Tactile Echoes: A Wearable System for Tactile Augmentation of Objects

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Abstract— We present Tactile Echoes, a wearable system for augmenting tactile interactions with any object. This system senses vibrations in the fingertip that are produced by interactions of the finger with a touched object. It processes the vibration signals in real-time via a parametric signal network and returns them to the finger as "Tactile Echoes" of the touch interaction. Just as acoustic echoes continuously respond to sound, Tactile Echoes are continuously generated in response to the sensed tactile contacts. A short finger tap produces discrete Echoes, while a slide can yield continuous feedback. We also render the signals as sound, yielding multisensory feedback. Many different effects can be designed using ten signal processing parameters. Distinct effects may be assigned to different touched objects or surface regions by sensing the hand location in a mapped environment. We investigated how Tactile Echoes are perceived in a behavioral study using semantic differential scaling and multidimensional scaling methods. This yielded low-dimensional, semantically grounded representations of the perceptual similarities between different Echoes. This system holds promise for enabling evocative haptic effects during a wide range of free-hand tactile interactions.

I. INTRODUCTION

Advances in haptic technologies are enabling new tangible digital experiences. Many haptic interaction techniques require specialized controllers or surfaces that prevent the hand from directly touching or interacting with arbitrary objects. This constrains the use of such systems to specialized activities. Emerging devices enable haptic feedback to be provided during free-hand interaction with direct skin-object contact. Such methods may enable a wider range of human activities to be augmented with useful haptic information and evocative haptic effects.

Here, we present Tactile Echoes (Fig. 1), a wearable system for the augmentation of free-hand tactile interactions with objects and surfaces. The system senses vibrations in the fingertip that are produced via contact between the finger and a touched object. It processes the vibration signals in real-time via a parametric signal network and returns them to the finger and the auditory system as tactile and sonic "echoes" of the touch interaction. Just as acoustic echoes are continuously produced in response to sound, these Tactile Echoes respond continuously to sensed fingertip interactions. A hard tap elicits a larger response than a light one, and a continuous slide produces feedback that is extended in time. Using the system, a large array of responsive effects can be designed via ten signal processing parameters. By integrating

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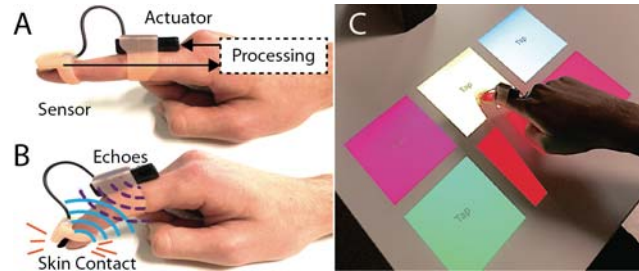
Fig. 1. (A) Tactile Echoes system and concept. The wearable device captures vibrations in the fingertip that are produced during touch interactions, and (B) processes them, and returns them to the finger as "echoes" of touch. (C) In this application, different Tactile Echoes are assigned to each region of the projected surface. The finger location is tracked via camera, enabling the feedback to vary with the touched location.

the system with additional cameras or trackers, distinct effects may be assigned to different objects or surface regions of a mapped environment for use in virtual, augmented, and mixed reality. This can yield responsive, surface-specific tactile feedback, which can be playful, bringing ordinary touch interactions can be brought to life, or made informative, by introducing palpable digital information layers onto our everyday physical reality. Here, we describe the design of such a system and present experiments elucidating the perceptual dimensions of these tactile experiences.

In the remainder of the paper, we provide context this work and describe the hardware and software algorithms. We present the results of three experiments and a multidimensional scaling (MDS) analysis in which we investigated how these effects are perceived, to aid understanding and design. We conclude with a critical discussion, and ideas for applications and future developments.

A. Background

The Tactile Echoes scheme shares similarities with prior haptic rendering methods based on modulating the perceived properties of real objects by imposing forces felt via a haptic interface [1], [2] or with vibrations presented from a stylus [3], [4]. Such systems rely on generating signals to be reproduced via a device in response to performed motions or forces, but do not provide feedback during direct manual contact with touched objects.

Several methods have been proposed for superimposing touch-dependent haptic feedback on a tactile surface [5], [6], [7], [8]. Similar to these methods, we compute the feedback via an algorithm that processes the input. However, most prior approaches provide feedback based on a particular interaction type, such as textural sliding or tapping. The

Tactile Echoes system uses the in-vivo tactile signals produced during the interaction. For this reason, feedback can be provided in response to any interaction, such as tapping, sliding, or scratching with a finger.

Recently, several groups, including our own, have explored wearable electronic systems for capturing, amplifying, and reproducing natural tactile signals via skin-worn sensors and actuators [9], [10], [11], [12]. These devices can provide evocative experiences by amplifying and reproducing tactile signals on the same limb or another part of the body, or via a tool, as in the "tactile magnification" system of Yao and Hayward [13]. Such approaches can also be compared to auditory effects like the parchment skin illusion [14]. In these approaches, the feedback is determined by the tactile interaction, but cannot readily be designed to programmed to depend on the surface being touched or the state of a digital application. Other approaches to haptic virtual reality have used electronic gloves or exoskeletons [15], [16], [17], finger mounted haptic devices [18], [19], [20], [21], [22], or grasped controls [23]. Such systems have rarely integrated feedback from both real and virtual objects during free-hand interactions.

Many methods have been used to investigate the perception of rendered haptic feedback or effects [24], [25], [26]. In the Tactile Echoes system, the feedback is not designed to correspond to natural sensations. We investigated how this feedback is perceived in behavioral experiments using a multidimensional scaling procedure based on user-supplied semantic labels and ratings. MDS methods have been previously used to assess the perception of natural haptic materials [27], [28], [29] and mechanisms [30], and have also been used to characterize the perception of synthetic haptic effects [31], [32].

II. System Design

The Tactile Echoes system is based on the idea of capturing and processing natural tactile signals in the finger. The system senses vibrations in the fingertip when they are produced by interactions of the hand with a touched object. It processes the sensed vibrations in real-time via a parametric signal network running on a computer processor, and returns them to the finger (Fig. 2). Signals are returned continuously to the finger, so that the experience augments natural tactile sensations with artificial feedback.

The wearable system is mounted on a custom rubber bracket. Touch-elicited vibrations are captured by a fingernail-worn piezoelectric sensor. The signals are amplified (Puremini and Pure XLR, K&K Sound) and converted by audio hardware (Model 624, Mark of the Unicorn), so to be processed by the computer. Actuator signals are amplified (LP-2020A, Parts Express inc.) and transmitted to voice-coil actuator (Haptuator Mark II, Tactile Labs Inc.). The processing is optionally modified based on the proximity of the finger to different objects in the surroundings. The tracking does not need to be contact-synchronized, because the required change acts by switching the algorithm that is used to process the contact data.
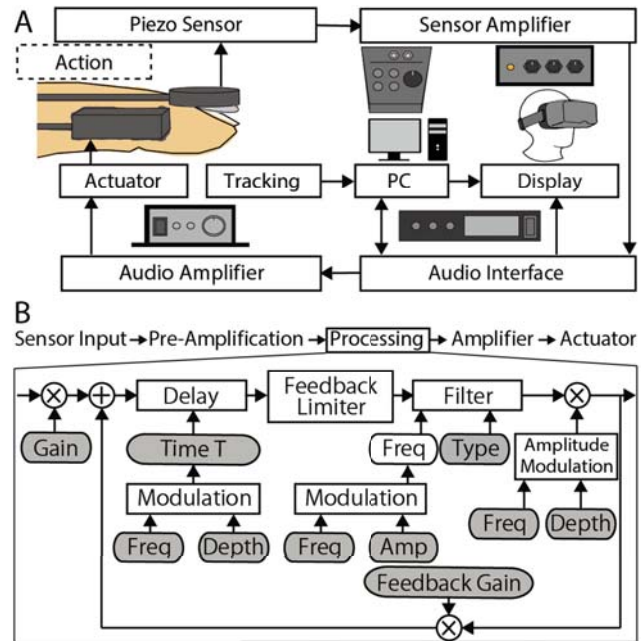

Fig. 2. A: System Diagram: A piezoelectric sensor worn on the finger captures vibrations in the fingertip. The vibrations are amplified and concurrently processed by a computer. A signal processing network parametrically modifies the signals, which are amplified and returned to the finger via an inertial voice-coil actuator. B: The tactile echoes are generated from the input via a fixed parametric signal network. It includes delay, nonlinear feedback limiting, and filtering. This architecture is sufficient to produce a wide variety of parametrized audio effects.

A. Tactile Echoes Algorithm

The vibration signals captured from the finger are processed in software to yield a variety of parametrically-controlled effects. In an early prototype of this system, we used a guitar multi-effects box to explore many alternatives. Subsequently, we implemented a multi-purpose signal processing network (B), inspired by digital audio effects processing. The same algorithm is used to generate a variety of Tactile Echoes. The processing network comprises a feedback delay with nested modulation, resonant multimode filter, and nonlinear limiting. Ten parameters control the processing: an overall gain, feedback gain, delay time, filter frequency, type, and resonance, delay time modulation frequency and depth, and amplitude modulation frequency and depth. The feedback delay is of variable length. Through experimentation, we found that delay times between 10 and 500 ms yielded the most interesting effects. A fixed feed-forward delay is also present, due to system latency. We measured this delay to be 20 ms with the system settings used in the experiments below. Rather than trying to minimize this delay, we found that ensuring at least 30 ms elapsed between the touch interaction and the feedback created much stronger perceptual effects. We conjecture that this is due to tactile masking. We intend to explore this phenomenon in future work.
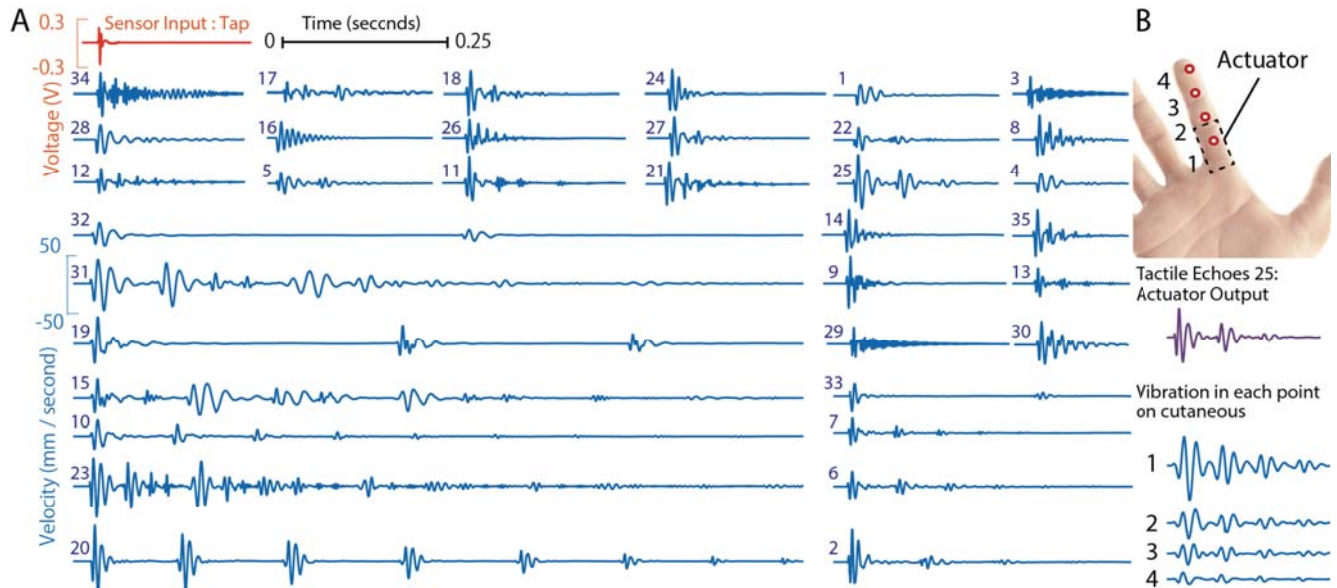
Fig. 3. Waveforms produced by 35 designed Tactile Echoes. The displayed waveforms (in blue) are the signals produced by different Echoes in response to a single, pre-recorded touch input (shown in orange). These Echoes each comprise one stimulus used in the perception experiments (Sec. III). Each Echo is specified via values of ten processing parameters. Different output waveforms are produced by each Echo in response to different touch inputs.

B. Design and Characterization of Tactile Echoes

We crafted a set of 35 stimuli (Fig. 3A), by combining the values of ten parameters. When reproduced via the wearable device, Tactile Echoes yield mechanical stimuli that propagate in the skin as viscoelastic waves [33]. From physics, the amplitude of such a wave is expected to decay exponentially in the skin as the distance d from the actuator increases. For a vibration component of frequency f, such an amplitude decay decay is given by

$$A(d) \sim \exp(-\alpha d f), \qquad (1)$$

where α a damping coefficient. We confirmed this by measuring skin vibration responses to Tactile Echo waveforms using a non-contact Laser Doppler Vibrometer LDV (Polytec PDV 100, Irvine, CA). The vibrometer measured the velocity in the normal direction to the skin at the actuator and four locations on the volar surface of the finger (Fig. 3B). The measurements confirmed that the Echo yielded a wave that propagated throughout the finger. The vibration waveform at remote locations was similar to the actuator signal. Propagation imparted frequency-dependent phase lag, and frequency- and distance-dependent attenuation, as expected from wave mechanics.

III. PERCEPTION

The goal of the experiments was to determine how the Tactile Echoes were perceived and to identify a perceptual space that adequately described the perceptual similarity of different Tactile Echoes. Because these stimuli are different from natural tactile signals, we designed the experiment so that the results would emerge from participant responses, and not just reflect our expectations. Our study is based on se- mantic labeling, sorting, and rating tasks, a multidimensional scaling (MDS) procedure, and a regression comparing the semantic ratings with the MDS analysis.

A. Apparatus, Stimuli, and Participants (All Experiments)

All experiments used the Tactile Echoes system, with the device worn on the participant's dominant hand. In two conditions, haptic or multisensory, participants felt the Tactile Echoes with or without sound. Tactile and sound feedback were produced via the same waveform. All experi- ments incorporated both conditions, haptic and multisensory. Every participant completed both, in a random ordering. Participants wore noise-cancelling headphones. A curtain ob- structed the view of the hand. A plastic-coated plywood sheet comprised the touch surface. Each type of echo stimulation was presented individually, one per trial, in random order and only once. During each trial, participants repeatedly tapped the surface at a rate of 0.67 Hz (based on a visual metronome) while maintaining a tapping force between 1 and 1.5 N. Before the experiment, participants briefly prac- ticed the procedure. Participants gave their written informed consent for the experiment, which was conducted according to the protocol approved by the UCSB ethical committee. Participants were compensated $10 per hour.

B. Experiments 1, 2: Semantic Labeling

In a first experiment, participants provided descriptive la- bels for the stimuli. Five native English speakers participated (ages 20 to 27, 3 male, 2 female). On each of the 35 trials, participants provided as many verbs and adjectives as they could that described how the stimuli felt. Participants could experience each stimulus for as long as they preferred while they responded. This experiment lasted about 40 minutes in total. In a second experiment, a new set of seven native English speakers (ages 20 to 29, 4 male, 3 female) voted on

the words that best described each stimulus. We aggregated all of the words from the first experiment, after merging similar words using dictionary definitions and thesaurus associations. During each trial, participants were presented with one stimulus and a master list, in randomized order, of words collected for any stimulus in the first experiment. For each stimulus, participants selected any and as many words from the entire list that described what they felt. Participants could experience each stimulus for as long as they preferred while they responded. This experiment lasted about 30 minutes in total.

C. Experiment 3: Semantic Scaling and MDS Analysis

In a third experiment, a new set of participants rated each of the stimuli on a set of twelve semantic differential scales derived from the semantic labeling experiments. Fifteen new individuals (ages 20 - 50 years old, 10 male, 5 female) participated. During each trial, participants rated one of the stimuli on 12 semantic differential continua. Responses were entered via computer. We used continua rather than Likert scales to avoid introducing quantization errors. The semantic differential labels were chosen as the eleven most voted labels in Experiment 2. One further label ("real") was added by the experimenters, but yielded ambiguous results. Each of the 12 scales consisted of the label at the left extreme of the visual analog scale, and "not (label)" at the opposite side. Participants could experience each stimulus for as long as they preferred while they responded. The duration was1 hour, including a ten minute break.

D. Data Analysis

The data from experiment 1 consisted of word sets that were aggregated to form the word list for voting in experiment 2. The word lists and votes were not further analyzed. The experiment 3 data consisted of semantic differential scale ratings of each of the 35 stimuli in each condition (haptic, multisensory) by each participant. We analyzed the haptic and multisensory stimuli separately.

To assess the number of independent perceptual dimensions needed to describe the responses, and to derive a space that could parametrize how the Tactile Echoes are perceived, we used the classical Multidimensional Scaling (MDS) algorithm. MDS minimized the mean residual error,
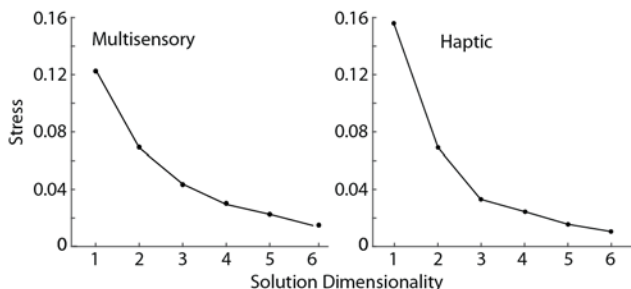

Fig. 4.   Scree plot showing the residual errors between the dissimilarity matrix and the MDS solutions as the number of dimensions increased.

called the "strain", between Euclidean distances (dissimilarities) among the original response vectors from the scaling experiment and the the distances between their images in a lower-dimensional embedding space. We computed MDS embeddings of dimension 1 to 6, and computed the strain residuals for each. We selected embedding dimensionalities ($M = 2, 3$) based on the knee in the plot of strain residual vs. dimension (scree plot, Fig. 4), see discussion below. We computed the corresponding MDS embeddings for each value of the dimension, yielding four spaces in total: one for each condition and one for each dimension value. We computed mean response ratings for each stimulus, and mapped each such value to one point in each MDS space. We assessed the quality of the embeddings via Shephard diagrams – scatterplots of the dissimilarities vs. distances for each stimulus – and calculated R^2 values for each.

To further interpret the MDS mappings, and assess their quality, we used the entire dataset to fit the response data for each semantic differential scale as a function of the embedding coordinates. This yielded a line through the origin in the respective embedding space. We computed the R^2 values for each fit in order to assess the regression quality for each scale. This allowed us to identify the semantic scales that were best predicted by the MDS coordinates, as those with the highest R^2 values. We identified M orthogonal scales with high R^2 values (where $M = 2, 3$ is the embedding dimension) in order to interpret the MDS spaces in terms of participant-provided responses.

IV. RESULTS

The results of Experiment 1 consisted of word sets that were aggregated to form a word list for voting in Experiment 2, which determined the semantic scales used in Experiment 3. The word lists are omitted for brevity.[1] The four MDS analyses yielded a monotonically decreasing stress residual as dimensionality increased (Fig. 4), as expected. The stress declined most as the dimension increased to 2 and from 2 to 3. Thus, we focused our analysis on MDS spaces of dimension 2 and 3.

As expected, for each stimulus, we computed the mean value of the rating across all presentations and mapped the resulting vector to the corresponding MDS space positions (Fig 5). The stimuli are widely distributed in all four spaces. Comparing the mean stimulus positions in the haptic and multisensory conditions, some Tactile Echoes that are proximal in the haptic condition remained so when audio was added (examples in the 2D plot include 19 vs. 20, 29 vs. 9, 2 vs. 22, 29 vs. 9). Others that were proximal in the haptic condition were farther apart in the multisensory condition (examples in the 2D plot include 10 vs. 34, 8 vs. 3, 2 vs. 25, 4 vs. 19). This is consistent with the informal report by participants that some Tactile Echoes features were more prominent acoustically than haptically. The regression analysis yielded a line embedding each semantic scale in

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[1]The word lists and related results are summarized at this website: `http://spectrum2.mat.ucsb.edu/anzukawazoe/conf/WHC2019.html`
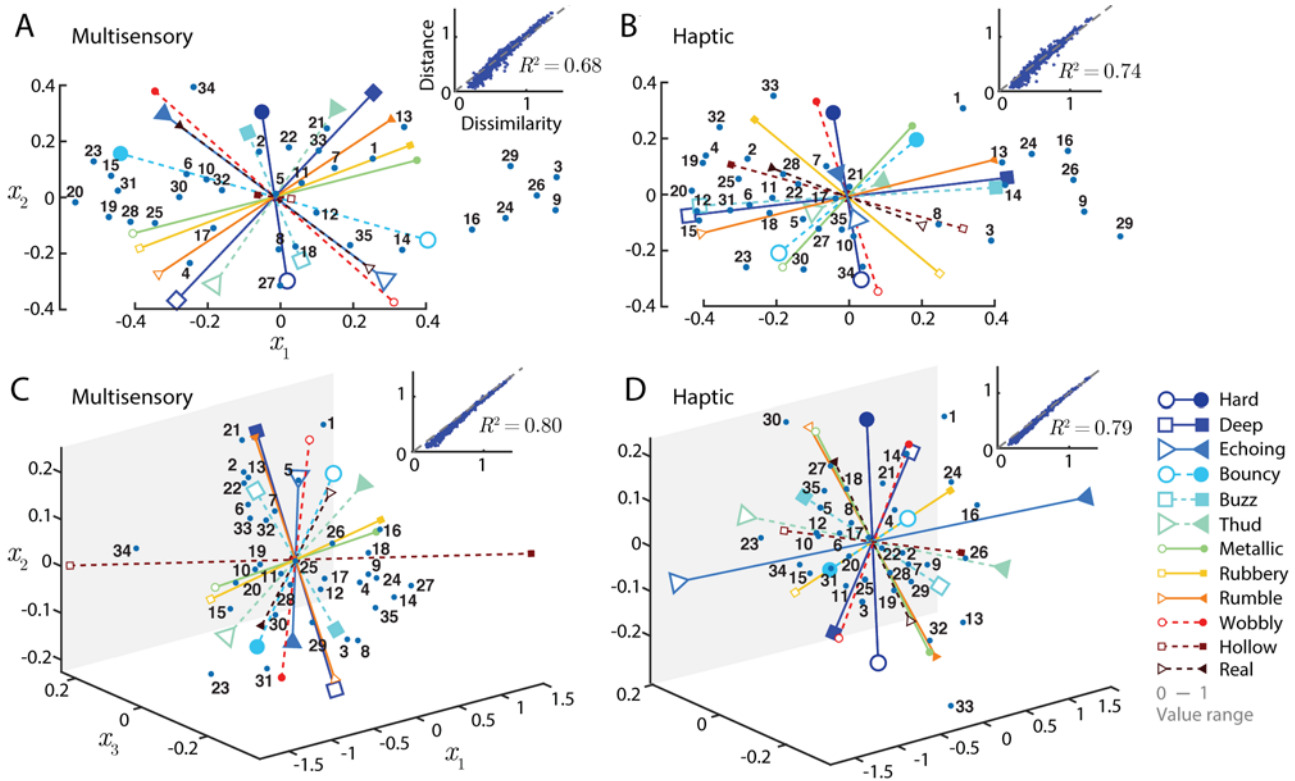
Fig. 5. The MDS analysis yielded embeddings of the Tactile Echoes stimuli in low dimensional spaces. The MDS embedding is computed so that stimuli that are embedded near to each other received similar ratings in the semantic differential scaling experiment. For each condition, we computed MDS spaces in two dimensions (A: Multisensory, B: Haptic) and three dimensions (C: Multisensory, D: Haptic). The Shephard plots (inset figures) show that the embedding quality increased for 3 vs 2 dimensions. The lines represent regression axes from MDS space to the semantic differential scale values, from 0 (hollow symbol) to 1 (filled symbol). The line length for each axis is proportional to the R^2 value of the regression, with longest lines denoting highest R^2 values.

each MDS space (Fig 5). In the figure, line length is proportional to the R^2 values for the respective regression. These values ranged from 0.5 to 0.9. Several of the scales were nearly parallel, and for a subset, such as wobbly and echoing, this was true in all MDS dimensions and conditions. This suggests that these scales were interpreted redundantly by participants. Others, including "hollow" , remained more orthogonal to other dimensions in all MDS cases, suggesting these ratings reflected complementary perceptual ratings to the others. While there is no objective threshold for what constitutes a meaningful relationship, other analyses have concluded that scales with R^2 values greater than about 0.7 reflect "substantial" relationships [30], [27], [28]. In all four analyses, deep, buzzing, rubbery, rumble, and wobbly yielded R^2 values greater than 0.7. It is often desired in such analyses to identify subsets of the scales of the same dimension as the space itself with high R^2 values. Such subsets can be used to interpret the MDS embedding for different stimuli. Suitable pairs in the 2D analyses include deep-wobbly in both the haptic and multisensory conditions, and rumble-wobbly or rubbery-rumble (among other possibilities) in the haptic condition. In the 3D MDS analysis, one can point to triplets such as wobbly-rumble-buzzing in the haptic condition, or to rubbery-buzzing-wobbly in the multisensory condition.

V. CONCLUSION AND DISCUSSION

This paper introduced Tactile Echoes, a wearable system for augmenting free-hand tactile interactions with augmented surfaces. This system enables haptic feedback to be integrated into a variety of manual activities, without the need for a handheld controller or instrumented surface. We feel that this system provides an interesting alternative for tactile augmented reality. Such augmentations might be compared with the effects provided by emerging wearable displays for visual and auditory augmented and mixed reality. The Tactile Echoes system can provide responsive, programmable feedback to a wide variety of manual interactions.

To explore the design and perception of the experiences it can create, we conducted a series of perception experiments. Participants rated what they felt using descriptors that were provided by participants. This culminated in an MDS analysis that suggested that the perceptual space of the designed stimuli can be approximated as 2 or 3 dimensional, and further suggested that this space could be associated with descriptors including wobbly or rumble, which evoke the idea of a dynamic touch interaction, or with terms like rubbery, that evoke a change in material properties.

While promising, there are several aspects of the system design and study that should be viewed critically. First, while the Tactile Echoes system produces novel effects,

the sensations are unmistakably synthetic or "cartooned". Research is needed in order to explore how such a feedback-based rendering method could reproduce natural touch sensations. In addition, while the experiments elucidate how these stimuli are felt in terms of a few abstract parameters, they do not yet provide a convenient means of designing stimuli with a small number of parameters. We are addressing this in ongoing work. Further, our conclusions about how these effects are felt should be considered in light of the differences in language abilities of participants in the study, the limited range of interactions included in it, the modest size of our participant pool (27 in total), and the choices we made in designing the Tactile Echoes. We plan to expand these aspects of the work in the future.

ACKNOWLEDGMENT

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