somewhat different sensing problem is understanding the user's present *emotional* state. Here, we look towards the emerging field of affective sensing (e.g. [23]). One place where this work has assumed practical dimensions is in human-robot interaction, for example to determine whether a human worker is paying attention to a (potentially dangerous) robot moving about in close proximity [16]. In a therapeutic application, Dauhtenham et al. are sensing the affective state of autistic children to influence the behavior of social robots who interact with them [5]. Yohanan and MacLean are studying how humans convey their emotional state when they touch a sensed, haptically expressive robot creature [26]. Meanwhile, others are working on tactile emotional display, including Rovers and Essen's work on emotionally expressive haptic instant messaging [24].

Contextual knowledge and appropriate timing will contribute greatly to capturing human attention effectively and non-disruptively. This paper will focus on the physical aspects of attention-getting, which if coupled with a system to use sensed context for interruption scaling and timing, would together produce a system with a modicum of social grace.

2.3 Using Synthetic Touch to Convey Social Cues

The attention-getting practices of current technology leaves room for improvement; the situation is particularly egregious for mobile devices being used "out in the world" [3, 22]. Many of the conventions surrounding new technology's use are social, and not necessarily beneficial either to human relationships or an individual's sanity [20]. Touch is as mis-used as any other modality in this respect; inopportune buzzes can be as annoying and disconcerting as an auditory ring or a pop-up window.

A number of designers have looked into the use of pre-existing tactile conventions, by using "feels" whose meanings are the product of shared or similar experiences among their recipients. For example, Dobson et al. demonstrated the utility of intuitive social perception using haptic cues. The Vibrobod and What's Shaking prototypes communicated with untrained users by mimicking known cues, producing a "visceral interface" that added additional social content to telecommunications [6].

Gumtau carried out experiments using a haptic box, subjecting participants to a number of tactile stimuli by allowing them to touch a variety of materials. Participants not only made observations as to the nature of the immediate sensation, but also inferred emotional, social and value attributes associated with the stimulus, such as *sweet*, *young*, *relaxed*, *valuable*, *cowardly* and *weak* in the case of silk - indicating how perceptions based on touch are tied into cognition on a level far beyond basic physical interaction [10].

2.4 Physical Brainstorming as a Design Tool

Physical brainstorming or sketching, the practice of early conceptual design used here, has been deployed to excellent effect in many past instances. Perhaps the most famous early example is Douglas Engelbart's experiments that lead to the first mouse [7], and another is Harrison et al.'s oft-cited prototyping of intuitive e-reading systems at Xerox PARC, at a time when laptop computers were not yet common [12]. One of the authors began using this approach with a physical interface design team for interacting with streaming media [19, 25], generating many early prototypes to come up with novel interaction techniques that would solve a difficult problem presented by new media formats; then committing significant engineering resources to further build/evaluate iterations. In one of the examples mentioned earlier, Gumtau used this methodology to quickly elicit social feedback on a variety of haptic sensations [10].

3 STAGE I: INITIAL PHYSICAL BRAINSTORMING

The initial round of prototyping is intended to provide broad coverage of the potential types of sensations. In this phase, diversity is key, allowing us to explore the possibilities of physical interaction and form, with feasibility as a secondary concern. Metal, plastic, wood, foam, clay, found items and repurposed components each afford different physical experiences. In the context of attention-getting touch, we focused on dynamic experiences that involved both taction and forces; engaging sensations for example of tapping, squeezing, shearing, pinching, poking and gentle pushing.

In this stage, we constructed a number of prototypes to help imagine various sensations when translated from a human- to machine-applied equivalent. Three of these early form-mockups are described here as examples of the process we went through.

Variable-Texture Surface: In our early brainstorming, we considered animalistic metaphors for communication, only later narrowing down to human-inspired channels. One initial mockup was inspired by a small body - e.g. a little creature held in the hand, like a bird or mouse - becoming alert or relaxed. We envisioned ways

Figure 1: The variable-texture surface prototype. A latex membrane (center) is stretched over a section of tube. Clay surfaces push against the membrane underside to alter its texture.

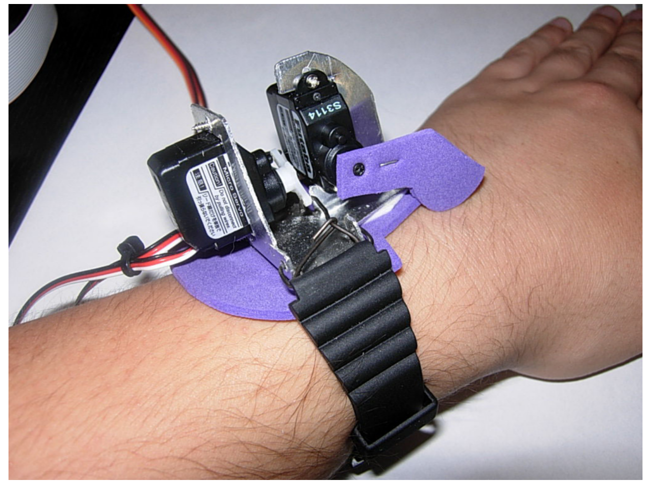

Figure 2: The ServoSqueeze and ServoTap mechanisms mounted on the watch body (in situ).

of capturing the feeling of variations in muscular tension, implemented by using a membrane with a replaceable understructure. When relaxed, the soft "skin" layer would provide a compliant, even texture. When activated, the soft layers would be pulled taut over the harder substructures, giving the impression of tensed muscles and changing the textural quality of the surface.

The brainstorming prototype consisted of a rubber membrane stretched over a frame, through which pieces of modeling clay with varying surface texture could be pushed (Figure 1). The textures we tried included a ribbed surface, a surface with hemispherical projections made from ball bearings, a surface with large pits and craterlike openings, and a surface with ridges made from flexible plastic. In practice, the clay surface only needed to gently touch the underside of the membrane for its texture to be detectable to fingers on the other side. Wire, ball bearings and pieces of plastic enhanced the texture for more dramatic effect. The differences in texture between the various understructures were easily detectable, even when the membrane was barely visibly deformed.

Creating an actuated version of this variable-texture device would be challenging, but the simple prototype demonstrated that it is possible to detect texture variations of a varying understructure through a membrane.

Squeezing: One of the gestures commonly observed by Jones and Yarbrough was a squeezing or holding motion, applied to an arm or shoulder [15]. This gesture was used for attention-getting as well as reassurance, support, appreciation and inclusion. The gesture is mechanically suited to duplication with a haptic device built into commonly worn jewellery or wristwatches. An actuated example could contract the wristband, approximating the feeling of a hand squeezing the wearer's wrist. Changes to the band length could allow the device to be located on other parts of the body, such as the non-vulnerable body parts (hands, arms and shoulders) as described by Jones and Yarbrough [15]. The initial prototype consisted of pieces of the Meccano construction toy and a wristwatch band connected with pieces of wire. While simple, it demonstrated the sensation of a contracting wristband when the two halves of the wristband were levered together. Reactions to this concept were promising enough to merit actuated prototyping during the next phase.

Tapping: Jones and Yarbrough also observed many "spot" touches and taps in communication [15]. We constructed several mock-ups of the part of a device that would make contact with the wearer in order to evaluate the differences in sensation caused by various materials and shapes while manually activating them.

The purpose of these prototypes was to begin to establish a vocabulary of forms, sensations and interactions - a baseline for the design process, and therefore their evaluation was informal and subjective. This emerging vocabulary of shape and feel serves better than a verbal or visual description when laying out the intended purpose of a haptic device, particularly during collaborative design.

4 Stage II: Low-Fidelity Prototyping and Evaluation

The objective of our low-fidelity prototyping design stage was to begin to drill down on the brainstorming concepts that have the most promise, with respect both to display effectiveness and feasibility of construction. Our emphasis was to assess the basic "feel" experience with a minimum of prototyping effort, to ascertain value in proceeding to a more careful design.

4.1 Prototype Descriptions

We chose two candidates for further prototyping, which were integrated into the same display platform for convenience of prototyping and evaluation (Figure 2). Both of these concepts further follow observations of how humans engage one another's attention in casual settings, wherein key gestures are gentle taps or squeezes [15]. One mechanism contracts a wristband while the other taps on the wearer's wrist. For both, we employed hobby servo technology for its rapid prototyping capabilities in both actuation and control.

1. ServoSqueeze: The wristband device is intended to emulate the sensation of a hand squeezing the wrist of the wearer. To accomplish this it should be able to apply a noticeable contractile force without becoming uncomfortable. It should be able to contract and relax at a variety of speeds, and sustain any position. Auditory noise must be minimized. Operation should be smooth, as mechanical vibration is not a characteristic of human hands and could impede experiential transfer.

ServoSqueeze consists of a wristwatch band with an adjustable clasp attached to a watchface-like body containing the actuators. The ends of the wristband, instead of attaching directly to the device body, are anchored to two small levered extensions (Figure 3). A Futaba S3114 micro-servo rotates a servo horn that is connected via linkages to the wristband levers. As the horn rotates, it pulls on the linkages, causing the wristband ends to draw towards each

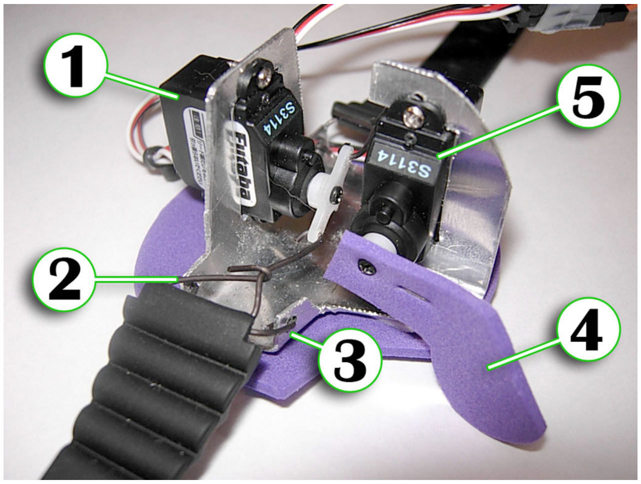

Figure 3: The ServoSqueeze and ServoTap mechanisms. 1) The Squeeze mechanism servo. 2) The Squeeze mechanism linkage. 3) The wristband connects to the body via a short lever to allow movement. 4) The ServoTap arm. 5) The ServoTap servo.

other, tightening the wristband. The servo utilizes an open-loop position control scheme, and so can be commanded to assume various positions, or follow a particular profile over time; there is no direct feedback on the band position or tension. The S3114 servo has a 60°transit time of 0.09s, however, its ability to rapidly change direction is limited, so its maximum reciprocation rate is somewhat less than 11 Hz [13].

2. ServoTap: The device body also houses a second S3114 servo, attached directly to a small, foam-tipped tapping finger. The tapping finger is intended to replicate the feeling of spot touches or tapping of a finger on the wearer's wrist. As such it must be able to perform single or multiple taps, either in a regular or irregular sequence, in order to duplicate the range of possible human gestures. It should also be able to hold in any position. Minimal auditory noise is desirable, as is control over force and contact speed. The servo is able to raise and lower the tapper to bring it into contact with the wearer's wrist.

Control, Communication and Bandwidth: Both servos are controlled with an Arduino Duemilanove microcontroller [1]. The controller emits a time-varying position signal to each servo. Each signal is a combination of up to eight functions, summed or multiplied together; the possible basis functions include sinusoids, triangle and sawtooth waves and non-periodic ramp functions. By combining different waves at different frequencies, the controller can produce a variety of repeating and non-repeating motion patterns. The microcontroller receives serial messages via USB from a PC, where a Python control script allows online mixing and control of the channels.

Actuation Quality Achieved:

ServoSqueeze: The squeezing actuation achieved desired levels of force and movement rate. If the device was properly adjusted (tight enough to allow a single finger to be pushed under the band when fastened) then the 1 cm of contraction was enough to produce a firm sense of tightening without undue discomfort. As a safety precaution, a servo with a stall torque of 1.728 kg-cm was chosen, which is small enough that the servo is unable to compress the wristband with hazardous levels of force.

The servo could maintain periodic motion profiles of up to 5 Hz, beyond which the servo's inability to keep up with the signal changes produced jerky behaviour. Additionally, the servo produced noticeable gear noise, proportional to speed and load. Future revisions must address this source of distraction.

ServoTap: In the tapping device, we were able to produce reciprocating motions of up to 10 Hz at a roughly 30°motion amplitude, with adequate displacement of the foam tapper. This involved running the servo near its speed limits, which caused audible motor and gear noise. When compared to the capabilities of human finger-tapping, 10 Hz is minimal; while a single finger can tap at up to about 10 Hz, drumming fingers can generate much faster tapping. Additionally, due to the position-control scheme used by hobby servos, it was not possible to effectively vary the velocity at which the tapper struck the skin, nor the force. Additionally, the servo was unable to rapidly change direction as called for by some of the motion profiles (detailed in the next section), leading to an unintended smoothing of the signals. Overall, ServoTap was effective for slow, single taps, but was clumsy and lacked the verisimilitude required to be truly expressive. Future prototypes should permit greater control over the dynamics of the tap, as well as being capable of higher reciprocation rates, at least up to 20 Hz.

Device Motion Profiles: The various waveforms (summarized in Table 1, while key basis waveforms are illustrated in Figure 4) were selected for their ability to produce motions with a range of symmetry. The sinusoid and triangle waves are symmetrical: motions in either direction have the same velocity. In this context, a "sawtooth" wave is defined as a lopsided triangle wave whose peaks occur at 1/4 or 3/4 of the distance between troughs. The consequent asymmetry translates into a motion that is fast in one direction and slow in another. In practice, these different types of motions can be evocative of different emotional states. For example, a sinusoid applied to the wristband contraction at a low frequency gives a smooth, repetitive expansion and contraction, akin to slow, smooth breathing. An asymmetrical sawtooth wave with a fast contraction and slower expansion can give the impression of hyperventilation: a sharp intake of breath followed by a slower release. Even at the same frequency the effect is markedly different from the smooth sinusoid.

For ServoTap, the waveforms specify the tapper's angle. The tapper itself is designed to be in contact with the wearer's skin in approximately the lowest 1/4 of its range of motion (this varies slightly with different placement on arms of different shapes). The perceived variability of the various waveforms thus derives largely from the tapper's motion in the lower half of its range - the part of the motion in which contact is imminent or actually occurring. The difference between a smooth transition from downward motion to upward (such as in a sinusoid wave) and an abrupt change (such as in a triangle wave) is apparent to the wearer. The sawtooth waves are distinguishable by the speed of the retracting motion as compared the speed of impact with the skin. The sound of the servo gears reflects the motion speed, so eliminating the auditory channel is important to ensure that respondents are not responding to the auditory profile rather than the tactile stimulus.

In the evaluation described next, we employed the motion profiles shown in Table 1, constructed from the set of basis waveforms and two types of multipliers (exponential and sinusoidal), shown in Figure 4, played at slow and fast frequencies. For feasibility in this exploratory study, we chose a representative sample from all possible combinations, using analogies to human or animal touches as inspiration. Demonstration of expressive capacity with these simple profiles would justify a larger study with a better prototype. Our immediate goal was to determine if a respondent would identify expressive variability between a few select profiles, and if multiple respondents would display consistency in their answers. It is important to note that determining the exact mapping of wristband or tapper motions to emotional or informational interpretation is beyond the scope of this initial study, and our results presentation and discussion to not attempt to address it.

We defined "slow" and "fast" frequencies for each of the devices

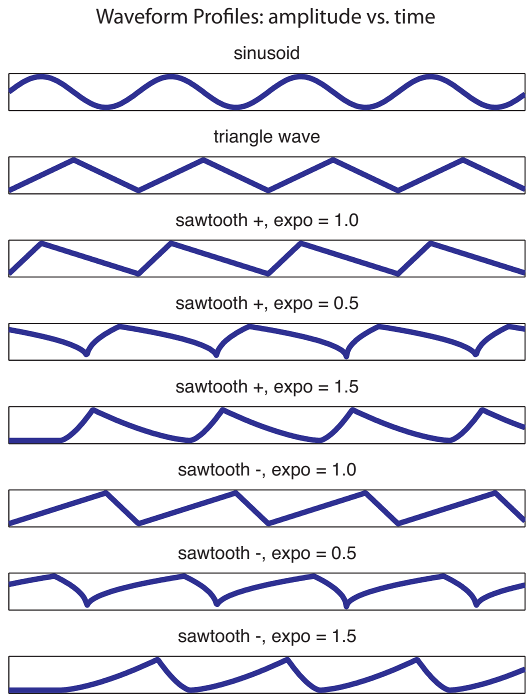

Figure 4: Waveform constructors of the 22 motion profiles used in evaluation (Section 4.2).

according to the natural rate of its biological analog - squeezing is inherently a slower gesture than tapping. Thus, slow and fast frequencies are 2 and 5 Hz for ServoSqueeze and 5 and 10 Hz for ServoTap, respectively. (Additionally, 2 Hz for ServoTap was considered "very slow"). The signals all had consistent amplitude - for ServoSqueeze this was a contraction of approximately 1 cm, and for ServoTap this was an angular amplitude of approximately 30°, which translates to a linear displacement of 1.5 cm. The majority of ServoSqueeze profiles (S10/S12) and ServoTap profiles (T9/T11) operated at their respective "fast" frequencies.

4.2 Low-Fidelity Prototype Evaluation

We conducted a lightweight but controlled pilot evaluation of both of our low-fidelity prototypes, with the aim of determining if the participants associated the motions produced by these devices with an emotional state or message, and to what consistency. A strong, consistent response associating some of the motions with particular emotional content would support our considering these the basis for "gestures", and justify further investigation with higher-fidelity prototypes. In our evaluation, we explored this by looking for clustering of adjective responses to specific motion profiles by the participants, for example using a 2D PCA projection as well as a matrix view of the frequency counts of responses to a given stimulus. The former will be most valuable for future steps of refining individual gestures; the latter is discussed below.

Methods: Each participant wore the integrated wrist device and experienced the test set of haptic position profiles described above. The profiles were presented in two blocks associated with the two prototypes (displaying either wristband contractions or tapping motions, but never both at the same time); so that each prototype could be analyzed separately, or compared to the extent their similarity allowed. Within each block, the ordering of the profile presentation was randomized, and the order of the blocks themselves was also determined randomly.

In each trial (a single profile presentation), the participant was given the set of adjectives listed in Table 2 and asked to circle any and all that they felt described that profile. The adjectives were arranged in pairs of antonyms, and were selected for their ability to characterize a stimulus. Of particular interest were the sense of urgency (*insistent* vs. *hesitant*), the sense of arousal (*relaxed* vs. *agitated*) as well as the conveyed emotional state. In addition, the words like vs. dislike and organic vs. mechanical were provided to allow the participant to express their own perceptions of the stimulus. Participants were also encouraged to add any additional descriptions they felt appropriate in a provided space. Participants generally added remarks to 2-4 stimuli. The remarks generally reinforced the chosen descriptors.

Table 2: Wavefom descriptions.

Insistent	Inquisitive	Reassuring	Relaxed
Hesitant	Detached	Anxious	Agitated
Happy	Energetic	Like	Mechanical
Sad	Fatigued	Dislike	Organic

The descriptive words were arranged in a 2-row by 8-column matrix with antonyms opposed vertically. The pairs were randomized with respect to which word appeared on top.

After experiencing all the profiles, each participant was given a questionnaire designed to ascertain their overall subjective response to the device and give them an opportunity to offer any other comments.

Results and Analysis: 13 participants between the ages of 18 and 30 volunteered for the study, and were each compensated for about an hour of time. To analyze the participants' adjective associations, we first looked for statistical evidence that profile type and which prototype was used (display type) evoked different kinds of responses. For all tests, we assumed statistical significance at $p < .05$.

A summary of the participants' adjective selection trends for each profile are visualized in Table 3 (for wrist squeezing profiles) and Table 4 (for tapping profiles). Profile indices correspond to those defined in Table 1. The most useful features of these graphical representations are the location of frequency of dark versus light cells, whereas it is of less value to study exact mappings between profiles and adjectives. A preponderance of dark cells indicate that participants found agreement in characterizing a given feel; whereas a row dominated by white suggests that characteristic was not well supported by that display (e.g. ServoTap does not appear to have found a way to do sad, but could hardly avoid being perceived as insistent). In making comparisons between the two graphs, keep in mind that there is not a one-to-one mapping between the profiles rendered for each device, although we strove to make the set subjectively comparable. Rather, it is revealing to look at overall characteristics of sparseness/density.

For each table, symmetric and asymmetric profiles are segmented by a vertical rule.

Test 1 - Statistical Effect of Profile Type: We first carried out a series of one-way between-groups ANOVAs to determine the impact of profile type (symmetrical, asymmetrical) on participants' selection of adjectives for each of the two devices. Analyses were undertaken for each device separately.

- For ServoTap, reassuring and relaxed were used significantly more often to describe symmetric profiles than asymmetric ($p = .021$ and $p = .030$ respectively.)
- For ServoSqueeze, insistent, agitated and dislike were used significantly more often to describe asymmetric profiles ($p = .043$, $p = .016$, $p = .025$); whereas reassuring, relaxed and like were used more often to describe symmetric profiles ($p = .048$, $p = .008$, $p = .011$).

Table 1: Wavefom descriptions.

Index	Profile	Amp	Freq	Exp	Description
ServoSqueeze Profiles: Slow = 2 Hz, Fast = 5 Hz					
S1	sin	unity	slow	1	A slow, smooth reciprocation.
S2	sin	unity	fast	1	Faster, but still smooth sinusoid.
S3	tri	unity	slow	1	A slow triangle wave - abrupt direction changes.
S4	tri	unity	fast	1	A faster triangle wave - abrupt direction changes.
S5	sin	sin ramp	fast	1	A ramped sinusoid, increasing in intensity to a peak and then fading.
S6	saw+	unity	fast	1	A linear sawtooth, fast contractions, slower release.
S7	saw+	unity	fast	0.5	A curved sawtooth, short decelerating contractions, long accelerating release.
S8	saw+	unity	fast	1.5	A curved sawtooth, short decelerating contractions, long decelerating release.
S9	saw-	unity	fast	1	A slow, smooth reciprocation.
S10	saw-	unity	fast	0.5	A linear sawtooth, slow contractions, fast release.
S11	saw-	unity	fast	1.5	A curved sawtooth, long decelerating contraction, short decelerating release.
S12	saw+	sin ramp	fast	0.5	A ramped version of S7, contractions increasing to a peak, then fading.
ServoTap Profiles: Very Slow = 2 Hz, Slow = 5 Hz, Fast = 10 Hz					
T1	sin	unity	very slow	1	Slow, gentle tapping, slows on impact.
T2	sin	unity	slow	1	Medium speed tapping, slows on impact
T3	sin	unity	fast	1	Fast tapping, slows on impact.
T4	tri	unity	fast	1	Fast tapping, does not slow, abrupt direction change.
T5	saw+	unity	fast	1	Fast approach speed, slower retraction, bounces on impact.
T6	saw+	unity	fast	0.5	Decelerating approach speed, accelerates away from impact.
T7	saw+	unity	fast	1.5	Fast accelerating approach, abrupt change of direction, decelerating withdrawal.
T8	saw-	unity	fast	1	Slow approach speed, faster withdrawal, as though reacting to impact.
T9	saw-	unity	fast	0.5	Slow, decelerating approach, faster accelerating withdrawal.
T10	saw-	unity	fast	1.5	Slow, accelerating approach, abrupt direction change, fast decelerating withdrawal.
T11	saw+	sin ramp	fast	0.5	Similar to T6, but with slow increase in intensity before peaking and fading away.

We can conclude from this test that reassuring and relaxed are used more often for symmetric profiles across devices (squeezing and tapping) than asymmetric profiles. ServoSqueeze was considered insistent, agitated and disliked more prominently in the case of asymmetric signals, whereas the use of these adjectives to describe ServoTap did not differ across profile types. We cannot infer a relationship between frequency and adjective selection; it remained relatively consistent across profiles on each device, and additional data would be required for this analysis.

Test 2 - Statistical Effect of Display Type: A one-way between-groups ANOVA was executed to determine the impact of display type (squeeze vs. tap) on participants' use of adjectives. Agitated was more likely to be used to describe tapping ($p = .038$), and organic for squeezing ($p = .047$). These results indicate that specifics of expressivity are indeed influenced by delivery mechanism, and different adjectives will be employed to describe the interactions afforded by the devices.

Discussion and Indications: These results suggest that the subjects found the various profiles to be expressive, and that a range of expressivity is achievable with variations in gestural profile parameters such as waveform for these devices.

We did find a promising degree of consistency among different participants' responses to some stimuli. For example, 76% of respondents said that profile S1 (a slow (2 Hz) sinusoidal contraction of the wristband) was *relaxed* with no respondents selecting *agitated*, the antonym. 54% selected *reassuring* and 0% selected *anxious* for the same motion. Some trends spanned the two delivery mechanisms. In the case of profiles using an asymmetrical sawtooth wave with an exponent of 0.5 (S7 and T3), 69% of respondents chose *insistent* with 0% choosing *hesitant*. Similarly, the same sawtooth wave but with an exponent of 1.0 (S6) had 69% of respondents choosing *insistent* and 8% (1 person) choosing *hesitant*. Insistence vs. hesitance and relaxation vs. agitation in particular showed strong polarization.

In summary, this evaluation gave sufficient evidence of both expressiveness and consistency in participant response to justify further prototyping effort. In the case of ServoSqueeze, the next step will be a higher fidelity prototype, which corrects servo-based issues of auditory noise and vibration mentioned earlier. While smoother, higher-quality servos exist which would improve the overall feel, servos are ultimately limited by their control software, which is position-controlled. A more sophisticated scheme such as velocity control could enable greater variation in the motion profiles.

	Symmetric Profiles					Asymmetric Profiles						
Adjective	**S1**	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**	**S11**	**S12**
insistent	23	62	15	31	15	69	69	46	54	54	31	38
hesitant	15		15		15	8		8				23
inquisitive	15	46		23	23	38	31	8	38	23	15	8
detached	8	8	23		8		8	15		15	8	15
reassuring	54		46	31	15	8	8	23	8	8	8	8
anxious		23	8	15		15	15	38	23	23	23	8
relaxed	77	8	54	46	38	15	8	23	8		15	15
agitated		15				15	46	15	23	23	15	8
happy	15	15		8	15	8	8	15		31	8	8
sad	8		8					8			23	8
energetic		23		8	8	15	46	8	8	23	15	8
fatigued	15	8	46	15	31	8			15	8	8	8
like	46	23	15	38	31	8	8	15	8	31	8	8
dislike	8		8	8	8	8	15	15	15	8	8	15
mechanical	8	46	15	8	8	15	31	38	46	38	31	8
organic	38	15	38	31	31	23	23		23	31	23	31

Table 3: Association of adjectives for ServoSqueeze. Cell values and coloring represent the percentage of participants that selected the corresponding adjective for a particular stimulus.

While we saw nothing to rule out the idea of tapping, our re-

Adjectives	Symmetric Profiles T1	T2	T3	T4	Asymmetric Profiles T5	T6	T7	T8	T9	T10	T11
insistent		23	69	85	62	77	46	62	54	46	62
hesitant		23			8				23		
inquisitive	8	23	15	23	15	15	31	38	23	8	23
detached	8	31	23		15	8	23	8	8	8	23
reassuring	46	54	15	8	8		8		8	8	15
anxious	46	8	8	38	15	46	31	38	31	15	15
relaxed	54	46	31		8		8	8	8	8	23
agitated	54		15	46	31	31	15	23	31	23	23
happy			23	8	8			23	23	38	8
sad		8						8			
energetic			23	23	15	54	8	31	8	54	
fatigued		8		8	15				8	23	
like	15	31	31	8					23	8	23
dislike	15		8		15	15	15	8	8	15	
mechanical	8	38	38	38	62	62	69	46	23	23	8
organic	8	23	23	31		8	15		23	15	

Table 4: Association of adjectives for ServoTap profiles.

sults confirmed our initial concerns that this prototype's approach to producing a tapping gesture, using a servo, did not achieve the desired effect: while it was able to provide expressive motions, participants generally found them unappealing. While higher-quality, more responsive servos are available, the overall concept of a servo-actuated arm for tapping is not an ideal solution for multiple reasons. Therefore, we proceeded to completely redesign the tapping mechanism in the next phase.

5 Stage III: Medium-Fidelity Prototyping

We thence developed another, more refined prototype of ServoTap, our first-generation tapping mechanism. We aimed to improve over the previous design iteration in three areas, allowing us to better assess its value and controllability as a "background" attention-getting device. First, it must support higher frequencies of oscillation in order to replicate the sensation of a human drumming their fingers. Secondly, it must operate with minimal audible noise. Thirdly, it should not be confined to tapping on the user's skin in a single spot. Finally, like the servo-actuated tapper, this new design should be able to produce non-periodic profiles, so should not rely on a crank mechanism or offset weight, which would only be able to produce a periodic profile, not individual impulses.

MagTap: A magnetic actuator similar to a solenoid was determined to possess the required characteristics. The resultant design was for a compact actuator incorporating a small electromagnet repurposed from a telephone relay. The electromagnet was mounted in a housing with a small sprung arm made of ferrous wire. When activated, the electromagnet caused the sprung arm to displace toward the magnet core, bringing the far end of the arm downwards into contact with the skin of the user through an opening in the housing. The low mass and spring-loaded return action of the arm allows the module to operate at frequencies in excess of 40 Hz, particularly when a resonance between the activation frequency of the electromagnet and the natural oscillatory rate of the spring is established.

The entire sub-assembly (one tapper) is 3cm x 1cm x 1cm in size, and could be miniaturized much further in future revisions through the use of manufactured springs and spiral printed coil circuits. Thus these magnetic tappers can be arranged in arrays and distributed across a variety of wearable items. For this prototype, eight actuators were arranged along a wristband made from an elastic medical bandage.

A drawback of the magnetic tapper mechanism is a reduced impact force compared to the servo-based tapper, and there is the possibility that it will have reduced detectability depending on the location of the stimulus on the recipient's body. The apparent force and intensity of the sensation increases when the sprung arm resonates, but this is only possible for periodic profiles and not for single taps. Larger electromagnets or higher power levels could of course achieve greater force, the challenge is in creating a powerful device in a compact form factor.

The ability to control a set of tappers in concert allows a wider range of possible profiles than the single tapper, while still following our model of gestures inspired by human social behaviour. For example, by firing the tappers in sequence, it is possible to create a sensation akin to human finger-drumming, with variable speed and direction. When the tappers are arranged as a wristband, it is possible to create a drumming sensation that moves clockwise or counterclockwise around the wrist. Other recognizable gestures include a multiple tap, an alternating drumming, or a slowly moving wave of vibration, passing from one tapper to another with a smoothly interpolated transition based on frequency of vibration.

The next step in the design process is an evaluative study to determine the expressivity of this magnetic tapper in a similar manner to the actuated wristband prototype. If the magnetic tapper is established as promising, it will proceed with the wristband contraction mechanism (but not the servo-based tapper) to a round of high-fidelity prototyping. These more refined prototypes would be the focus of a larger, more elaborate user study situated in an application context, proceeding with confidence that the devices under study have the potential for significant results.

6 Discussion and Future Work

The prototyping process and subsequent evaluation have provided us with valuable insight into the ability of people to associateemotional content with physical sensations. The study participants did attribute emotional descriptions to the various motions, in some cases with strong consistency. It is important to note that they did so when asked to attribute an emotion; when looking for emotional content, the participants showed encouraging results. Doing so unprompted would be a stronger confirmation that the current evaluation could not expose.

The statistically confirmed consistency of the responses in the case of the slow sinusoid contractions, or of rapid, asymmetric motions in both contractions and tapping is encouraging. During the initial brainstorming process, these were thought to be some of the more "intuitive" profiles, and the high levels of consistency suggest

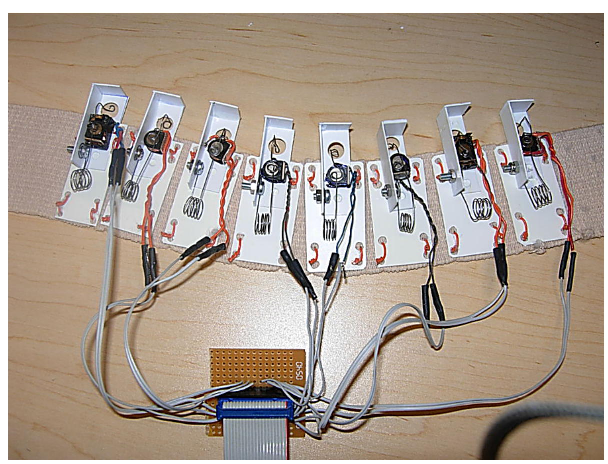

Figure 5: An array of MagTap actuators.

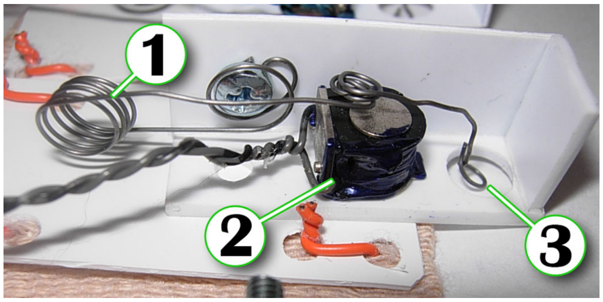

Figure 6: A magnetic actuator. 1) The springloaded tapper arm. 2) The electromagnet. 3) The contact point above the opening through which it contacts the wearer's skin.

that this is true.

Participants' qualitative responses indicated that ServoSqueeze evoked the impression of an animal or human, particularly for slow motions. Participants expressed overall positive reactions to the feeling of the device. ServoTap was less successful in inspiring the impression of an animal, with large numbers of participants remarking at its mechanical feeling.

There are a great deal of options for future development. In the software realm alone the range of possible signals is limited only by the physical capabilities of the device. One possible approach is to record tactile signals produced by humans and to attempt to duplicate them. This may prove unnecessarily limiting, as there is no reason to assume that human-producible signals are the only interpretable signals.

One option for development is to begin to combine the various actuators, to create a system with an array of abilities that can be used in concert. A machine with an array of communicative abilities and an established role to play will have a stronger metaphor under which its actions will be interpreted.

It is important to stress again at this point that the mental metaphor engaged by the participants colors their interpretation of the motions. Not only do they attribute the ability to possess both intent and emotion to the device, but they do so despite the obvious physical reality that the device is in fact a metal and plastic machine. This suspension of disbelief must be maintained in order for the communication metaphor to continue. Defining that metaphor will be one of the major challenges of emulating humanlike body language. Humans of differing social status and immediate role will have different permissible actions, and different intended meanings to a particular type of touch. Perhaps the most interesting aspect of our future study will examine the kind of persona a participant attributes to the device, and how to influence this: a butler, a companion, a pet, a spirit, a robot, or perhaps something entirely new.

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