Use of materials science to understand haptic perception

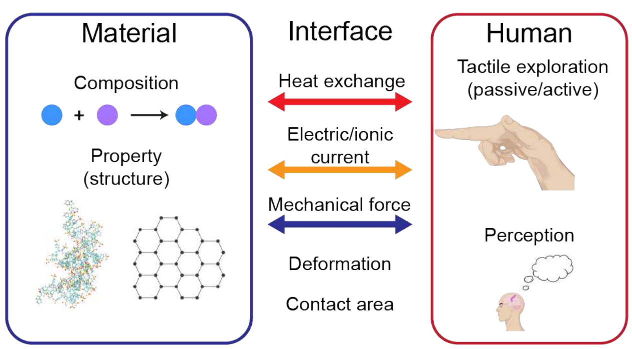
Laura L. Becerra,† Nicholas B. Root,‡ Robert Ramji,¶ Romke Rouw,‡ and Darren J. Lipomi*,¶

†*Department of Electrical and Computer Engineering, University of California San Diego, La Jolla, CA 92093*

‡*Psychology Department, University of Amsterdam, Amsterdam, Netherlands*

¶*Aiiso Yufeng Li Family Department of Chemical and Nano Engineering, University of California San Diego, La Jolla, CA 92093*

E-mail: dlipomi@ucsd.edu



Conspectus

The haptic sense is the catch-all term that captures information arising from the somatosensory system—the sensor system of the body excluding the eyes, ears, nose, and tongue. That is, it captures stimuli arising from the skin (i.e., touch), along with those originating from internal structures (i.e., the musculoskeletal system and internal organs). The field of research called *haptics* is concerned with understanding and manipulating this sense, often using engineered technology, and usually for creating novel or realistic touch sensations. Fundamental to every tactile interaction is an interface between the skin and a material. Given that essentially all material objects are composed of or covered in organic media, we reasoned that we, as organic materials scientists, might be able to contribute to the understanding of the sense of touch by manipulating the properties of materials on the molecular scale. Over time, our research group acquired additional skills in electrical engineering and also developed strong collaborations with cognitive and behavioral scientists. With a shared curiosity about the sense of touch, we were able to make what we believe are original contributions to the field of haptics.

Our approach is guided by a paradigm consisting of four layers from which hypotheses can be generated, experiments can be designed, and whose analytical techniques may be applied. The layers are (1) material composition, (2) material properties, (3) interfacial properties between the skin and the material, and (4) human perception. For example, a material may be composed of one part silicon and two parts oxygen (material composition), which leaves the surface terminated in dipoles and thus a high surface polarizability (material properties). These dipoles may then interact with the skin with a strong van der Waals interaction and high friction (interfacial properties). This friction may lead to stick-slip behavior and could possibly be perceived as fine texture or roughness, even if the surface is smooth (perception).

Another useful organizing principle is that of active vs. passive touch. That is, engaging with an object with intent (where conscious perception is influenced by some degree of expectation) vs. having an object brushing up against one's skin (where the sensation may come as a surprise or without expectation). In either case, the sensation perceived can be described as either fundamental (e.g., roughness, coldness, compliance, and slipperiness) or blended (e.g., wetness). Beginning with an example of how our approach can be used to understand active touch of a blended sensation, we show how polyacrylamide hydrogels can be tuned by adjusting both the mechanical compliance and thermal conductivity to elicit different levels of perceived wetness. We then show how a purpose-designed conductive polymer can render sensations of roughness in the context of a virtual reality simulation that operates by both passive and active modalities. Lastly, we demonstrate a form of haptic "holography" using the photoacoustic effect; that is, π-conjugated materials coated on the skin can render sensations of vibration (perceived passively) when exposed to pulsed light. Throughout this Account, we describe how control of materials can be used to elicit senses artificially for both fundamental knowledge and for the ultimate development of richer human-machine interfaces.

Introduction

The tactile sense is activated by interaction of the skin with matter,[1] and thus there is a significant opportunity for research within the field of haptics. Namely, to understand how the structure and properties of matter–as modulated by the tools of materials chemistry–affect human tactile perception of the physical world. The properties of materials registered by structures of the somatosensory system ultimately arise from atomic and molecular composition, which gives rise to, for example, electrical charges, dipoles, and polarizabilities, along with exclusion forces arising from quantum mechanics. Materials also have macroscopic observables such as roughness, thermal conductivity, density, modulus, and so forth, that are derived not only from chemical composition but also by the ways in which their atoms and molecules are arranged in the solid state.

Researchers in the field of haptics have historically used readily available materials whose properties have been engineered for other purposes (not for studies of haptic perception). Such materials, i.e., slabs of different plastic[2,3] or different grits of sand paper,[4–6] have been the mainstay of research in haptic perception. However, to examine mechanisms of tactile perception using materials whose attributes such as chemical structure, surface properties, and bulk properties are precisely controlled, it is necessary to have a degree of precision not available in "off the shelf" materials. Nevertheless, when it comes to the question of how humans cognitively perceive materials and their properties through touch, materials scientists reach a limitation without knowledge of psychology and neurophysiology. Moreover, to active such materials in such a way as to stimulate skin or the peripheral nervous system in a precise way, it is necessary to recruit the expertise of the other engineering disciplines, i.e., mechanical and electrical engineering.

Laura recently obtained her PhD in electrical and computer engineering. She entered her PhD program with an interest in human-machine interactions, particularly for biomedical applications. Knowing very little about materials engineering or psychology, she joined Darren's research group and learned about soft materials from her laboratory colleagues. Darren is a professor whose area of research is organic materials chemistry. He became interested in haptics and soon realized that tactile interactions are often mediated by organic species at the surfaces of objects. While this is obviously true in the case of plastic objects or those covered with organic coatings (i.e., latex paint), it is also true of nominally abiotic, inorganic media, such as metals and oxides coated with adventitiously adsorbed organic structures by van der Waals "bonds." This led him to explore how manipulating organic media properties could recreate the feeling of real objects in virtual environments.

Prior to Laura's arrival, our research group made a small number of interesting contributions to the field of haptic perception of materials with engineered properties. For example, we found that human subjects were able to discriminate otherwise identical surfaces that differed by the presence of a single molecular monolayer.[7] By constructing a bespoke surface force apparatus, we found evidence for the role of differential stick-slip friction in permitting the discrimination.[7] Moreover, we determined that fingerprint-like relief structures in mock fingertips amplified differences in tangential friction traces compared to those generated by "fingertips" lacking such structures.[8] In a separate set of experiments, we were able to contribute to the understanding of how the microscopic contact area of the skin with a surface combines with macroscopic stiffness to affect the percept of "softness" in humans.[9] We did so by manipulating surface relief using soft lithographic molding, and manipulating the stiffness by altering the slab thickness and the ratio of base to crosslinking in commercial silicone elastomers. Experiments done with cognitive scientists V.S. Ramachandran and Nicholas Root (UC San Diego Department of Psychology) revealed that microstructured surfaces were perceived as harder when the finger's penetration depth into the sample was held constant.[9]

From this work, we learned that collaborations with neurobiologists and behavioral scientists were necessary to assure that our study designs and statistical analyses were meaningful and reproducible. During her graduate program, Laura was invited to collaborate with psychologists Nicholas Root and his advisor, Romke Rouw, from the University of Amsterdam. Romke's lab conducts research on sensory (visual, auditory, tactile) perception, including special cases of perception (misophonia[10]) and multisensory perception (synesthesia[11]). Laura designed and developed haptic stimuli for a study led by Nick investigating touch-color synesthesia. Nick designed and created the psychological experiments and statistical approach of sensations evoked by touching these materials, using a paradigm known as psychophysics (see below). This work formed an international and interdisciplinary collaboration between Darren's materials science lab and Romke's psychology lab. With these intellectual resources at our disposal, we have begun to develop a foundation of knowledge in psychophysical experiment design, and human cognition in haptic material perception.

In this Account, we explore how to use the properties of engineered materials to understand the tactile sense. By modulating the microscopic properties of materials as "independent variables," we examine how these attributes manifest in consciousness through tactile interaction. This Account begins by describing what aspects of materials and human-stimuli interactions are critical in haptic material design and how to use psychophysics in material exploration studies. We then discuss some of the characteristics of the haptic sense (e.g., passive vs. active touch, touch-blend sensations) and highlight three projects done by our research group demonstrating how engineered materials and psychophysical testing can be used to study cognitive perception of haptic stimuli.

The role of human skin receptors in touch

The skin has a variety of nerve endings called receptors sensitive to specific sensory inputs, each attuned to a range of frequencies, thresholds, and types of stimulus.[12,13] The primary receptor types for tactile stimuli are mechanoreceptors, thermoreceptors, and nociceptors. Mechanoreceptors detect mechanical stimuli such as pressure and texture, while thermoreceptors respond to temperature variations. Nociceptors, on the other hand, alert humans to potentially harmful stimuli, including extreme temperatures and intense pressure. Mechanoreceptors for non-painful stimuli generally terminate in a hair follicle or end organ. The end organs found in the fingertips and palmar surface of the hand—called glabrous, non-hairy, skin—consist of Meissner's and Pacinian corpuscles, Ruffini endings, and Merkel cell-neurite complexes. The Meissner's and Pacinian corpuscles respond to low and high frequency vibrations, the Ruffini ending responds to stretch, and the Merkel cell-neurite complex responds to small static deflections of the skin.[12] One or more of these end organs is connected to the nervous system by a heavily myelinated nerve fiber.

The nerve ending, along with other structures of the end organ (e.g., Merkel cells), contains mechanically activated ion channels, the most famous of which is PIEZO2.[14,15] A tactile stimulus, whether it be a gentle caress or a sharp poke, causes the flow of ions through the membrane and initiates an action potential. However, the information contained in the generation of action potentials is sensory only; it does not necessarily predict the affective reaction (i.e., emotional valence) or cognitive response (i.e., interpretation in context) of the stimulus. Therefore, our group sought to use engineered materials and psychophysics as tools to understand the cognitive response of touch interactions.

Psychophysics for touch perception

The field of psychophysics studies the relationship between stimuli and perception.[16] Tools and methods in this field, developed over decades, explore detection limits, accuracy, and discrimination thresholds of various stimuli. The combination of psychophysical experiments with materials science allow us to understand how material properties influence perception, an insight difficult to achieve through either field alone.

When developing materials for haptic manipulation, we envisioned the design space using a four-layer framework (Figure 1). One layer is the composition or ingredients that make up the stimuli, such as chemical composition. Closely related is the layer associated with the inherent properties of the stimuli/material itself, that result from the composition layer. This property layer can be thought of as quantitative characteristics that can be tuned and measured, such as stiffness or electrical conductivity. Adjacent to this layer is the interface layer, where the interface is usually between the skin and the material. Attributes of the interface layer include those which require contact to arise, e.g., rate of heat exchange and friction. Finally, the perception layer is where the response of the human user takes place, after stimuli interaction. All four of these layers play a key role in developing a comprehensive perceptual space to understand human perception of stimuli characterized by specific properties.

After designing the procedures for fabrication of materials with varying tactile properties, psychophysical experiments are conducted. One common paradigm is to ask a human participant to interact with two different stimuli side by side and choose one that best follows a predetermined criterion. For example, in a study to investigate stiffness, two materials differing in stiffness would be placed side by side and the participant would be asked to touch both materials and select which one felt the most stiff (a "paired comparison" design). This experimental design allows the researcher to characterize discriminability while controlling for participant characteristics (e.g., a liberal or conservative response criterion): so long as enough trials are included for each participant, it is possible to characterize both average

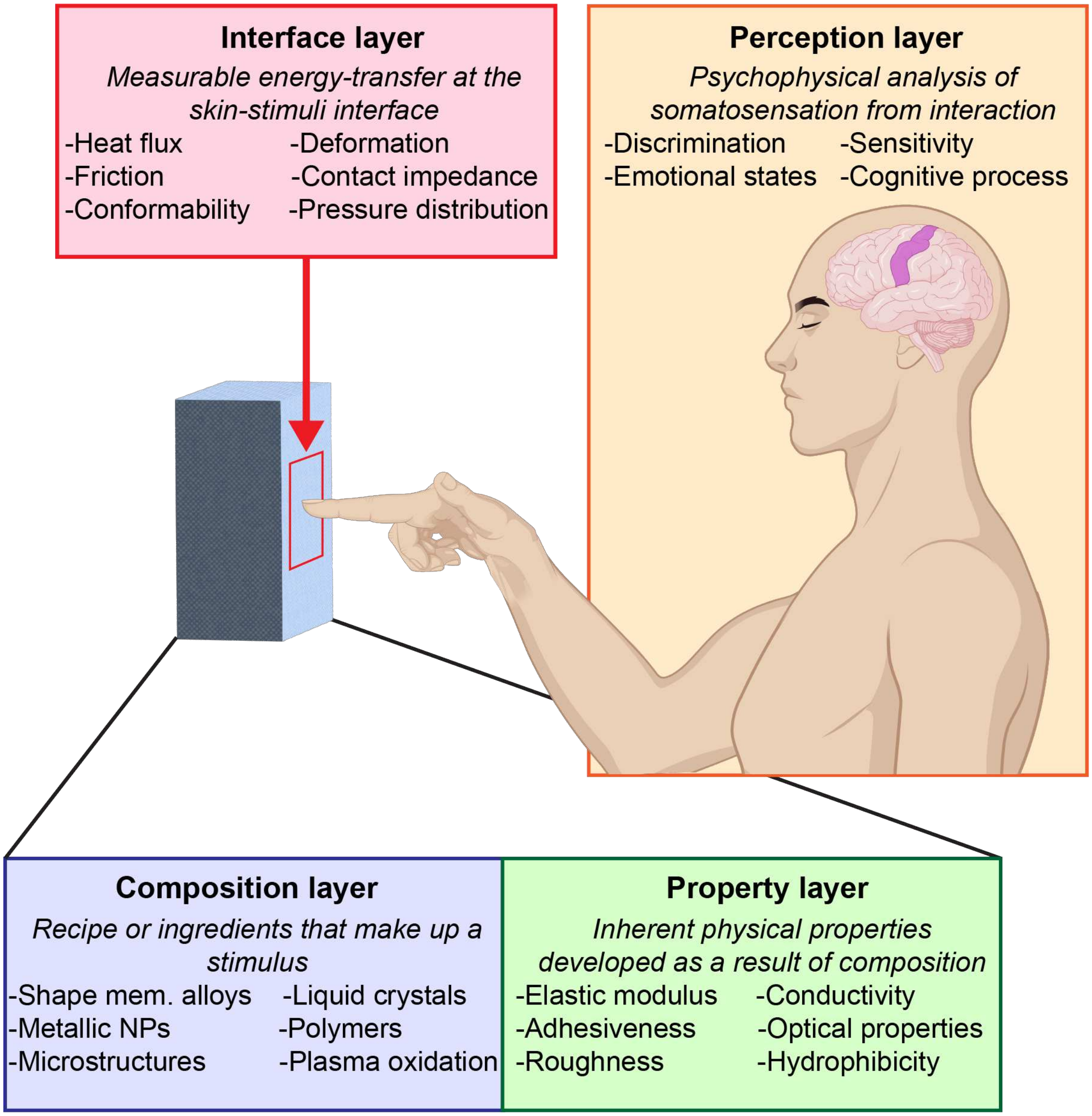


Figure 1: Four layers of haptic material design that play a role in human perception in tactile interactions.

performance and also variability across participants.[17]

Typically a Bradley-Terry (BT) statistical model is used to evaluate the pairwise comparison data. The BT model quantitatively describes the preferences of stimuli selected by participants in the experiments.[18] The results can then be used to back-calculate the properties of the material most likely to elicit a tactile percept. That is, it allows one to establish guidelines for subsequent iterations of stimuli.

Given $P(i > j)$, the observed probability that sample i is selected over sample j, the model infers the "scores" p_i and p_j that satisfy the relationship:

$$P(i > j) = \frac{p_i}{p_i + p_j} \tag{1}$$

If these score terms are parameterized using an exponential function (e.g., $p_i = e^{\beta_i}$), then the equation can be re-written into a form suitable for logistic regression:

$$log \frac{P(i > j)}{P(i < j)} = \beta_i - \beta_j \tag{2}$$

Going back to the stiffness experiment example, let's say we collected paired comparison data from 10 participants, with 8 trials of every possible pairwise comparison between 6 samples. This would be a total of 120 trials per participant (8 trials x 15 unique comparisons). The data might look like this:

Table 1: Sample data for 2-AFC experiment

Sample Pair	Wins	Losses	Sample 1 Stiffness(kPa)	Sample 2 Stiffness (kPa)
A vs B	100	20	100	1
B vs C	75	45	1	0.5
A vs C	110	10	100	0.5
...	...	...	...	...

The wins and losses are the values that represent the probabilities on the left side of Eq. (1). For example, $P(A > B) = 100/120$. The next step is to infer the parameters β_i and β_j that best fit the data, using an estimation method. A simple method that is commonly used is maximum likelihood estimation (MLE). Most software programs/languages, such as R, Python, and MATLAB, contain statistical packages that are capable of taking win/loss data and calculating parameters. Software is typically used to calculate parameters because it is easy, quick, mitigates calculation error, and avoids having to solve complex equations by hand.

After calculating parameter values for each sample, they can be plotted against the stiffness of the sample. This will provide a visual comparison of the "win rate" across samples as a function of their stiffness. To statistically test whether or not stiffness is a significant predictor of β, a two-stage regression can be constructed in which the "score" parameter (e.g., β_i) is not fit directly, but is instead a dependent variable in a separate regression (e.g. $\beta_j = \alpha_i + \epsilon$, where α_i is the stiffness of sample i and $\epsilon \sim \mathcal{N}(0, \sigma^2)$). Software such as the BradleyTerry2 R package can be used to fit such a model and to calculate the Wald Z test statistic and corresponding p-value. If this p-value is significant then we would reject the null hypothesis that there is no relationship between the physical stiffness and participants' stiffness judgements. Once this model is fit, other measures can be calculated as well: for example, given material with a certain stiffness, the model can predict the just noticeable difference (JND): the minimal change in stiffness that would be necessary for participants to perceive a difference.

Wald Z tests of Bradley-Terry model parameters are one of several techniques to analyze paired comparison data, and paired comparison is one of several methods that might be grouped under the more general umbrella of 2-alternative forced choice designs. Regardless of the experimental design or statistical method, using psychophysics as a metric to evaluate the efficacy of haptic material perception enhances our understanding of sensory experiences and informs our strategies in material design for human-computer touch interfaces.

Haptic exploration: Active and passive touch

There are two modalities in which animals collect information about their environments through tactile interactions: passive touch and active touch.[19] In passive touch, a stimulus interacts with the skin without conscious exploration by the individual. An example is a falling leaf landing on your shoulder when walking in the park. The distinguishing characteristic of passive touch is that the subject is not "trying" to learn something through the interaction with the stimulus, or to affect its movement. On the other hand, active touch implies conscious exploration, such as when an individual pets a cat, or pushes a lawnmower. There is some degree of conscious expectation of a stimulus feeling a certain way, or exerting a certain kind of force. Lederman and Klatzky have placed the modes of touch exploration modes into categories, including lateral motion, pressure, static contact, unsupported holding, and contour following.[20] When these modes of exploration are used, information is obtained about surface properties, such as texture, weight, and compliance, and about geometric and spatial properties, such as curvature, orientation, size, and shape.

In our research group, we have performed experiments designed to understand aspects of both active and passive touch, along with modes of interaction in other modalities—such as in VR—that may be difficult to categorize cleanly between active and passive. A strategy we have relied upon to understand how physical variables manifest as tactile percepts is to fabricate arrays of material samples which vary in one or more parameters, such as compliance,[9] or elastic modulus and thermal conductivity.[21] Of the following sections highlighting projects done by our group, the first project is an example of using an array of engineered materials for active touch exploration.

Active touch: Tunable mechanical and thermal properties in hydrogels for wetness perception

Inspired by the inherent multisensory nature of human perception,[22] Laura took a particular interest in tactile sensations that are not associated with a single receptor type (i.e., in the way that high frequency vibrations activate the Pacinian afferent). These types of sensations are called "learned sensations" or "touch-blend sensations" as they blend signals originating from multiple cutaneous receptors.[23] Examples of this are stickiness,[24] greasiness,[25] or wetness.[26] Individuals are able to label the touch experience with a learned descriptor, yet do not have receptors in their skin to specifically detect these experiences. Such percepts can in principle be generated by engineered systems which exploit the interpretive biases of human cognition, e.g., to generate a "haptic illusion".[27,28] For example, chemically, haptic sensations can be rendered using topical stimulants, such as capsaicin for heat, menthol for cool, and sanshool for tingling.[29,30] Tactile sensations such as stiffness and vibration can be rendered without physical contact with an object using mid-air ultrasound technology.[31,32]

A salient everyday example of a touch-blend sensation is that of wetness.[33,34] In pioneering work in the turn of the (19th) century by Bentley,[35] human participants were asked to submerge their fingers into beakers of liquids of different temperatures covered by a rubber sheath. From the results of the study, Bentley developed the sensory-blend hypothesis stating that the perception of tactile wetness is determined by a combination of light pressure and coldness. (A useful analogy is the perception that grass in a lawn can feel wet, even in the absence of dew or rain. The reason it feels wet is that the interior of the plants comprise mostly water, and its compliance allows it to touch the skin in many places.) This study is a prime example of how haptic stimuli can be engineered to elicit a target sensation without providing the true stimulus (in this case, actual contact with the liquid).

Laura designed a study using hydrogels to understand the perception of wetness through active touch of participants. That is, participants were given a series of hydrogel slabs and asked to probe the slabs with their fingertips. As material substrates, we tuned a series of polyacrylamide hydrogels to have a range of stiffnesses (by manipulating the crosslinking chemistry[36]) and thermal conductivities (by manipulating the ratio of miscible liquids within the hydrogel matrix) (Figure 2). Inspired by the classic experiments of Bentley,[35] gels were covered by a thin polymer film so that participants would not be contacting the gels nor the liquids therein directly.

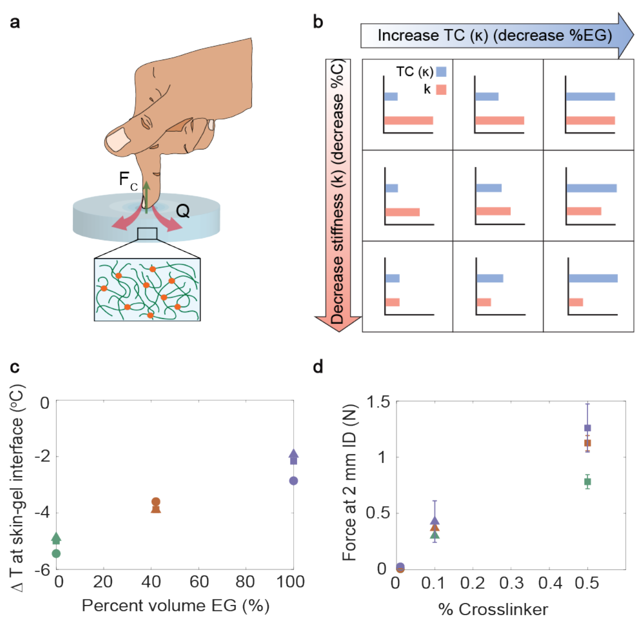


Figure 2: Tuned mechanical and thermal properties of hydrogels. (a) Schematic diagram of tactile interaction. F_c is the compression force exerted onto the finger from the hydrogel. Q is the heat flux across the skin-gel interface. (b) Matrix of variable properties for each material tested. There are three degrees of thermal conductivity (κ) in the gel soaking solvents and three degrees of stiffness (k). (c) Change in temperature at the skin-gel interface as a result of different dilutions of EG in water used to soak the hydrogels. (d) Compression force at 2 mm indentation depth of gels with different crosslinker-to-monomer ratios. Reproduced with permission from ref.[21]

Thermal properties were tuned by soaking each hydrogel in a bath containing a specified ratio of ethylene glycol to water. We aimed to select dilution ratios that corresponded to thermal conductivities (TC) that were noticeably distinct in coldness from the TC of the other stimuli. This minimum value (0.125 w/mK) was determined from a 2-AFC pilot experiment performed on 10 blindfolded participants. Based on this threshold, we selected dilutions of ethylene glycol to use for the primary psychophysical experiments. We verified the differences in thermal properties by measuring the thermal conductivity of the solvent-soaked gel, as well as the change in temperature at the gel/skin interface (Figure 2c).

Mechanically, the gels were made stiffer by increasing the ratio of crosslinker relative to monomer during synthesis. The stiffer the gel, the less contact area they would make with the finger while holding force constant. We made three levels of stiffness by using three different crosslinker-to-monomer ratios of 0.01%, 0.1%, 0.5%. Once the three crosslinker ratios were chosen, the gel stiffnesses were characterized using rheometry and separately using compression measurements from a force gauge and linear actuator, which more closely resembled the human subject context (Figure 2d).

Considering our four-layer framework for experimental design (Figure 1), manipulation of the composition layer consists of dialing in crosslinker-to-monomer ratio of the gel and ethylene glycol-to-water ratio in the soaking solvent of the gel. The corresponding properties that are affected by this layer are the stiffness and thermal conductivity, respectively. At the skin-stimulus interface, changes in the stiffness cause different compression forces upon applying force and indentation to the stimulus. Similarly, changes in thermal conductivity of the soaking solvent cause rates of heat transfer across the interface upon contact to vary. The final perception layer was assayed using a 2-AFC pairwise comparison test.

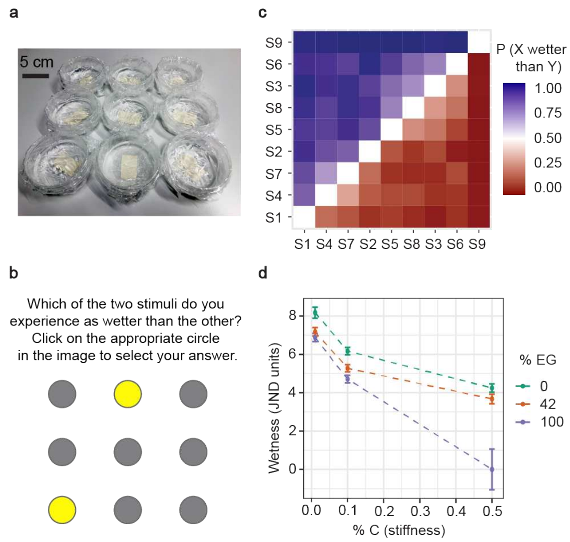


Figure 3: Psychophysical results (a) Photo of gels in psychophysical test setup (b) Graphical user interface for comparison instructions and stimulus selection (c) Resulting transitivity matrix of all pairwise comparisons of stimuli (d) Relationship between perceived wetness, and stimulus composition (percent crosslinker and percent EG) in the paired comparison psychophysics experiment (N=20 participants). Y-axis values are Bradley-Terry ability score parameters normalized to JND scale (divided by log(3)). Reproduced with permission from ref.[21]

After establishing a 3 x 3 matrix of gels (Figure 2b and Figure 3a) varying in stiffness and thermal conductivity, we tested human perception of wetness of the gels on 20 participants using a computer interface (Figure 3b). One of the key findings of this study was the transitivity across the nine samples with unique combinations of stiffness and thermal conductivity (Figure 3c). Transitivity implies that if Sample A is perceived as wetter than Sample B and Sample B is perceived as wetter than Sample C, then Sample A is also perceived as wetter than Sample C. Transitivity suggests that the selections of the wetter stimuli in the paired comparisons were not arbitrary, and that all 20 participants experienced the sensation of wetness on a unidimensional scale. The general trend observed in the psychophysical data (utilizing the Bradley-Terry model) was that the higher the thermal conductivity of the soaking solvent (the smaller ethylene glycol-to-water ratio), the wetter the sample was perceived (Figure 3d). The higher the stiffness (the higher the crosslinker-to-monomer ratio), the less wet the sample was perceived. It is important to note that Bentley's hypothesis involved only light pressure on the skin. It has been noted in previous literature that too much pressure will actually reduce the sensation of wetness,[37] which is indeed what we observed in our experiments.

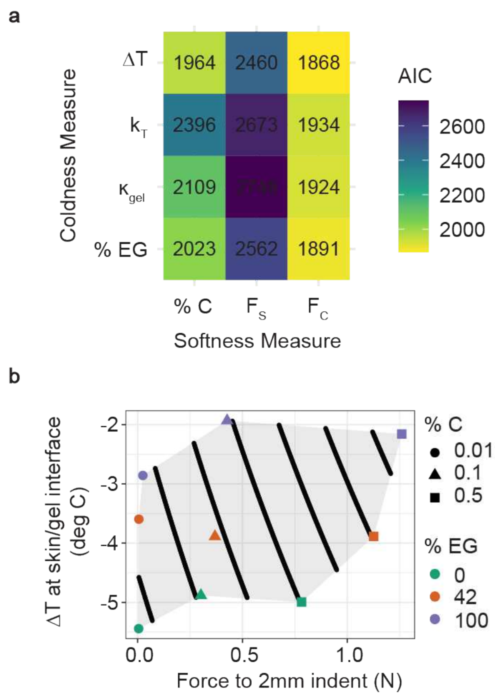


Figure 4: Psychophysical results (a) Prediction model comparison (AIC values) across possible input parameters for coldness (ΔT is total change in interface temperature, k_T is the rate of change of interface temperature, κ_{gel} is the gel thermal conductivity, %EG is percent EG in the soaking solvent) and softness measures (%C is percent crosslinker of the gel, F_s is shear force, F_c is compression force) (b) JND space from human-like physical properties with markers for stimuli recipe composition (%C and %EG) overlaid. The black lines represent distinct levels of wetness perception. Reproduced with permission from ref.[21]

Lastly, we also evaluated what input parameters, characterized by the samples, provided the best wetness prediction model using the Akaike Information Criterion (AIC) (Figure 4a). AIC measures prediction error of the model. The coldness parameters tested were ethylene glycol-to-water ratio, thermal conductivity of the gel, the rate of temperature decrease at the skin-gel interface over time upon initial contact with the gel, and total change in temperature over 20 seconds at the skin-gel interface. The softness parameters used were crosslinker-to-monomer ratio, shear force, and compressive force needed to achieve 2 mm indentation.

Interestingly, of these parameters, the most accurate model was a result of using total change in temperature over 20 seconds after contact with the gel and compression force from 2 mm indentation of the gel. These parameters are the most human-adjacent of the possible input parameters, meaning they closely pertain to how the participant interacts with the stimulus, as opposed to the parameters that relate to synthesizing the actual material.

Given this prediction model and AIC evaluation, we were able to construct a guide for successfully creating stimuli that will be judged as distinctly wet from another using the compression force and total change in temperature at the interface upon contact. Using these measurements, we can "back calculate" what change in temperature at the interface and compression force from 2 mm indentation depth is necessary to deliver a certain level of wetness sensation to a human user (Figure 4b). From an engineering perspective, this capability is valuable not only because it will ease design of hydrogel materials designed to deliver a sensation of wetness, but also because there is a generality to the result. That is, rather than being restricted to hydrogels modified using ratios of crosslinker-to-monomer and ethylene glycol-to-water, a more general parameter such as change in temperature at the interface and compression force from indentation can be used. The knowledge of how to manipulate these interfacial parameters opens the doors to a variety of materials and designs.

Passive and active touch: Rendering hardness, temperature, and roughness in a VR glove

The simple demarcation between passive and active modalities of touch may break down in VR, or at least the ways in which haptic effects are currently implemented in virtual contexts. For example, one may reach for a virtual object but have no (or an incorrect) expectation of what sensation the object may evoke. In VR, we have used purpose-designed stimuli responsive materials (i.e., in a glove or handheld device) in concert with conventional means of stimulation (i.e., vibrotactile motors and thermoelectric devices).[38]

A summary of these experiments is shown in Figure 5. In short, we obtained a commercial golf glove and sewed in electrical components for both sensing and actuation. The goal was to produce sensations reminiscent of three types of near-surface properties: hardness, temperature, and roughness. To generate these sensations, we chose three types of haptic transducers or actuators, two of which were of the commercial, off-the-shelf variety, and one that was designed and synthesized for this purpose. The two commercial actuators were vibrotactile motors for simulating hardness and thermoelectric devices for affecting warm and cool sensations. To produce sensations of roughness, we used electrotactile stimulation (constant signal for smooth, intermittent signal for rough). The electrodes were composed of our purpose-synthesized conductive polymer. This material takes, as its starting point, well known conductive polyelectrolyte complex poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate) (PEDOT:PSS).[39] The key enabling element of our material was that the PSS segment was chain extended with a bottlebrush unit to form a block copolymer.[40] The bottlebrush unit (an acrylic backbone bearing short side chains of oligo(ethylene oxide), or PEG) was chosen to maximize the mechanical conformability and to retain the ability to be processed from aqueous suspensions. Moreover, the combination of mechanical compliance and mixed electronic and ionic conductivity leads to good physical and electrical coupling with the skin. The low impedance which results from this combination of characteristics leads to reduced currents and voltages required for stimulation, potentially greater control over the types of sensation that can be generated, and a lower probability of galvanic reactions or pain.

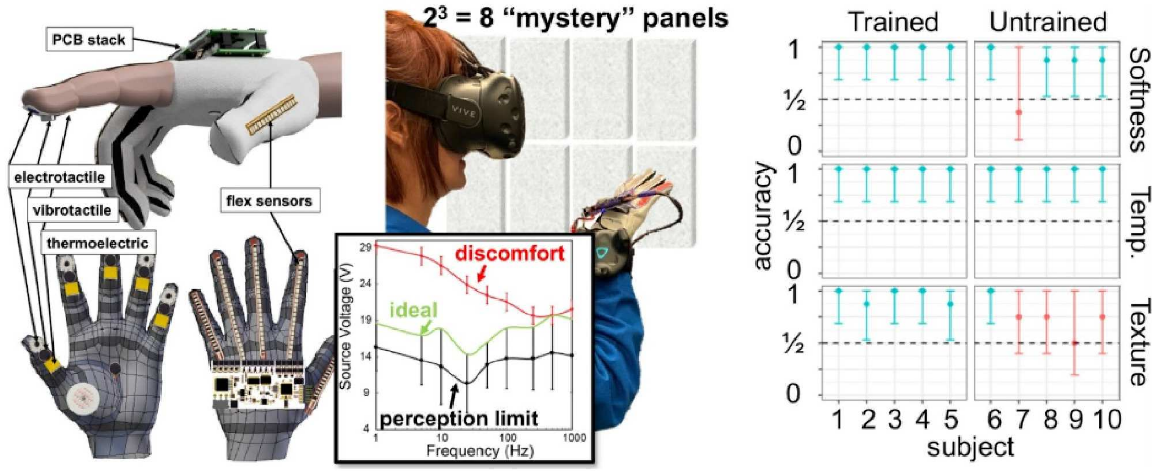


Figure 5: Schematic of VR glove with stimuli-responsive materials for psychophysical testing of softness, temperature, and texture. Accuracy results are shown on the right side. Reproduced under terms of the CC-BY license.[38] Copyright 2020, The Authors, published by WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

The instrumented glove could be used to control both a robotic hand ("physical complement") and a representation of a hand in VR ("virtual complement"). The system was designed as a closed loop. That is, sensors on the glove were used to control the movements of the physical and virtual complements; once these complements came into contact with a real (physical) or programmed (virtual) obstacle, information was sent back to the haptic transducers on the glove. In psychophysical experiments in a virtual environment, participants were presented with an array of eight "mystery panels"—slabs of virtual material with binary gradations of the three tactile properties: hardness, temperature, and roughness (2^3=8). A cohort of ten participants was divided into groups of five. One group of five was trained—that is, each participant was allowed to feel each sensation, which was identified verbally by the experimenter. Each participant was then exposed to the array of "mystery panels," each of which exhibited three properties all at the same time. The other group of five participants was untrained—that is, each individual was put in the VR environment containing the mystery panels without ever having been exposed to the sensations individually. Participants in the "trained" group correctly identified the combinations of sensations present in each panel. Gratifyingly, participants in the "untrained" cohort identified the sensations with probabilities much higher than chance, though one had trouble with discerning roughness generated by electrotactile signals emanating from the conductive polymer. These encouraging results affirmed the potential of such a system containing combinations of off-the-shelf components and molecularly engineered materials to affect complex, information-rich sensations to human participants in virtual and augmented environments.

Passive touch: Dye sensitizers for haptic holography based on the photoacoustic effect

A different angle in materials engineering for haptic stimuli is to exploit optical properties of materials, as opposed to bulk physical properties, particularly at the skin interface. Our lab has recently explored the use of pulsed light to generate perceivable vibrations in the skin (fingers) with the use of a thin layer of dye on the skin surface acting as an optical absorber[41] (Figure 6a). The mechanism responsible for the optically induced mechanical vibration is the photoacoustic effect, which is the generation of pressure waves from thermoelastic expansion of material upon absorption of pulsed light.[42] The photoacoustic effect is used widely in biomedical imaging,[43,44] usually in concert with ultrasound, where pulsed light with a repetition rate of a few tens of Hz is absorbed by endogenous structures (i.e., hemoglobin) or exogenous contrast agents (i.e., dyes). Rapid thermalization of the optical energy leads to elastic expansion and rebound and a resulting acoustic wave containing many frequencies which depend on the wavelength (often red or near-IR) and pulse duration (typically ns in biomedical contexts).[45,46] Acoustic frequencies in the kHz-MHz are of value in ultrasound detection, but are too high to be felt by cutaneous mechanoreceptors. However, the pulse repetition rate can be tuned to lie precisely in the “sweet spot” of skin sensitivity.[47,48]

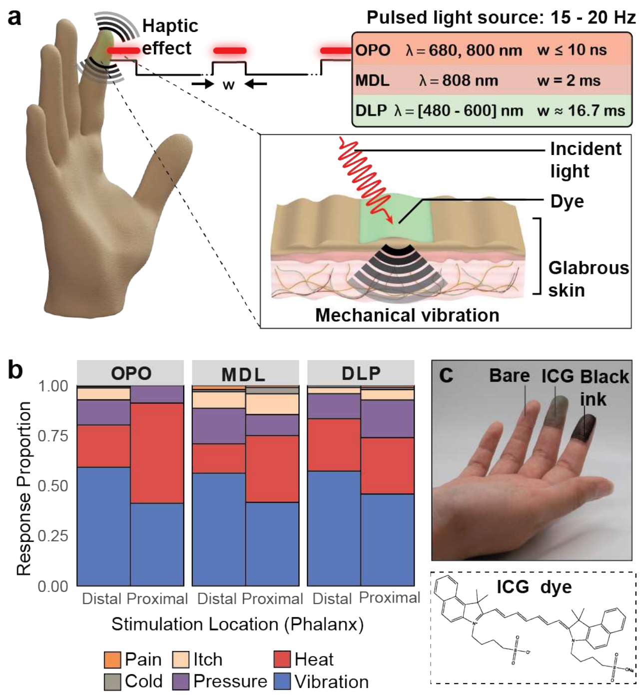


Figure 6: **A brief overview of the effect and key result described in this work.** (a) Schematic diagram of the use of pulsed light to generate tactile sensations mediated by the photoacoustic effect. Light incident on the surface generates a mechanical effect detected by cutaneous receptors. (b) Summarized proportions of tactile sensations reported by human participants after applying the optical stimulus on the distal (fingertip) and the proximal phalanges. (c) Photograph of a participant's fingertips coated with dyes used to sensitize the skin to the photoacoustic effect. The bottom panel shows the chemical structure of the IR-absorbing dye, indocyanine green (ICG). Reproduced with permission from.[41]

We thus conducted a series of psychophysical experiments to test for the sensations which can be generated by the photoacoustic effect. To examine the generality of the technique for a future form of holographic or "mid-air" haptics, we used various light sources. These sources included a diverging pulsed laser for photoacoustic tomography (optical parameter oscillation, OPO) (Figure 7), a miniature diode laser (MDL), and a commercial digital light processing (DLP) projector (i.e., an office slide projector) (Figure 8). We demonstrated that participants could accurately detect and discern the direction of travel of the pulsed light signal (Figure 7). Detection accuracy was high across all light sources, with the predominant sensation being mechanical vibration at the distal and proximal phalanges of the fingers.

Thermal sensations were less frequently perceived as the primary sensation at the fingertip than mechanical ones. We found that these haptic effects were consistent across a range of pulse widths, spot sizes, optical energies, and wavelengths.

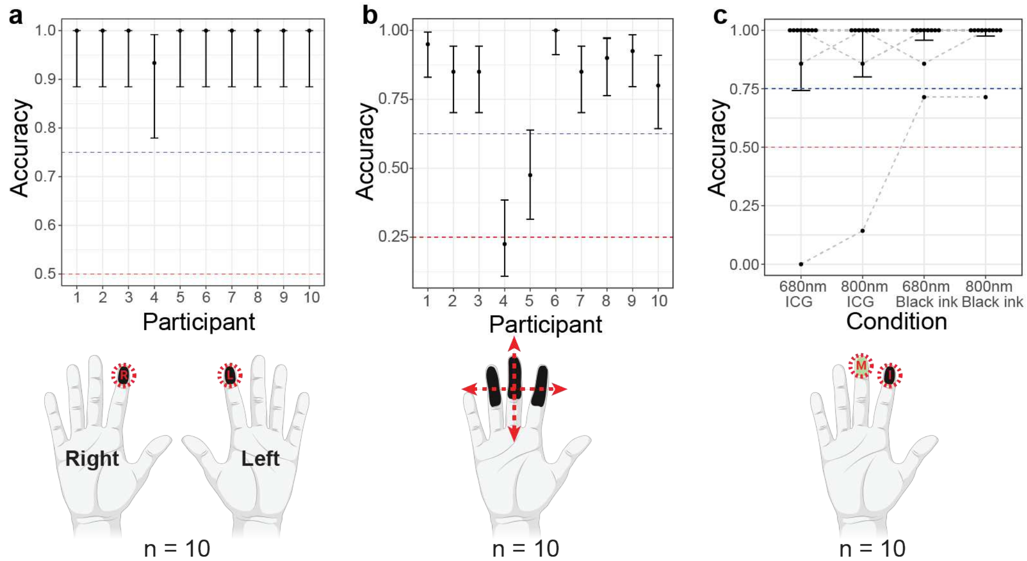


Figure 7: Perception accuracy of the effect in various conditions and effect categorization results produced using OPO system. (a) Accuracy results of 2-AFC experiment to test for detection of stimulus on the index fingers marked with black ink. (b) Accuracy of 4-AFC test for stimulus sweep in four different directions (red arrows) across distal and middle phalanges with black ink. (c) Accuracy results for detection of stimulus with different wavelengths and ink types. Reproduced with permission from.[41]

Our experiments highlight the robustness of photoacoustic stimulation in generating tactile sensations when the fingers were coated with a thin layer of dye absorber. For the OPO laser, we achieved a detection accuracy of $d' = 4.95$, while the modulated MDL and DLP projector yielded $d' = 2.11$ and $d' = 2.38$, respectively. The primary sensation reported was vibration, with a higher occurrence at the fingertip than at the proximal phalanx. The direction of pulsed light travel was also discerned with significant accuracy, indicating good spatial resolution of the mechanosensory response.

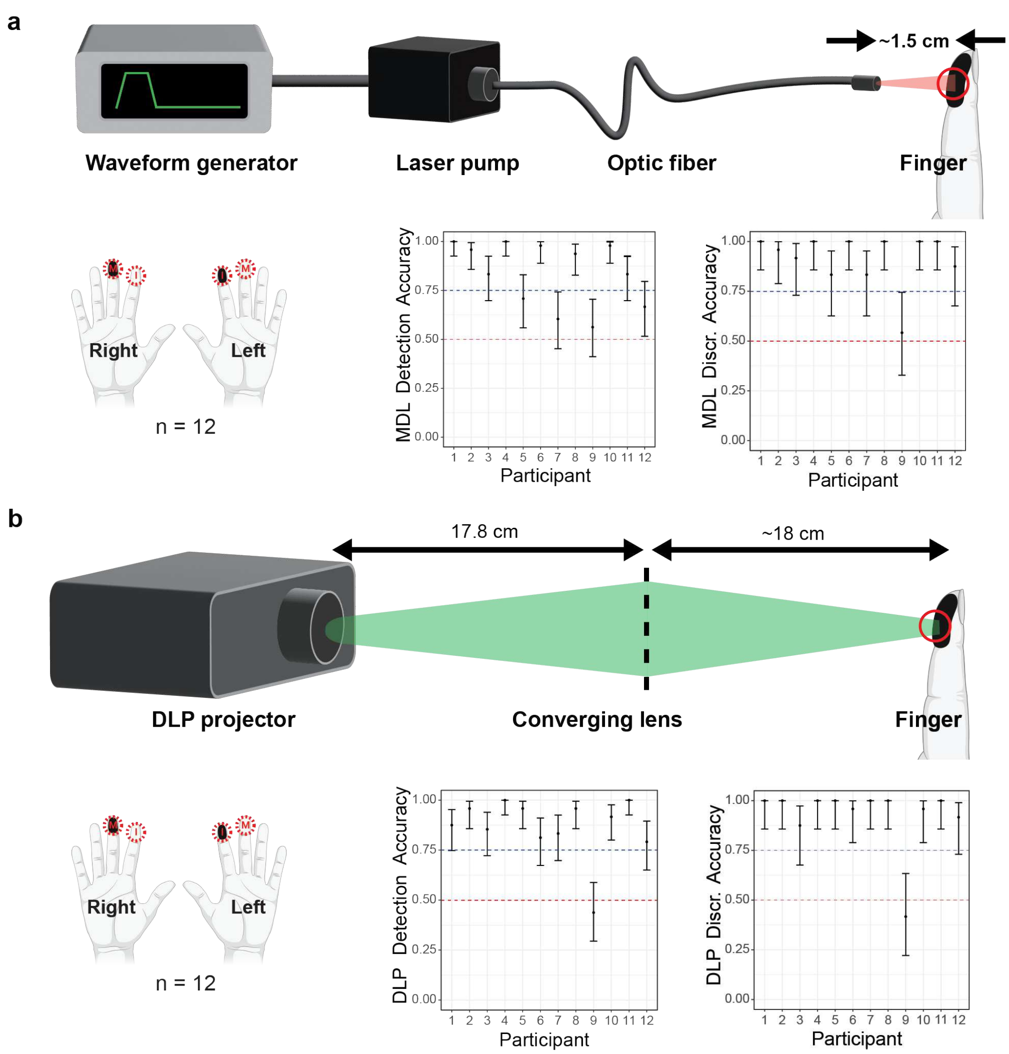


Figure 8: Schematics of the MDL laser and DLP projector systems and psychophysical results. Schematics of the (a) MDL and (b) DLP set up for 2-AFC experiment with sham trials (denoted by hand schematic), and corresponding detection and discrimination accuracy results. Reproduced with permission from.[41]

Conclusion

Our group's niche in the field of haptics sits at the intersection of materials science and human perception. The defining feature of our approach has been the manipulation of the molecular structure and microstructure of materials as the independent variables in psychophysical experiments. The use of bespoke materials surpasses the limitations of the properties of off-the-shelf materials like sandpaper, which are constrained to single-parameter investigations and were not designed for haptic applications. Organic materials offer a unique advantage as they can replicate the sensations of organic solids and recognize that organic species naturally coat virtually all objects due to adventitious adsorption. The capabilities of chemistry and materials synthesis are thus uniquely suited to haptics research.

In our studies, manipulating the static properties of materials has led to important insights into tactile sensations perceived during active modalities of touch during free-exploration experiments, such as those involving surface energy, softness, and wetness. Conversely, manipulating time-variable, dynamic responses, as demonstrated with electrotactile stimulation in the VR glove and photoacoustic vibration, provides insights into sensations registered by passive touch, since the stimulation can be produced without forethought or engagement by the user. Collaboration with psychologists and and the application of robust psychophysical methodologies have been essential in ensuring the reliability and validity of our findings.

Despite these advancements, challenges remain. For example, it is relatively straightforward to manipulate stimuli that produce mechanical sensations, as both electrotactile and photoacoustic stimulation ultimately yield sensations of vibration and/or pressure. However, generating "organic" sensations such as wetness, tack, and slipperiness requires dynamically controllable materials whose molecular structures or phase behavior can be altered in real-time. This alteration must be achieved using stimuli that are not directly perceivable by the human somatosensory system, necessitating an orthogonal approach to stimulation.

The integration of this materials-centric "channel" of interaction into systems intended for human-machine interfaces holds significant potential. Of course, such work must be approached with all due considerations of safety (using materials and stimulation parameters that are already in use in medical contexts is a start) and also reproducibility (the reliance on human subject responses necessitates greater attention to statistics than conventional methods of assaying the properties of materials, such as NMR and XRD.) Finally, the challenges in chemistry of materials intended for understanding and manipulating the haptic sense provide a rich substrate for innovation in research.

Acknowledgement

The authors thank the support provided by National Science Foundation BRITE-Pivot program under award number CMMI-2135428, the National Science Foundation Graduate Research Fellowship Program under Grant DGE-2038238, and the Achievement Rewards for College Scientists (ARCS) Foundation. Authors N.R. and R.R. acknowledge support from the Dutch Research Council (NWO) under Grant 406.21.GO.021. This research was supported in part by the NSF through the UC San Diego Materials Research Science and Engineering Center (DMR 2011924). The human schematics in Figure 1 and the abstract figure were created using BioRender.com.

Biographies

Laura Becerra earned her BS in electrical engineering from University of San Diego in 2019. She graduated with her MS in 2021 and PhD in 2024 in electrical and computer engineering from UC San Diego. Her research, co-advised by Darren Lipomi and Tse Nga Ng, includes haptic materials and flexible sensing for point-of-care medical technology.

Nicholas Root obtained his PhD in Psychology in 2019 from the University of California San Diego under the supervision of V.S. Ramachandran. His research focuses on the psychophysics of synesthesia and multisensory perception: using statistical modeling to quantify the relationship between conscious sensations and the properties of the stimuli that produce them.

Robert Ramji earned his BS in nanoengineering and BA in Chinese studies from University of California, San Diego in 2020. His research, co-advised by Darren Lipomi and Tod Pascal, focuses on atomistic simulations of advanced polymers and organic-inorganic nanomaterial interfaces.

Romke Rouw obtained her PhD in Psychology from Tilburg University under supervision of professor de Gelder in 2001, the same year she began her faculty position at the University of Amsterdam. Her research focuses on (multi)sensory perception and unusual perceptual conditions, including synesthesia and misophonia.

Darren Lipomi earned his PhD in chemistry from Harvard University with George Whitesides in 2010. Following a postdoctoral fellowship at Stanford University with Zhenan Bao, he began his independent career at UC San Diego in 2012. His research interests include the work described in this Account, along with materials for human-machine interfaces.

References

(1) Saddik, A. E.; Orozco, M.; Eid, M.; Cha, J. *Haptics Technologies: Bringing Touch to Multimedia*; Springer Berlin Heidelberg: Berlin, Heidelberg, 2011; pp 45–66.

(2) Liu, X.; Yue, Z.; Cai, Z.; Chetwynd, D. G.; Smith, S. T. Quantifying touch–feel perception: tribological aspects. *Measurement Science and Technology* **2008**, *19*, 084007.

(3) Jones, L.; Berris, M. Material discrimination and thermal perception. 2003; pp 171–178.

(4) Hollins, M.; Risner, S. R. Evidence for the duplex theory of tactile texture perception. *Perception & Psychophysics* **2000**, *62*, 695–705.

(5) Lederman, S. J.; Klatzky, R. L. Hand movements: A window into haptic object recognition. *Cognitive Psychology* **1987**, *19*, 342–368.

(6) Bergmann Tiest, W. M.; Kappers, A. M. Haptic and visual perception of roughness. *Acta Psychologica* **2007**, *124*, 177–189.

(7) Carpenter, C. W.; Dhong, C.; Root, N. B.; Rodriquez, D.; Abdo, E. E.; Skelil, K.; Alkhadra, M. A.; Ramírez, J.; Ramachandran, V. S.; Lipomi, D. J. Human ability to discriminate surface chemistry by touch. *Mater. Horiz.* **2018**, *5*, 70–77.

(8) Dhong, C.; Kayser, L. V.; Arroyo, R.; Shin, A.; Finn, M.; Kleinschmidt, A. T.; Lipomi, D. J. Role of fingerprint-inspired relief structures in elastomeric slabs for detecting frictional differences arising from surface monolayers. *Soft Matter* **2018**, *14*, 7483–7491.

(9) Dhong, C.; Miller, R.; Root, N. B.; Gupta, S.; Kayser, L. V.; Carpenter, C. W.; Loh, K. J.; Ramachandran, V. S.; Lipomi, D. J. Role of indentation depth and contact area on human perception of softness for haptic interfaces. *Science Advances* **2019**, *5*, eaaw8845.

(10) Rouw, R.; Erfanian, M. A Large-Scale Study of Misophonia. *Journal of Clinical Psychology* **2018**, *74*, 453–479.

(11) Rouw, R.; Scholte, H. S. Increased structural connectivity in grapheme-color synesthesia. *Nature Neuroscience* **2007**, *10*, 792–797.

(12) Zimmerman, A.; Bai, L.; Ginty, D. D. The gentle touch receptors of mammalian skin. *Science* **2014**, *346*, 950–954.

(13) Lumpkin, E. A.; Caterina, M. J. Mechanisms of sensory transduction in the skin. *Nature* **2007**, *445*, 858–865.

(14) Chesler, A. T. et al. The Role of <i>PIEZO2</i> in Human Mechanosensation. *New England Journal of Medicine* **2016**, *375*, 1355–1364.

(15) Ranade, S. S. et al. Piezo2 is the major transducer of mechanical forces for touch sensation in mice. *Nature* **2014**, *516*, 121–125.

(16) Gescheider, G. A. *Psychophysics: The Fundamentals*, 3rd ed.; Psychology Press: New York, 1997.

(17) Holmes, N. P., Ed. *Somatosensory Research Methods*; Neuromethods; Springer US: New York, NY, 2023; Vol. 196.

(18) Rao, P. V.; Kupper, L. L. Ties in Paired-Comparison Experiments: A Generalization of the Bradley-Terry Model. *Journal of the American Statistical Association* **1967**, *62*, 194–204.

(19) Gibson, J. J. Observations on Active Touch. *Psychological Review* **1962**, *69*, 477–491.

(20) Lederman, S. J.; Klatzky, R. L. Hand movements: A window into haptic object recognition. *Cognitive Psychology* **1987**, *19*, 342–368.

(21) Becerra, L. L.; Root, N.; Clark, A.; Rafeedi, T.; Brown, W.; Chen, A. X.; Qie, Y.; Blau, R.; Miller, J.; Kapadia, K.; Nga, T. N.; Rouw, R.; Lipomi, D. J. Decoupling Coldness and Softness in Tactile Wetness Perception Using Tunable Hydrogels. *Nature Human Behaviour* Submitted.

(22) Helbig, H. B.; Ernst, M. O. In *Human Haptic Perception: Basics and Applications*; Grunwald, M., Ed.; Birkhäuser Basel: Basel, 2008; pp 235–249.

(23) Gallace, A.; Spence, C. *In Touch with the Future: The sense of touch from cognitive neuroscience to virtual reality*; Oxford University Press, 2014; _eprint: https://academic.oup.com/book/0/chapter/156072431/chapter-ag-pdf/44950392/book_9318_section_156072431.ag.pdf.

(24) Lee, H.; Lee, E.; Jung, J.; Kim, J. Surface Stickiness Perception by Auditory, Tactile, and Visual Cues. *Frontiers in Psychology* **2019**, *10*.

(25) Tang, W.; Zhang, J.; Chen, S.; Chen, N.; Zhu, H.; Ge, S.; Zhang, S. Tactile Perception of Skin and Skin Cream. *Tribology Letters* **2015**, *59*, 24.

(26) Filingeri, D.; Havenith, G. Human skin wetness perception: psychophysical and neurophysiological bases. *Temperature* **2015**, *2*, 86–104.

(27) Lederman, S. J.; Jones, L. A. Tactile and Haptic Illusions. *IEEE Transactions on Haptics* **2011**, *4*, 273–294.

(28) Suzuki, K.; Arashida, R. Geometrical haptic illusions revisited: Haptic illusions compared with visual illusions. *Perception & Psychophysics* **1992**, *52*, 329–335.

(29) Lu, J.; Liu, Z.; Brooks, J.; Lopes, P. Chemical Haptics: Rendering Haptic Sensations via Topical Stimulants. The 34th Annual ACM Symposium on User Interface Software and Technology. New York, NY, USA, 2021; p 239–257.

(30) Brooks, J. Chemical interfaces: new methods for interfacing with the human senses. Adjunct Proceedings of the 36th Annual ACM Symposium on User Interface Software and Technology. New York, NY, USA, 2023.

(31) Reardon, G.; Dandu, B.; Shao, Y.; Visell, Y. Shear shock waves mediate haptic holography via focused ultrasound. *Science Advances* **2023**, *9*, eadf2037.

(32) Marchal, M.; Gallagher, G.; Lécuyer, A.; Pacchierotti, C. Can Stiffness Sensations Be Rendered in Virtual Reality Using Mid-air Ultrasound Haptic Technologies? Haptics: Science, Technology, Applications. Cham, 2020; pp 297–306.

(33) Shibahara, M.; Sato, K. Illusion of Wet Sensation by Controlling Temperature and Softness of Dry Cloth. Haptics: Perception, Devices, Control, and Applications. Cham, 2016; pp 371–379.

(34) Fan, C.; Zhang, Z. Comparison of reality and illusion of wetness on soft materials and the multisensory perceptual space of wetness illusion. *Textile Research Journal* **2024**, 00405175241226619.

(35) Bentley, I. M. The Synthetic Experiment. *The American Journal of Psychology* **1900**, *11*, 405–425.

(36) Denisin, A. K.; Pruitt, B. L. Tuning the Range of Polyacrylamide Gel Stiffness for Mechanobiology Applications. *ACS Applied Materials & Interfaces* **2016**, *8*, 21893–21902.

(37) Filingeri, D.; Redortier, B.; Hodder, S.; Havenith, G. Thermal and tactile interactions in the perception of local skin wetness at rest and during exercise in thermo-neutral and warm environments. *Neuroscience* **2014**, *258*, 121–130.

(38) Keef, C. V.; Kayser, L. V.; Tronboll, S.; Carpenter, C. W.; Root, N. B.; Finn III, M.; O'Connor, T. F.; Abuhamdieh, S. N.; Davies, D. M.; Runser, R.; Meng, Y. S.; Ramachandran, V. S.; Lipomi, D. J. Virtual Texture Generated Using Elastomeric Conductive Block Copolymer in a Wireless Multimodal Haptic Glove. *Advanced Intelligent Systems* **2020**, *2*, 2000018.

(39) Kayser, L. V.; Lipomi, D. J. Stretchable Conductive Polymers and Composites Based on PEDOT and PEDOT:PSS. *Advanced Materials* **2019**, *31*, 1806133.

(40) Kayser, L. V.; Russell, M. D.; Rodriquez, D.; Abuhamdieh, S. N.; Dhong, C.; Khan, S.; Stein, A. N.; Ramírez, J.; Lipomi, D. J. RAFT Polymerization of an Intrinsically Stretchable Water-Soluble Block Copolymer Scaffold for PEDOT. *Chemistry of Materials* **2018**, *30*, 4459–4468.

(41) Rafeedi, T.; Becerra, L. L.; Root, N.; Qie, Y.; Brown, W.; Qi, B.; Fu, L.; Esparza, G.; Sasi, L.; Kapadia, K.; Rouw, R.; Jokerst, J.; Lipomi, D. J. Enhanced dye-sensitized

mechanosensation utilizing pulsed and digitally modulated light. *Advanced Science* Submitted.

(42) Sunandana, C. S. Physical applications of photoacoustic spectroscopy. *Physica Status Solidi (a)* **1988**, *105*, 11–43.

(43) Beard, P. Biomedical photoacoustic imaging. *Interface Focus* **2011**, *1*, 602–631.

(44) Steinberg, I.; Huland, D. M.; Vermesh, O.; Frostig, H. E.; Tummers, W. S.; Gambhir, S. S. Photoacoustic clinical imaging. *Photoacoustics* **2019**, *14*, 77–98.

(45) Gao, R.; Xu, Z.; Ren, Y.; Song, L.; Liu, C. Nonlinear mechanisms in photoacoustics—Powerful tools in photoacoustic imaging. *Photoacoustics* **2021**, *22*, 100243.

(46) Cho, S. W.; Park, S. M.; Park, B.; Kim, D. Y.; Lee, T. G.; Kim, B. M.; Kim, C.; Kim, J.; Lee, S. W.; Kim, C. S. High-speed photoacoustic microscopy: A review dedicated on light sources. *Photoacoustics* **2021**, *24*.

(47) Jun, J.-H.; Park, J.-R.; Kim, S.-P.; Min Bae, Y.; Park, J.-Y.; Kim, H.-S.; Choi, S.; Jung, S. J.; Hwa Park, S.; Yeom, D.-I.; Jung, G.-I.; Kim, J.-S.; Chung, S.-C. Laser-induced thermoelastic effects can evoke tactile sensations. *Scientific Reports* **2015**, *5*, 11016.

(48) Kim, H.-S.; Kim, J.-S.; Jung, G.-I.; Jun, J.-H.; Park, J.-R.; Kim, S.-P.; Choi, S.; Park, S.-J.; Choi, M.-H.; Chung, S.-C. Evaluation of the possibility and response characteristics of laser-induced tactile sensation. *Neuroscience Letters* **2015**, *602*, 68–72.