Spatiotemporal Haptic Effects from a Single Actuator via Spectral Control of Cutaneous Wave Propagation

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***Abstract*— A key challenge in haptic engineering is to design methods for stimulating the skin – a continuous medium with infinitely many degrees of freedom – via practical devices with few degrees of freedom. Here, we show how to use a single actuator to generate tactile stimuli with dynamically controlled spatial extent. The method is based on the frequency-dependent damping of propagating waves in the skin. We use full-field optical vibrometry to show that vibrations introduced at the fingertip elicit waves in the finger that propagate proximally toward the hand. We show that these waves travel distances that decrease rapidly with frequency. We demonstrate the utility of these results by designing haptic effects that produce wave fields that expand or contract in size, and that can be delivered via a single actuator. In a perception experiment, subjects accurately (median >95%) identified these stimuli as expanding or contracting without prior exposure or training. These findings demonstrate how the physics of waves in the skin can be exploited for the design of spatiotemporal tactile effects that are practical and effective.**

I. Introduction

The skin is a distributed sensory medium whose infinitely many coupled degrees of freedom are excited in complex ways during tactile interactions. A central challenge in haptic engineering is to find methods for stimulating this continuous medium via practical devices with few mechanical degrees of freedom.

It has long been observed that locally applied vibrations evoke mechanical waves distributed in the skin [1], [2], [3]. Such processes partly explain somatosensory specializations such as the large receptive fields associated with vibration-sensitive Pacinian Corpuscle (PC) afferents [4], [5]. During manual activities, touching an object also excites propagating mechanical waves in the skin that reach remote locations [6], [7], [8], [9]. These waves propagate in a manner that reflects not only the anatomy and mechanics of the skin, but also the properties of touched objects, the locations of contact with the skin, and the frequency content of tactile inputs [6], [10]. To date, the influence of propagating waves on tactile perception is not fully understood. While the transmission of vibrations in the skin has been considered to affect the performance of haptic devices [3], it is rarely accounted for in their design.

Many spatiotemporal vibrotactile phenomena, including apparent motion, saltation, funneling, and contrast phenomena, have been discovered, beginning in the 1900s and extending to the present day [11], [12], [13], [14], [15], [16], [17]. Such effects often reflect the spatiotemporal integration of cutaneous vibrotactile stimuli that are (in most cases) applied at multiple skin locations. For example, in 1957, von Békésy studied the spatial integration of vibrotacile sensations elicited by stimuli applied to the forearm skin, which he considered as a model system for understanding the cochlea [18].

The present work is inspired by research on cochlear auditory processing for which von Békésy received the 1967 Nobel Prize [19]. Using methods analogous to those we employ here, he combined optical measurements of basilar membrane vibrations with mechanical modeling in order to deduce that the selective transmission of lower frequency waves to greater distances provides a tonotopic spatial mapping in the basilar membrane. This mechanical process underlies frequency encoding in early auditory processing. In the vibrotactile system, an analogous frequency-dependent transmission of vibrations in the skin has been deduced to give rise to distinct population responses in cutaneous mechanoreceptors [7], but the implications for tactile perception are not fully understood.

Here, we present a new method for rendering unique, spatiotemporal vibrotactile stimuli via a single actuator. Our method exploits the viscoelastic properties of the skin, which cause propagating waves to decay in a frequency-dependent manner with increasing distance from the location at which they are applied. We hypothesized that by designing the frequency content of locally applied vibrotactile signals, we could control the spatial extent of propagating waves they excite in the skin. We further hypothesized that this could be exploited to enable a single actuator to generate spatiotemporal haptic effects.

To investigate this, we first considered a physical description for the frequency-dependent transmission of vibrotactile signals in the skin. We empirically assessed the transmission of such signals using in-vivo measurements captured via optical vibrometry. This results confirmed that the frequency content of locally applied vibrotactile stimuli determines their spatial extent in the skin, with low frequencies reaching greater distances, as in the mammalian cochlea. To demonstrate the utility of these results for haptic engineering, we design vibrotactile stimuli that excite spatially expanding or contracting fields of vibration in the skin. In a perception experiment, we demonstrate that subjects perceive these stimuli as expanding or contracting, without prior exposure or training.

In the next sections, we describe the mechanics of vis-

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coelastic waves in the skin, yielding predictions that we test in in-vivo optical vibrometry measurements that are described in the following section. We then present the design of new methods for synthesizing spatiotemporal vibrotactile stimuli from a single actuator, informed by the vibrometry results. We also present a behavioral experiment in which we demonstrate that the spatiotemporal properties of these designed stimuli are reflected in how they are perceived. We conclude with a discussion of the results and their implications for haptic device engineering and for the rendering of haptic effects via the control of waves in the skin.

II. Viscoelastic Waves in the Skin

Tactile sensation arises from mechanical stresses and strains felt via numerous cutaneous afferents. An idealized physical model of the transmission of such strains is an elastic wave equation,

$$\rho \frac{\partial^2}{\partial t^2}\boldsymbol{\xi}(\mathbf{x},t) = ((K+\mu/3)\boldsymbol{\nabla})\boldsymbol{\nabla}\cdot\boldsymbol{\xi}(\mathbf{x},t) + \mu\nabla^2\boldsymbol{\xi}(\mathbf{x},t) \quad (1)$$

where $\boldsymbol{\xi}(\mathbf{x},t)$ is the time varying strain vector, $\mathbf{x}$ is position, t is time, ρ is density, and K and μ are the bulk and shear moduli [20]. Solutions may be written as expansions in harmonic plane waves, $\boldsymbol{\xi}(\mathbf{x},t) = e^{j(\mathbf{k}\cdot\mathbf{x}-\omega t)}$ where $\omega = 2\pi f$ is the angular frequency, $\mathbf{k}$ is the wave vector, and the wave velocity $\mathbf{v}=(\omega/k)\hat{\mathbf{k}}$. At vibrotactile frequencies, mechanical transmission in bulk occurs primarily via transverse (shear) waves, $\boldsymbol{\xi}_T(\mathbf{x},t)$ satisfying $\boldsymbol{k}\cdot\boldsymbol{\xi}_T = 0$. Such waves appear to travel in soft tissues rather than via bone [6], [1], but the relative contribution of tissue types (including dermis, tendon, and muscle) is unclear. Shear waves travel at speeds $c_T = \sqrt{\mu/\rho}$. For soft tissues, the speeds, $c_T < 30$ m/s, are much lower than those of compression waves ($c > 1500$ m/s) [1], [21]. Near the skin surface, surface waves (including Rayleigh waves) develop, with speeds similar to those of bulk shear waves.

Soft tissues are viscoelastic. Waves in such tissues are damped and dispersive, yielding frequency-dependent damping $\delta(f)$ and speeds $c(f)$ [22], [7], [23]. In a linear viscoelastic model, damping imparts complex wavenumbers, $k = k_1 + i\delta$, to harmonic plane wave solutions, where δ, is the damping factor, and $k_1 = 2\pi f/c(f)$. In biological tissues, damping increases approximately linearly with frequency, $\delta = \alpha f$. Harmonic components thus satisfy

$$\boldsymbol{\xi}(x,t) = e^{-\alpha x f} e^{j2\pi f(x/c(f)-t)}. \quad (2)$$

This describes an oscillating wave that decays exponentially with distance. It causes higher-frequency waves to attenuate over shorter distances than lower frequency waves. An arbitrary plane-polarized wave has a Fourier expansion,

$$\boldsymbol{\xi}(x,t) = \int_{-\infty}^{\infty} df\ \phi(f) e^{-\alpha x f} e^{j2\pi f(x/c(f)-t)}. \quad (3)$$

Here, $\phi(f)$ is the amplitude and phase of a frequency component f, which decays over length scale $x_D = (\alpha f)^{-1}$. Thus, the relative weighting in $\phi(f)$ of low and high frequency content determines the distance that a propagating wave is expected to travel before attenuating. This suggests that the spatial extent of vibrotactile stimuli is greatly affected by their frequency content. We test this prediction using vibrometry experiments, and use it to guide the design of spatiotemporal haptic effects.

III. In-Vivo Vibrometry Experiments

We assessed the frequency-dependence of the spatial propagation of vibrations in the hand via time-resolved optical vibrometry. This provided non-contact measurements of skin vibrations at numerous points on the glabrous hand surface in response to vibration inputs applied to the distal end of the finger. We analyzed this data to relate the frequency content of the stimuli to the spatial distribution of skin vibrations they excited in the hand.

A. Subjects

7 subjects volunteered for the experiment (5 male; 20 to 45 years of age). All gave their informed, written consent. The experiment was approved by the Human Subjects Committee of the University of California, Santa Barbara.

B. Apparatus

Cutaneous vibrations were captured via non-contact scanning laser doppler vibrometer (SLDV; model PSV-500, Polytec, Inc., Irvine, CA). The right hand of each participant was positioned within the SLDV field of view. The hand was stabilized in an open posture via custom 3D printed brackets affixed to five fingernails via adhesive tape (Fig.1). The arm, hand, and brackets were supported via a pneumatically-isolated table. Subjects were seated in a reclined chair raised to a height at which their arm could remain relaxed.

Vibration stimuli were applied normal to the tip of digit 2 along the axis of the finger via an electrodynamic actuator (Type 4810, Brüel & Kjær, Denmark) driven by a laboratory amplifier (PA-138, Labworks Inc.). Prior to the experiment, we measured the frequency response of the amplifier-actuator system to be flat over the entire measurement range (± 3 dB). The finger was attached to the actuator along a 49

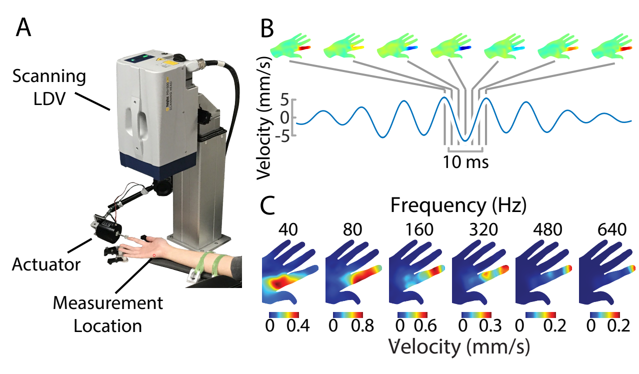

Fig. 1. A) Measurement Apparatus. Hands were positioned within the field of view of the SLDV, which captured the velocity of skin vibrations across the entire volar hand surface in response to stimuli applied at the tip of digit 2. B) The stimuli elicited propagating waves in the skin. The data comprises of one trial for one participant, with the 80 Hz windowed stimulus. C) The RMS velocity of skin oscillations illustrate the frequency-dependent spatial extent of the wave fields elicited in the skin (shown here for one subject). Low frequencies stimuli excited waves that extended farther in the finger.

mm^2 interface via adhesive tape to prevent the skin from decoupling during actuator retraction.

C. Stimuli

Two types of vibration stimuli were applied via the actuator: periodic frequency sweep (chirp) and windowed sinusoidal signals. The frequency sweep extended from 20 Hz to 1000 Hz. The driving signals were generated by the PSV-500 system, ensuring sample-accurate synchronization of the driving signal with the measurement. The sinusoidal frequencies ranged from 40 Hz to 640 Hz in steps of 40 Hz. To avoid transient artifacts, we applied a Hanning window function to each sinusoid, with a duration of 10 cycles (thus, longer for low frequency signals). To avoid interference between different stimuli, a pause of 150 ms was enforced between measurements. Amplitudes were selected to provide sufficient signal-to-noise ratio and to be comfortable even during extended stimulation.

D. Procedure

After each participant was seated at the apparatus, a 3D scan of the volar hand surface was performed via the integrated geometry scan unit of the SLDV. Vibrometry measured the velocity of skin motion normal to the volar hand surface at 300 points that were equally distributed across the surface. We selected this spatial resolution because we estimated it to be approximately 10× finer than the wavelength of cutaneous vibrations in the tested frequency range. The measurement sampling frequency was 20 kHz.

For each scanned measurement point, the finger was presented with all stimuli while data was collected at the measurement point. The vibrometer captured the vibration velocity in a direction normal to the volar hand surface. The experiment took a total of 80 minutes per subject.

E. Analysis

The data consisted of velocity signals describing skin vibrations at 300 measured locations for each of the 16 signals and 7 subjects. We focused our analysis on the skin vibrations elicited by the chirp signals. We reconstructed the time domain response at different frequencies and computed root-mean-squared (RMS) averages for each measurement trial, frequency, and participant. This yielded RMS velocities $v(\boldsymbol{x})$ at the 3D positions $\boldsymbol{x} = (x_1, x_2, x_3)$ of all measurement locations. To assess the spatial extent of skin vibrations elicited for different stimulus frequencies, we evaluated the RMS velocities v along a straight line extending from the actuator probe to the the base of the hand. For each frequency, velocity values at 200 points on this line were computed via interpolation. For each frequency f, we computed the median spatial extent of skin vibrations as the the distance $D(f)$ up to which the signal energy reached half of the total, averaged across all subjects. We fit $D(f)$ to a power law, $D(f) = c_1 f^{c_2}$, where c_1 and c_2 were the fitting parameters.

F. Results

The results indicate that stimulation at the fingertip elicited time-dependent wave fields that reflected the stimulation frequency (Fig. 1A) and extended proximally from the fingertip (Fig. 1B), reaching the palmar surface within 10 ms.

Consistent with predictions from wave mechanics, the vibration-elicited waves decayed with the distance they traveled from the stimulation point, and did so in a frequency-dependent manner (Fig.2). For all subjects, the highest frequency stimuli (f=640 Hz) elicited cutaneous waves of greatest amplitude (velocity, m/s) near the fingertip, where they were applied and decayed rapidly over the course of 40 mm. Near the base of the finger, 80 mm distant, these vibration velocities were attenuated by an average of 95%. In contrast, the lowest frequency stimuli (40 Hz) elicited cutaneous waves that increased in amplitude, reaching maxima near the base of the finger. We attributed this increase to two factors. First, to an effect of spatial oscillation. The model predicts such a wave to have the form $\exp(-\alpha f) \exp(j(kx - \omega t)$, where $k = 2\pi/\lambda$, with λ being the wavelength. At low frequencies, λ is large, yielding a gradual increase superimposed on the gradual decay with distance. Second, the stimuli were applied parallel to the finger axis. In preliminary testing with a 3-axis vibrometer, we found the conversion of axial stimuli into vibrations normal to the volar hand surface to develop over the course of a fraction of a wavelength. Thus, the 1-axis measurements may not capture all energy in the fingertip at low frequencies. As frequency increased from 40 Hz to the 640 Hz, the spatial extent $D(f)$ of cutaneous waves decreased from more than 85 mm to less than 30 mm (Fig.2B). This was adequately captured by a power law fit ($R^2 = 0.74$). The deviation from exponential decay could be attributed to the aforementioned spatial oscillation (consistent with the model), and to mode conversion, as noted above. Such a wave pattern is also similar to a standing wave mode. Results were similar for all participants. We attributed inter-subject differences to variations in hand geometry and contact conditions. Across subjects, the standard deviation of the normalized amplitude $v(f)/\max_f v(f)$ was 0.03, underlining the consistency of this effect.

IV. Design of Spatiotemporal Haptic Effects

The in-vivo measurements were consistent with theoretical predictions, and reflected that low frequency ($f < 160$ Hz) stimuli excited wave that extended throughout the finger, whereas damping confined waves excited by high frequencies ($f > 160$ Hz) near to their locus of application (Fig. 1).

The vibration measurement procedure entailed the successive application of N brief sinusoidal stimuli with frequencies f_k that increased monotonically, $f_{k+1} > f_k, k = 1, 2, \ldots, N-1$. This yielded skin vibrations that successively decreased in spatial extent. Participants reported that these increasing-frequency sequences elicited the sensation that the spatial extent of vibrations was contracting over time. In contrast, when we tested sinusoidal stimuli with constant frequency, the spatial extent of skin vibrations was difficult

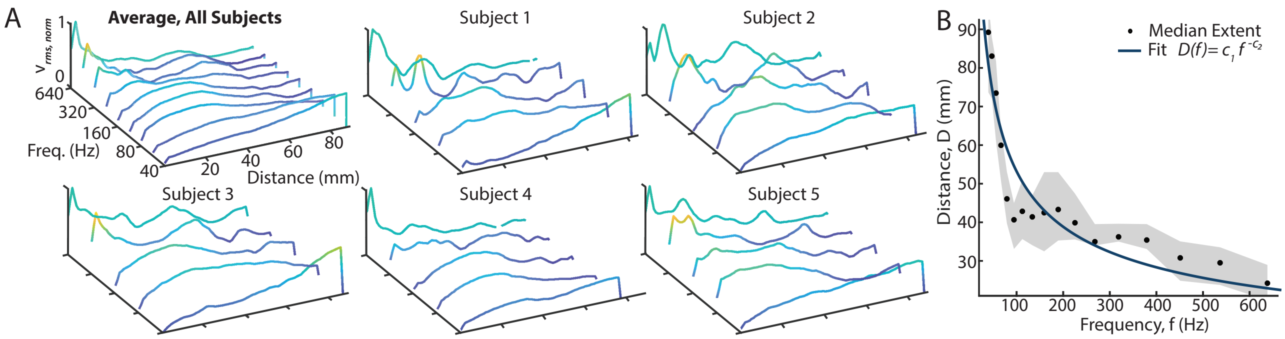

Fig. 2. The amplitude (normalized rms velocity $v(f)/\max_f v(f)$) of propagating waves decreased with distance in a frequency-dependent manner. A) The magnitude of skin responses varied with distance from the location at which they were applied on the fingertip and the frequency content of the stimulus. Distances extend proximally along the midline of the finger. B) The median spatial extent of vibrations decreased supralinearly with increasing frequency. This reflected the spatial decay and spatial wavelength of the propagating wave. A power law fit $D(f) = 435.5f^{-.46}$ provided a good fit ($R^2 = .74$) to the measurements. The shaded region represents the quartiles of distribution of the measurements

to discern without special attention. (This might explain why the effects we describe have not received greater attention.)

Informed by these findings, we designed vibrotactile effects comprised of sequences of N short segments $x_k(t),\ k = 1, 2, \ldots, N$ of successively increasing or decreasing frequency content. We designed the changes in frequency to span a range from 12.5 Hz to 333 Hz, which matched the range over which the spatial extent of skin vibrations changed most rapidly (Fig. 2B). We first tried sequences of sinusoidal segments. However, we observed them to elicit ancillary sensations of ascending or descending "tones" that were distracting. To avoid this, we instead designed sequences of wavelet-like segments $x_k(t)$, whose energies were more broadly distributed in frequency (Figure 3). The segments consisted of scaled window functions modulated by a fixed frequency, $f_0 = 25$ Hz.

$$x(t) = \sum_{k=1}^{N} x_k(t - r_k), \quad (4)$$

$$= \sum_{k=1}^{N} A_k\, g_k(t - r_k)\, \sin(2\pi f_0(t - r_k)). \quad (5)$$

Here, $T = 100$ ms is a short delay time between segments, and A_k is a gain factor that compensated for differences in the perceived magnitude of the segment signals. The onset time of segment k is $r_k = \sum_{j=0}^{k-1}(\tau_j + T)$. The window function $g_k(t)$ is a truncated Gaussian of duration τ_k and standard deviation $\sigma = \tau_k/5$,

$$g_k(t) = \text{rect}\,(t/\tau_k)\,\exp\left(\frac{-t^2}{2\sigma^2}\right), \quad \sigma = \tau_k/5 \quad (6)$$

$$G_k(f) = \sqrt{2\pi}\sigma\,\text{sinc}(f\tau_k) \star e^{-2(\pi f \sigma)^2} \quad (7)$$

where $\star$ denotes convolution in the frequency domain and $G_k(f) = \mathcal{F}(g_k(t))$ is the window spectrum. The spectrum, $X_k(f) = \mathcal{F}(x_k(t))$, of each signal segment is given by

$$X_k(f) = A_k G_k(f) \star \frac{j}{2}\left[\delta(f + f_0) - \delta(f - f_0)\right] \quad (8)$$

It is centered at frequency f_0 with a segment bandwidth of approximately $f_k = 1/\tau_k$. For the concentrating stimulus, we designed signals $x(t)$ with N segments having frequency bandwidths f_k that increased in a logarithmic series over time, from $f_1 = 12.5$ Hz to $f_N = 333$ Hz. For the expanding stimulus, the sequence was reversed. Stimuli used in the experiments had $N = 10$ segments.

V. Perception of Spatiotemporal Haptic Effects

We next sought to determine whether our theoretical and mechanical findings linking the frequency content of tactile signals to their spatial extent would be reflected in perception. To this end, we designed a simple experiment in which participant classified either the wave-based effects (described in the preceding section) or control signals as "expanding" or "contracting".

A. Participants

Fifteen participants volunteered for the experiment (12 male; 19 to 30 years of age). All subjects were naïve to the purpose of the experiment and gave their written informed consent. The experiment was conducted according to the protocol approved by the UCSB Human Subjects Committee.

B. Apparatus

Vibration stimuli were applied to the distal end of the index finger using hardware identical to that used in the

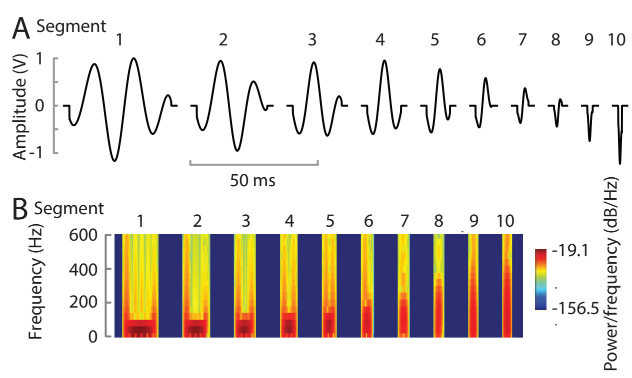

Fig. 3. The tactile effects were designed to elicit sensations of spatial expansion or contraction via sequences of segments with respectively increasing or decreasing frequency content. For contracting effects, the segments were wavelet-like signals (A) of decreasing duration, and (B) logarithmically increasing bandwidth.

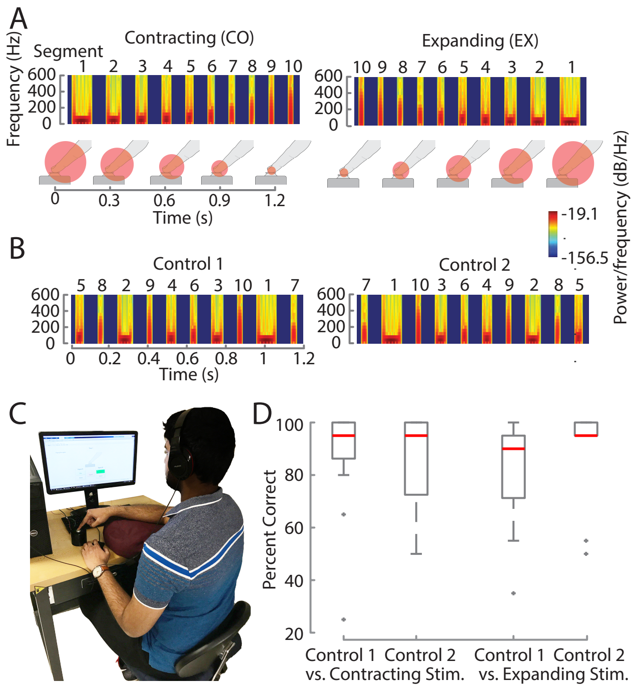

Fig. 4. Perceptual experiment. A. Spectrogram of the designed stimuli that produce contracting (CO) and expanding (EX) sensations and associated animations used. B. Spectrogram of the control stimuli, with permuted segments. C. Experiment setup. Subjects contacted the actuator with their right index finger. D. Results of the experiment for four pairs of designed versus control stimuli. Subjects consistently identified the designed stimuli.

measurements. Subjects were seated, with their index finger in contact with a flat surface (diameter 15 mm) on the actuator (Fig. 4C). The finger was held at a 45° angle and a contact force of 2 Newtons (a force gauge was used for comparison). Subjects wore foam earplugs (attenuation rating 33 dB) and circumaural headphones playing pink noise sufficiently loud to mask feedback from the actuator. The experiment was automated via a computer's graphical user interface.

C. Stimuli

The stimuli consisted of the designed "expanding" (EX) or "contracting" (CO) stimuli described in the preceding section (Fig. 4A). We also designed two different control stimuli (Fig. 4B). The control stimuli were composed from sequences of the same signal segments that as in the EX and CO stimuli, in permuted (shuffled) order. Because we hypothesized that the sequence of changes in frequency extent of the EX or CO stimuli would cause them to be perceived as expanding or contracting, we selected permutations so that there was no systematic increase or decrease in frequency extent over the course of each entire control signal, or over the first or second half separately (Fig. 4B).

D. Procedure

The experiment was based on a two-alternative forced choice task in which subjects were presented with one designed stimulus (EX or CO) and one control stimulus. Subjects were also presented with an animated visual representation of "expansion" or "contraction" at the fingertip matching the presented designed stimulus (Fig. 4A). We did not describe what these represented, nor did we present the stimuli, which subjects felt for the first time on the first recorded trial of the experiment. In pre-testing, we determined that visual representations were understood better than text labels. Subjects were allowed to experience the two stimuli and asked to report the stimuli which caused a perceptual sensation closest to what is indicated in the displayed animation. The stimuli were presented in random order and their position was randomized on the computer screen. We randomly selected one designed and one randomly control stimulus for each trial, yielding four possible combinations. Each of the designed or control stimulus was presented a total of 40 times, for a total of 80 trials per participant. In a post-experiment questionnaire subjects were asked to describe the strategy they used to respond. They then felt the designed stimuli again and were asked to describe them.

E. Analysis

We computed the percentage correct as the median proportion of responses that assigned the designed stimuli to the corresponding visual depiction for each of the four combinations for each subject. The proportions were computed from all presentations (including either control stimulus). We considered a percentage correctness of 75% as a threshold for a positive effect relative to chance performance (50%). Because the distributions violated normality assumptions, we used non-parametric one sample Wilcoxon signed rank tests. We tested the null hypothesis that the median was less than or equal to 75%. We also assessed the effect of the control stimulus choice using Mann Whitney U tests.

F. Results

Without training or prior exposure, subjects consistently associated the designed stimuli with the visual representations of "expanding" or "contracting". The designed stimuli were selected with median probability 96.7% (CO stimuli: 97.5%, EX: 95%). The control stimuli were selected with median probability 3.3%. These values were significantly greater than a positive effect threshold of 75% ($p = 0.0163$ and $p = 0.0039$ for CO and EX). There was no significant effect of the control stimulus presented ($p > 0.7$ and $p > 0.08$ respectively).

G. Discussion

The results indicate that the designed stimuli were consistently associated with the corresponding visual depiction. This suggests that subjects felt them as respectively expanding or contracting, consistent with predictions from theory and mechanical observations, without any prior exposure or training. The high median accuracy reflects the robustness of these associations. The associations were unaffected by the control stimulus used for the comparison.

After repeated exposure, participants would have had little difficulty identifying either the designed or control stimuli, due to the differences in timing and frequency content. Consequently, they could have based their decisions on arbitrary cognitive criteria. However, a priori, we would expect such criteria to result in a bistable response pattern. In our experiment, no subjects consistently inverted the aforementioned associations to expansion and contraction. Further, the control stimuli were selected with a very low median response rate (3.3%). Together, these results indicate that the effect was not bistable, and suggest that arbitrary criteria were not applied.

We conclude that the increasing or decreasing frequency content of the designed stimuli caused them to be perceived as spatially expanding or contracting. This conclusion is supported by the questionnaires, in which participants spontaneously described sensations such as "concentrating to / spreading from the fingertip" and proceeding "from bigger portion of the finger to smaller portion / vice versa."

The designed stimuli were selected with greater frequency after the first few trials, from 87.5% (median percentage for trials 1-4) to 100% (trials 5-20). Because participants did not feel any stimuli prior to trial 1, this could reflect increasing familiarity with the protocol. It could also reflect strengthened associations after repeated exposure.

VI. Conclusions

A central challenge in the engineering of tactile interfaces is to stimulate the continuous medium of the skin via practical mechanical instruments with very few mechanical degrees of freedom. In this work, we show how to use a single actuator to generate tactile stimuli with dynamically controlled spatial extent. The methods are based on the physics of frequency-dependent damping of propagating waves in the skin. We provided empirical evidence for this through new observations from full-field optical vibrometry. This revealed that the frequency content of locally applied vibrotactile stimuli shapes their spatial extent in the skin. We demonstrated the utility of these results by designing expanding and contracting vibrotactile stimuli that can be delivered by a single actuator. Using a perception experiment, we demonstrated that the designed stimuli were perceived as respectively expanding or contracting, consistent with predictions from theory and mechanical observations. These findings demonstrate how the wave physics of the skin can be exploited to design methods for spatiotemporal haptic feedback that are practical and perceptually evocative.

We showed that these phenomena can be exploited to realize spatial effects using a single actuator. It is interesting to consider how they may be integrated in multi-actuator configurations to generate effects of heightened tactile apparent motion. We aim to explore this in future work.

Although the results are promising, several issues merit further investigation. First, the wave phenomena involved are complex, and further research is needed to fully characterize them. Second, the experiments involved a simpler binary forced choice paradigm and further research is needed in order to clarify how such effects are perceived. Further, this study focused primarily on the fingertip, the region of the body with which we frequently contact objects. However, the generality of these physical phenomena suggests that similar effects could be elicited at other body locations.

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