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Establishing direct relationships between soft material perception and rheology

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In soft materials, a clear relationship between material properties and human sensory perception has long been desired for design of consumer products, but the link has remained evasive. Favorable perception indicates that customers enjoy a product and are likely to continue using it or purchase it again. Perception is frequently measured subjectively by consumer test panels in terms of descriptive sensory words such as softness, smoothness, thickness, *etc.* that lack established scientific definitions. In this work, we move beyond ambiguous definitions and detail a method to objectively measure and quantify human-material interactions using a representative series of viscoelastic putties. We show that human behaviors have direct rheological meaning with features that are characterized using transient recovery rheology. The rheology scales logarithmically at perception-relevant timescales, akin to Fechner's law. Our work explains variability in user-reported perception and demonstrates a way to construct direct relationships between user behavior and measurable rheology.

Introduction

Soft materials, which include material classes such as polymers, colloids, foams, gels, and others, exhibit a broad range of viscoelastic behavior that makes them well suited for many applications. Consumer applications such as food, hygiene, or cosmetic products are unique in that materials need to be designed not only for functionality (does the product solve a problem?), but also for consumer perception (will people enjoy the product and purchase it again?).[1] Designing materials for human perception is a daunting task, for myriad reasons. Humans are highly diverse, and perception is an inherently subjective phenomenon. In sensory studies, participants often lack consensus or give ambiguous feedback that leads to little insight. This is because the end user of consumer goods is generally a scientific layperson, unfamiliar with technical terminology, and unable to provide the objective quantitative evaluation of their subjective sensory preferences that a scientist desires.

While scientists are comfortable describing materials with numerically well-defined physical measures, such as a modulus or viscosity, the layperson is not. Instead, laypeople rely on natural lingual descriptors,[2] such as how soft, smooth, thick, *etc.* the material feels, that are ambiguously defined – a significant barrier to a product formulator. That is, a scientist will find it much easier to design a fluid with a quantifiable viscosity than with an abstract sensory descriptor such as how smooth it feels.

Various efforts have been made to affix more rigorous definitions to sensory words, particularly in the food industry.[3–7] However, different users tend to perceive even objectively identical materials as different. It is common to use consumer test panels wherein human participants rank materials on an arbitrary numerical (hedonic) scale; for example, a characteristic like smoothness is ranked on a scale from 1 to 9.[1] The panels may or may not be trained to judge samples in a "standardized" way. Regardless, their material evaluations will have some inherent amount of variability amongst them, and the average value is generally taken for simplicity. While averages are convenient, they can discard individual's experiences and lead to "one-size-fits-all" products rather than identifying different clusters that are better served by multiple products.[8]

Summarily, this means that scientists are often faced with ambiguous design criteria that create significant barriers to product formulation. Ideally, scientists will have a precise understanding of how material properties relate to individuals' perceptions of them. This yields clear design criteria which facilitate cost- and time-efficient direct design of materials. Practically, these relationships are unknown and scientists have had to make do with some combination of physical measures and sensory statistical correlations.[9–13]

Direct links between measurable material properties and their perception is the field of psychophysics. The psychophysics of soft materials has been explored since at least the 1930s,

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stemming from the investigations of Scott Blair[14–22] and Katz[23] into materials such as bread dough or dairy products, a field that Scott Blair termed psychorheology.[24,25] Scott Blair's early work included several interesting insights. In the examination of a rubber cylinder, he found that perceived softness (1) scales logarithmically, (2) is time-dependent, and (3) is not equivalent to the measured rheology.[18] Logarithmic scaling in perception is a well-known result, typically referred to as Fechner's law,[26] and has been shown for several different stimuli.[27–29] Time-dependence in perception is likewise important. Human-material interactions occur over short timescales; they are generally no more than a few seconds.[30,31] This is incongruous with standard rheological protocols, such as amplitude, frequency, or flow sweeps, wherein measurements are taken at steady state and return singular time-averaged values of properties like the viscosity or storage and loss moduli.[32] Conversely, humans report a range of experienced values. From a strictly physical perspective, this is odd; objectively identical materials are experienced as being subjectively different. Since current standard rheological tests do not reflect the reality of perception, better tests are needed.

In this work, we detail a rigorous study of the physics of *in situ* human touch of a representative set of viscoelastic putties. We couple the physics of touch with transient recovery rheology to quantify perceived material behaviors, as summarized in Fig. 1. Recovery rheology is an excellent technique for mirroring human–material interactions as it separates viscous and elastic behavior, is usable over all measurable timescales, works with arbitrary stress inputs, and is applicable to linear or nonlinear rheology. In recovery rheology, one imposes a stress or strain protocol, measures the resulting strain or stress, then applies a state of either zero stress or zero strain-rate and measures the material's strain or stress recovery. At zero stress, some amount of strain is elastically recoverable, and some is viscously unrecoverable. Recoverable strains can be thought of as extensions of bonds or microstructures within the material that store energy while unrecoverable strains can be thought of as center of mass motions where energy is dissipated. Tests are performed in an iterative manner to construct a transient view of the viscous and elastic contributions to flow. Recovery rheology has been used since at least as early as 1932, and has seen a good variety of use and discussion since.[33–50] Since strain components are more fundamental than traditional total strain-based measures, and their summation recovers the total-strain, recovery rheology always provides more information about materials than traditional rheological tests, such as amplitude, frequency, or flow sweeps, where only the total strain is used for evaluation.

This work details a comprehensive methodology to quantify how people fundamentally use touch to explore and evaluate materials. We translate these results to rheological terms and provide methods for their measurement. We believe this work will serve as a basis for developing objective design criteria in consumer soft materials – namely with immediate applicability to touch and as a framework for more complex interactions such as mouthfeel. We also lay groundwork for mapping of complex viscoelastic material interactions to choice, linking material dynamic interaction to decision outcomes.

Results

Human behaviors during touch

In this work, human subjects (n = 103; 50 male, 53 female) were asked to complete several tasks, internally designated Task 1a,

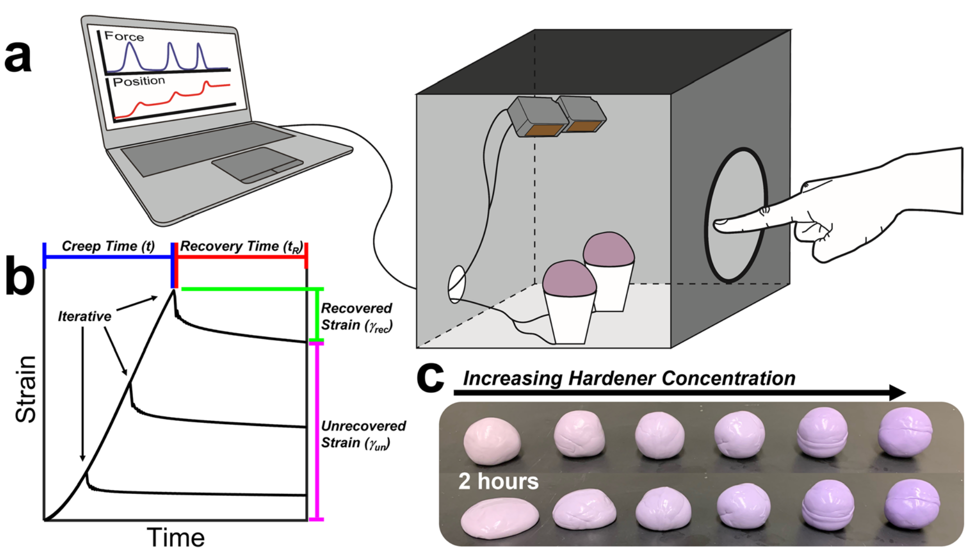

Fig. 1 Overview of experimental setup for human and rheological testing. Simplified schematic (a) of the human testing apparatus. Subjects were presented with two samples in an opaque box. Sensors measured the force applied to the sample and how far they pressed into it (position) as a function of time. Measures from the human testing were compared with data collected from recovery rheology (b). In recovery rheology, a series of iterative creep and recovery tests were used to measure the recovered and unrecovered strain with respect to the creep and recovery times. For this experiment, a series of putties (c) were used. The putties are commercially available therapeutic exercise putties that consist of a base putty mixed with a variable amount of hardener (4.7, 14.1, 23.6, 33.3, 42.4, or 51.8 wt%) to increase resistance.

1b, 2a, and 2b. In each task, the subjects were presented with a series of trials, each consisting of two samples in an opaque box (Fig. 1a) and required to report which sample felt''more firm'', a two-alternative forced choice (2AFC). The individual samples were either one of the commercially available viscoelastic putties or a solid (*i.e.*, not irreversibly deformable by a human) rubber ball, depending on the task. Putty was chosen as it is a model viscoelastic material that is chemically stable, skin-safe, leaves no residue on the finger, and is not unfamiliar to most people. Six different putties were used, each consisting of a base putty mixed with different concentrations of a hardener used to modify the rheological properties (Fig. 1c). In Task 1a, subjects compared, unknown to them, sets of identical putties using their bare index finger. Comparisons at each concentration were made. In Task 1b, subjects compared one putty of each concentration with the rubber ball. We designed this protocol to simulate comparisons that are extremely hard (1a, stimuli are physically same) or easy (1b, compare to solid), hoping to elicit different exploration modes. In Tasks 2a and 2b, subjects made the same comparisons as in Tasks 1a and 1b, but the subjects wore a rigid plastic cover over their fingers to remove direct cutaneous feedback with the putty. Throughout the experiment, users' force and position data were measured as a function of time with no restriction on how much force or time they could use. Left/right placement of the samples and order of the samples were randomized, and the task order was semi-randomized. Subjects completed the first two tasks randomly chosen from 1a, 2a, 1b, 2b, and were then given a twenty-minute break. They then completed a third task (not reported here), were given a twenty-minute break, and completed the remaining two tasks.

Since a core goal of this work is to understand how physical behaviors affect rheological measures, we describe the user data *via* definitions with direct rheological equivalencies. For example, a user's applied force is analogous to an applied stress on the rheometer, and the extent to which they press into the putty is analogous to strain. In total, 14 terms are defined which are fully detailed in SI Table S1. The terms possess strictly physical definitions with clear meaning that are defined from the time, force, and position data. While it is possible to define more terms, these are sufficiently comprehensive to describe most interactions.

One of the clearest results of this work is that people display a diverse range of behaviors. As an example, Fig. 2a–e show force signals used by five different individuals to explore a putty in Task 1a. Qualitatively, some people use multiple pulses (2a and b) to make a determination while others need only one pulse (2c and d). The amount of time spent on any pulse can be shorter (2a and c) or longer (2b and d). Other strategies are less regular (2e) and are not well-described by any single behavior.

A way to quantitatively characterize the participants' physical behaviors was developed. Each force signal is normalized by its maximum, and, to mitigate noise, only peaks with a height and prominence of at least 5% are identified. The force associated with a peak is defined by the maximum of the peak. For viscoelastic materials, it is informative to separate their viscous and elastic responses. The time during which the material experiences viscous flow is termed the creep time, t, and is defined as a force peak's full width at half maximum since this is the time interval where the material irreversibly deforms the most. The period of elastic recovery is termed the recovery time, t_R, and is defined as the time interval between two peaks where the force is less than 2.5% of the signal's maximum. The recovery time is undefined for the last pulse in a sequence since the finger cannot be assumed to remain in contact with the putty. An example of these definitions as applied to a signal is shown in Fig. 2f. While it might be most appropriate to define the material as always being in either creep or recovery (*i.e.*, a continuous transition from creep to recovery), these definitions were developed so that they incontrovertibly correspond to where predominantly viscous and elastic responses occur.

Fig. 2g–i display boxplots of the force, creep time, and recovery time applied to only the left sensor of Task 1a by each individual that participated in this study. Showing only data from the left sensor controls for any bias that may be introduced by the left sensor on the right sensor. However, we note that, in general, behavioral differences between the left and right sensors are negligible aside from participants using up to approximately 5 to 30% less time for their evaluation, as shown in SI Fig. S9 and S10. Importantly, the data shows that there is a distribution of forces applied, not only from person to person, but also within the individual. That is, while one can affix an average value to how a person or group behaves, it is a simplification. With no single defining behavior, there are important rheological implications. Consider that all rheological measures are fundamentally determined from stresses, strains, the rates thereof, and the timescales considered. That none of these values can be singularly expressed from the human perspective means there is unlikely to be a singular-valued rheological term, such as a viscosity or modulus, to base a product's design around. Instead, design criteria should be thought of as a range of values and the phenomena they encompass. Rheological maps may prove to be more useful tools. Different proportions of users will belong to different regions of the map, and products can be suitably tailored for each group. This avoids one-size-fits-all approaches that may garner approval of some, but not all, users.

A further point of consideration is whether people behave the same irrespective of what they are examining. That is, it would be convenient if there were some universalities to how people touch. Fig. 3 shows that this is apparently true for some metrics but not others. The upper plot in Fig. 3 shows the median behavior of the group for each of the putties in Task 1a relative to the 4.7 wt% putty for each metric. The lower plot shows a p-value for a paired t-test between the 4.7 wt% putty and the higher concentration. A p-value less than 0.05 is commonly used as an indicator of statistical significance and is depicted by the red line in the lower plot. The data shows a clear trend indicating that as the concentration of hardener is increased, people apply more force (stress) to the sample, but

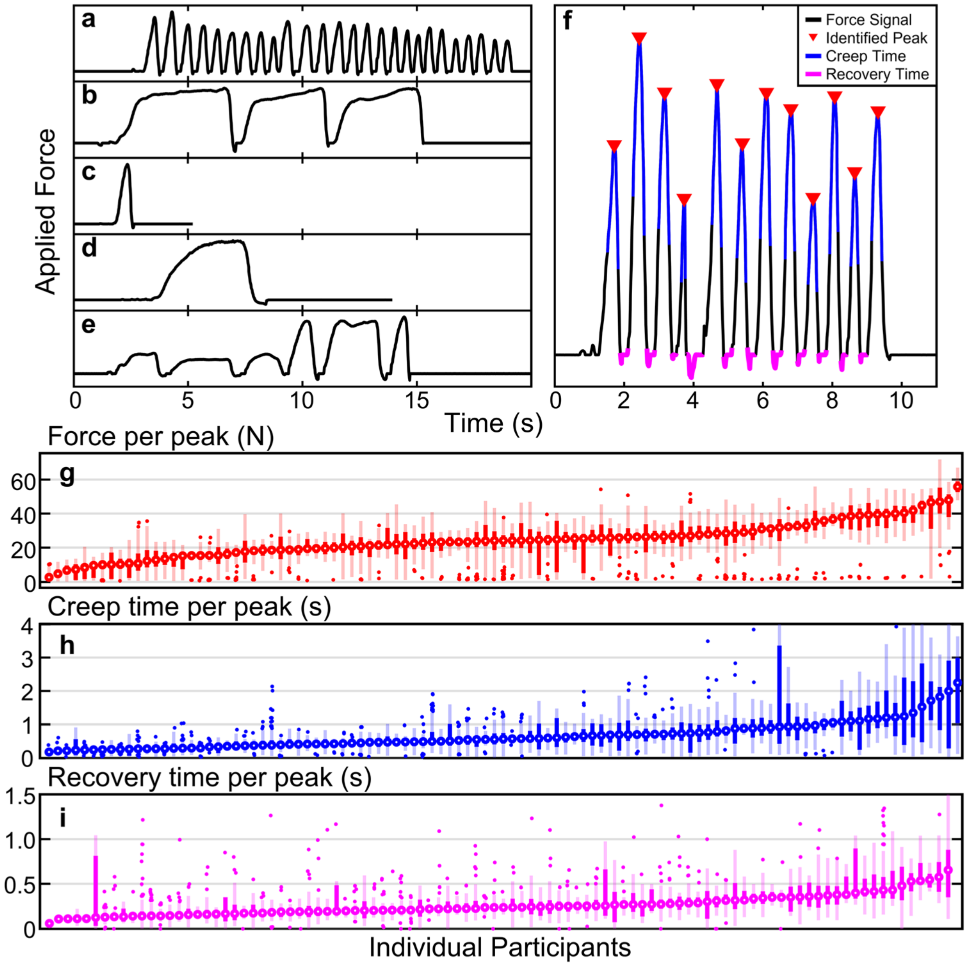

Fig. 2 Examples of subject behavioral data in Task 1a. Diffe rent individuals have different strategies for exploring putties (a–f). The strategies include rapid pulsing (a), slow pulsing (b), quick single pulses (c), long single pulses (d), or more complex strategies (e). Analytically, a user's force data is split into different regions (f), including a creep time where the material experiences force and a recovery time where the material experiences elastic recovery. Applying this analysis to data for all the subjects allows for construction of comparative boxplots (g–i). The boxplots show the median (red, blue, or magenta solid-colored circles with white center), interquartile range (solid-colored bars), whiskers (lighter-colored bars), and outliers (solid-colored points) for the maximal applied force per peak (g), creep time used per peak (h) and recovery time used per peak (i) for data from only the left sample of Task 1a. Subjects in each boxplot are placed in order of ascending median value to emphasize the distribution of behaviors. The distribution of values suggests that no single behavior can describe the population in a general sense.

they deform (strain) the putty less. There is likewise a change in the rates at which people press and pull their finger into and from the putties (stress rate). There does not appear to be a significant change in the amount of time used or number of peaks.

User behaviors are also dependent upon the nature of the task itself. While there is no notable difference in the time used per sample during Task 1a, this does not hold for other tasks. For example, subjects spent more time probing the putties than the rubber ball. If the comparison is relatively difficult, as in Tasks 1a and 2a where subjects must distinguish identical materials, users tend to spend more time making their determination. If the comparison is relatively easy, as in Tasks 1b and 2b where subjects must distinguish highly dissimilar materials, users quickly decide which material is firmer, evidenced by fewer peaks and time used. A full overview of these comparisons can be seen in SI Fig. S1–S10.

That people behave differently when completing different tasks is important. It suggests that while the values measured in this work may serve as approximations, they cannot be assumed to translate to other scenarios. Human–material interactions, and the perceptions thereof, are context dependent. That is, people behave differently in different situations – likely dependent on what information they are trying to gather and the specific materials they are considering. The methodology detailed here is powerful because it provides a means of quantifying different user behaviors that is applicable to any soft material.

From a user's data, one can define any number of features. This does not mean that each feature weighs equally, or even at all, in users' behavior. To develop materials, establishing good design criteria requires an understanding of which factors most affect perception. A scientist will likewise find it more

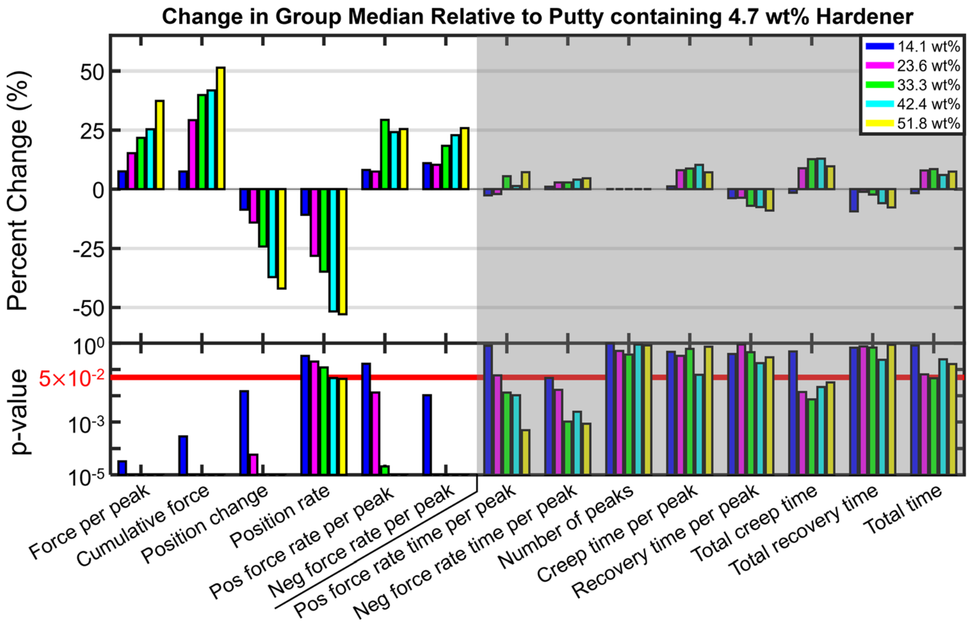

Fig. 3 – Comparison of user behaviors at different putty hardener concentrations in Task 1a. The top plot shows the percentage change in the group median at different hardener concentrations relative to the lowest concentration (4.7 wt%). Users apply more force and experience less deformation with increasing hardener concentration, but do not alter their behavior otherwise. The lower plot shows the p-value associated with a paired t-test (two-tailed) between each putty and the lowest concentration. Bars not shown indicate a p-value less than 10^{-5}. P-Values much less than 0.05 indicate that the sample medians are statistically significantly different at the different concentrations. The grayed region is meant to deemphasize those terms that have minimal behavioral change, such as different time measures.

convenient to design for a select few behaviors rather than all of them. A dimensionality reducing technique is therefore beneficial. There are many popular algorithms available in the literature.[51–58] In this work we used principal component analysis (PCA). In PCA, existing variables are redefined *via* solution of an eigenvalue/eigenvector problem into a fewer number of new variables (principal components) while preserving as much variability as possible.[59]

Several of the terms defined in this work are closely related. For example, someone that presses the sample many times (larger number of peaks) likely spends more total time probing the sample than someone who presses only once, even if the variables can be controlled independently. Correspondingly, there should be fewer principal components of significance than variables. An example of results from PCA as applied to the data from Task 1a is shown in Fig. 4. The results of the analysis indicate that 76% of the variance can be explained with just 3 principal components, and about 91% of the variance can be explained with 6 components (Fig. 4a).

Examining each component (Fig. 4b–d) shows that they roughly correspond to specific behaviors. Component 1 clearly relates to the total time spent on a sample. The variables with the greatest contribution to component 1 (number of peaks, total creep time, total recovery time, total time, cumulative force) all scale directly with how long someone interacts with a sample. Component 2 appears to correspond to the rate of deformation; its largest contributors are the positive and negative force rate, the position rate (*i.e.*, strain rate), and the creep time per peak (how long force is applied). Component 3 apparently relates to the applied stress or strain since the largest contributors are the force per peak and the overall position change (*i.e.*, strain). Component 4 may be related to system elasticity, as its largest contributor is the recovery time per peak. Component 5 is likewise most probably related to elasticity as its largest contribution comes from the amount of time used per peak where the rate of the applied force is positive, which is expected to be related to the short-term elastic response, and the recovery time used per peak. Component 6 may be related to the strain, as its largest contribution is the overall position change.

Relating perception to rheology

By establishing which features in the transient touch data have the most variance, we develop understanding of which rheological features may play the largest role in governing perception. That is, since the touch behaviors examined in this work were defined on a physical basis, they can easily be translated to rheological terms. For example, the principal components examined in Fig. 4 were identified as corresponding to specific timescales, stresses, strains, and their rates. With this knowledge, an analogous rheological test can be developed to determine precisely how the material behaves when someone is perceiving it. Since subjects' touch behaviors are highly transient and irregular, the best rheological method for describing their behavior is recovery rheology.

In recovery rheology, a stress or strain is applied for some time, subsequently removed, and the transient recovery of the resultant strain or stress is observed. In this work, we chose to

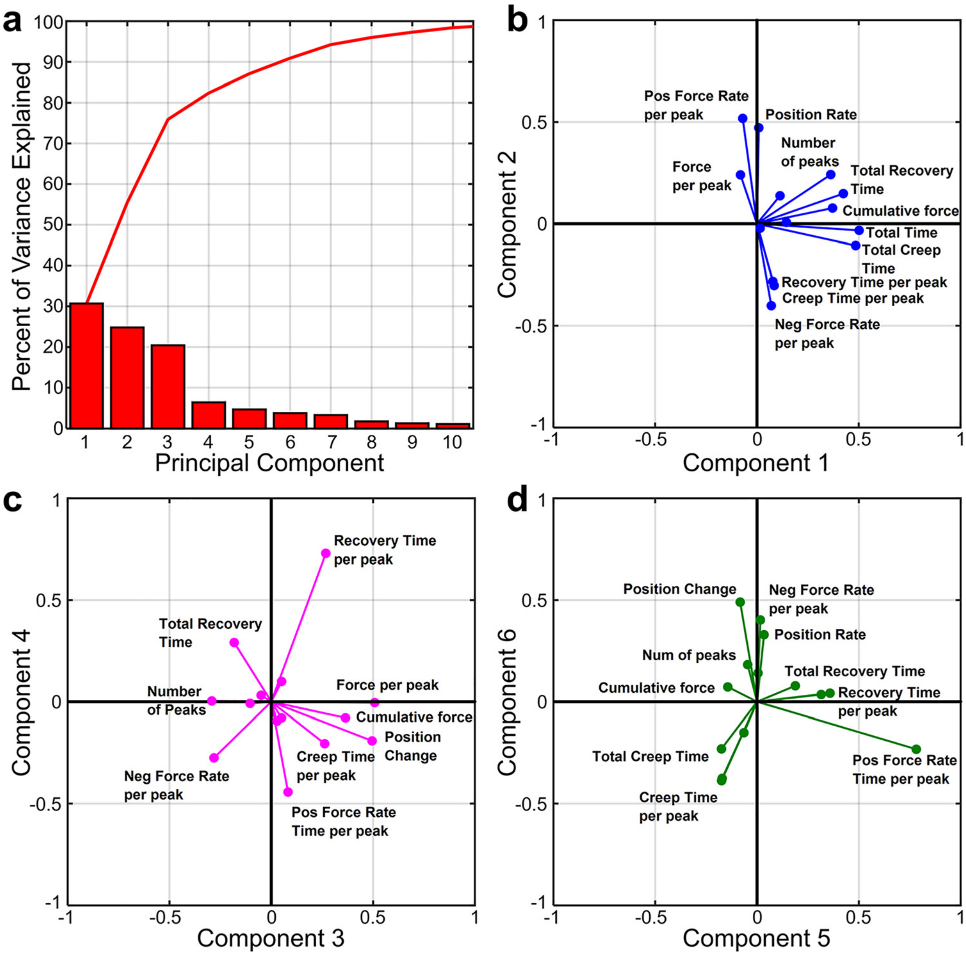

Fig. 4 – Results of principal component analysis (PCA) applied to data from Task 1a. A Scree plot (a) shows what percentage of the variance in the data may be attributed to each principal component. About 91% of the variance can be explained with 6 components, indicating the dimensionality of the variable space can be reduced. A loadings (b–d) plot examines which variables contribute most to each component to identify trends. Components 1 and 2 (b) likely correspond to time and stress rate. Components 3 and 4 (c) likely correspond to stress or strain and elasticity. Components 5 and 6 (d) likely correspond to elasticity and strain rate.

apply stresses and measure strains since the control of stress is more biologically natural than strain.[60] Upon removal of the applied stress, the strain component which is recovered corresponds to elastic deformation while the unrecovered component corresponds to viscous deformation. By performing a series of iterative recovery tests, a transient view of the extent of viscous and elastic deformation at each instant is constructed (*cf.* Fig. 1b). The force someone applies is directly proportional to the stress, σ, by a scaling factor equal to the inverse of the contact surface area, *i.e.*, their finger surface area, $\sigma = F/A$. The extent to which someone presses into the material is directly proportional to the strain. Any elastic recovery that is experienced when someone ceases to apply force is characterizable as recovered strain, and the remaining permanent deformation is unrecovered strain.

Parameters are defined in the typical rheological sense but with respect to two independent timescales: the creep time, t, and the recovery time, t_R. The creep time describes the interval over which stress is applied – the time in which the material is being actively deformed. The recovery time describes the interval over which the stress is zero – the time in which the material is elastically recovering. Correspondingly, the recovered strain, $\gamma_{rec}(t, t_R)$, is an increasing function of recovery time, and the unrecovered strain, $\gamma_{un}(t, t_R)$, is a decreasing function of recovery time. While the recovered strain in the limit of infinite recovery time describes the full extent of elasticity in the material, use of the recovery time is important for psychorheological applications because someone's perception is limited to what is presently measurable.

Material parameters, such as moduli or viscosities, are defined in terms of stresses and strains or strain rates. For such definitions, we use the stress immediately prior to switching to zero-stress, *i.e.*, at zero recovery time, $\sigma(t) = \sigma(t, t_R = 0)$. Since strains are defined for all times and recovery times, we plot them as a function of both dimensions using contour plots. For example, Fig. 5a shows the evolution of the recovered strain as a function of the creep and recovery times for a putty containing no added hardener following an applied constant stress of 100 Pa. The first five seconds of creep and recovery, the approximate upper bound used by any individual in Fig. 2h and i, are shown. Along the abscissa where the recovery time is zero, the recovered strain is likewise zero because the material has been given no time to recover. With increasing recovery time, the material recovers strain at a decaying rate until it reaches its equilibrium position. Along the ordinate where the creep time is zero, the recovered strain is zero because the material has not experienced any stress. At longer creep times, the material becomes increasingly extended, and more strain is recoverable. In general, materials can only be extended a finite amount, and the recovered strain approaches a maximum with increasing creep time. The unrecovered strain is the simple difference between the total and recovered strains. Since unrecoverable strain is a center of mass motion, it can increase unbounded and is most useful to discuss as a rate. Strain rates are calculated by differentiating only with respect to the creep time because the stress causes the strain. Material parameters are defined in the typical way. The modulus, G_{rec}, is defined as the stress divided by the recovered strain, $G_{\mathrm{rec}}(t, t_{\mathrm{R}}) = \sigma(t)/\gamma_{\mathrm{rec}}(t, t_{\mathrm{R}})$. Two viscosities are defined: the retardation viscosity from the recoverable strain-rate, $\dot{\gamma}_{\mathrm{rec}}$, and the flow viscosity from the unrecoverable strain-rate, $\dot{\gamma}_{\mathrm{un}}$, where the strain rates are found by differentiating the respective strain terms with respect to the creep time. They are correspondingly defined as $\eta_{\mathrm{retardation}}(t, t_{\mathrm{R}}) = \sigma(t)/\dot{\gamma}_{\mathrm{rec}}(t, t_{\mathrm{R}})$ and $\eta_{\mathrm{flow}}(t, t_{\mathrm{R}}) = \sigma(t)/\dot{\gamma}_{\mathrm{un}}(t, t_{\mathrm{R}})$. Retardation and relaxation times are defined as the ratios of the appropriate viscosities and the modulus, $\tau_{\mathrm{retardation}}(t, t_{\mathrm{R}}) = \eta_{\mathrm{retardation}}(t, t_{\mathrm{R}})/G_{\mathrm{rec}}(t, t_{\mathrm{R}})$ and $\tau_{\mathrm{relaxation}}(t, t_{\mathrm{R}}) = (\eta_{\mathrm{retardation}}(t, t_{\mathrm{R}}) + \eta_{\mathrm{flow}}(t, t_{\mathrm{R}})/G_{\mathrm{rec}}(t, t_{\mathrm{R}})$. Plots of the moduli, viscosities, and timescales are shown in Fig. 5b–e for a putty containing no added hardener following a constant applied stress of 100 Pa. Similar plots for all other hardener concentrations are provided in SI Fig. S25–S30. We note that the base putty containing 0 wt% hardener is itself viscoelastic and represents the ''softest'' or most compliant version of the putty possible.

The results shown in Fig. 5 are for the simplest case of a constant applied stress. Realistically, humans use a range of forces, applied at varying rates (*e.g.*, SI Fig. S40, S43, S44). The rates at which stresses are applied are important rheologically. For example, the simplest model of a viscoelastic fluid, the Maxwell model, is described by the constitutive equation $\sigma(t) + (\eta/G)\dot{\sigma}(t) = \eta\dot{\gamma}(t)$. Both stress and stress rate appear in the Maxwell model, and they govern the resulting strain rate. The Maxwell model has the simple mechanical analogue of a spring in series with a dashpot. Real materials are more complex and are often modeled by more elaborate combinations of springs and dashpots or inclusion of other nonlinear terms.[32] In such models, both the stress and its rate likewise appear in the constitutive equation. Summarily, both the magnitude of the applied stress and its rate are rheologically important, and their effects are of interest.

To consider the effects of the stress magnitude, we examined the evolution of the recoverable modulus following a constant applied stress of 100 Pa and 3162 Pa (SI Fig. S31a and b). In SI Fig. S31c, the ratio of the plots is shown. The results show that despite a more than thirtyfold increase in the stress, the modulus is largely unaffected. It increases by about no more

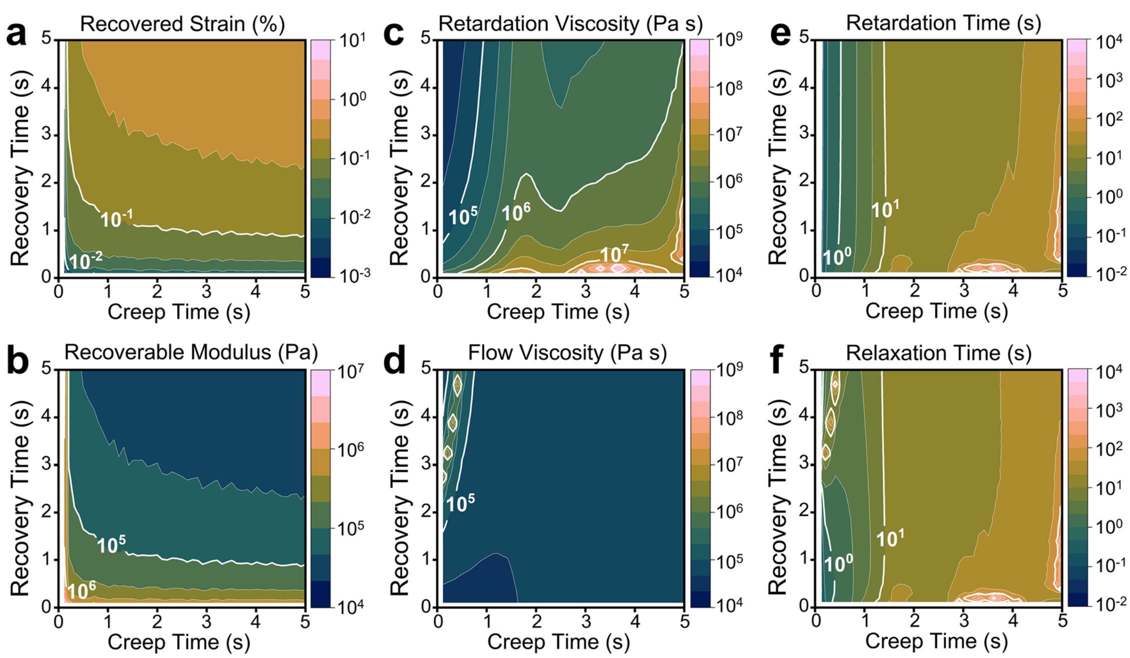

Fig. 5 – Example of results from recovery rheology. Shown here are results for a putty containing no hardener (0 wt%) after experiencing a stress of 100 Pa. The recovered strain (a) shows how much strain recovers after the stress is removed from the sample. The recoverable modulus (b) is the ratio of the previously applied stress to the recoverable strain. The retardation viscosity (c) is the ratio of the stress to the recoverable strain rate. The flow viscosity (d) is the ratio of the stress to the unrecoverable strain rate. The retardation time (e) describes the timescale of elastic flows while the relaxation time (**f**) describes viscous flows. The putties are changing most rapidly at the earliest times, scaling several decades in under five seconds.

than a factor of two within five seconds of creep and recovery. The other rheological terms show similar results (SI Fig. S32). That the putties' properties are relatively stress independent indicates that the amount of force that people use is unlikely to yield qualitatively diverse information when perceiving them. This is not a universal result since other materials, such as yield stress fluids, have a large and obvious change in properties at sufficiently large stresses. Nonetheless, the methodology used here is likewise applicable to such materials.

The effect of the stress rate was examined by measuring the response to non-constant stresses. A simple example of a continuously changing stress rate is a sinusoidal wave. We measured the rheology throughout the application of a single period of both sine and cosine waves with stress amplitude of 100 Pa and period of 5 seconds. Compared to the constant stress case, there is minimal change in the magnitude of the measured modulus (SI Fig. S33). In both constant stress and oscillatory stress experiments, the modulus adopts values on the order of about 10^4 to 10^6 Pa. The significant difference is that the different magnitudes of the modulus occur at different timepoints. That is, if two individuals applied the same maximal stress but reached it at different rates, or equivalently, they reached the stress at different times, then they will perceive a different material response. The timescales of deformations are thus highly important rheologically – a finding which reinforces the results of the principal component analysis. Further examples detailing all the rheological properties following several different stress waveforms such as constant, ramp, and oscillatory input stresses are shown in SI Fig. S34–S39.

Discussion and conclusions

Understanding the perceptive judgements of real people probing complex materials in complex ways is an important, yet highly difficult challenge in the design of materials for consumer approval. While a material's underlying physical properties dictate people's perception of the material, there has historically been no way to convert between the physics and its perception without some sort of abstract translation mechanism. Most commonly, translation has taken place *via* consumer test panels. These panels provide subjective evaluation of materials in the form of lingual descriptors (softness, firmness, *etc.*) that are related to the physics by scientists using statistical correlations. However, lingual descriptors lead to ambiguous results because their colloquial meanings lack rigorous physics-based definitions. They can also be problematic because some words have different meanings in different contexts (*e.g.*, a soft sound *vs.* a soft material), are inherently subjective, or they might not have direct translations in other languages or cultures.[2] In this work, we introduced a more rigorous methodology where users do not need to interpret descriptors themselves. In our method, individuals' interactions are measured directly and quantified using physics-based definitions. These definitions are directly convertible to practical experimental procedures such as recovery rheology, which can be applied to virtually any behavior pattern of force/stress in time.

We have thoroughly characterized behavioral variations in a 2AFC firmness discrimination task with model viscoelastic materials. This force-time behavior is widely varying across subjects, and reducing the dimensionality of this force-time behavior suggests that time, force, and force rate are the most salient behavioral features when describing the variance in behavior across subjects and stimuli. It has recently been shown that time and force rate are key factors in discrimination of compliant (solid) objects; our results suggest that this also extends to model viscoelastic materials.[31,61]

Furthermore, despite the narrow range of stress and times considered, the rheology in *e.g.*, Fig. 5 depicts a broad range of behavior. Notably, all of the properties (5a, b, c, e and f), aside from the flow viscosity (5d), scale rapidly. That is, they span about two to three orders of magnitude within less than 5 seconds of creep and recovery. An interesting parallel may be observed here with Fechner's law,[26] which states that subjective perception scales logarithmically with stimulus intensity. That is, certain stimuli must be appreciably different on a logarithmic scale for humans to perceive them as being different. The applicability of Fechner's law has also been discussed in previous rheological studies.[18,27] Our results do not necessarily confirm that Fechner's law holds for rheological properties, but it is interesting to note that we do measure logarithmically varying properties at perception-relevant timescales. For example, the median force peak for any individual typically spanned no more than about two seconds of creep and recovery (Fig. 2h and i). Fig. 5 shows that the first two seconds are where the apparent rheological properties are changing most rapidly. Consequently, even minor differences in user behavior can lead to drastically different rheological responses. As a result, our experimental methods provide a potential explanation for why two different individuals may report that the objectively same material feels subjectively different. In contrast, traditional rheological tests, such as amplitude or frequency sweeps, measure the oscillatory responses of materials at steady-state and discard early transience. Traditional measures can produce consistent experimental results, but they ignore a wealth of information.

Using recovery rheology we demonstrate for the first time how rheological properties of model viscoelastic materials change during perceptually-relevant timescales. Over typical stresses and times applied by subjects to the putties, instantaneous moduli, viscosities, and timescales vary orders of magnitude due to the viscoelastic nature of these materials. This is in stark contrast to compliant solid-like and Newtonian liquid-like materials, where rheological responses are essentially independent of force and time. This rich and complex material response, however, can be accurately and quantitatively described by recovery rheology, which shows that percepts vary as a small movement in time causes large differences for these materials. This facilitates the mapping of complex viscoelastic material responses to perception and choice, an interesting problem which we will leave for future work.

Since our experimental setup relies on measurement of human finger touch, it is not universally applicable to all human–material interactions of interest. For example, oral processing of food is a complex and difficult to measure process involving transient rheological, tribological, and chemical effects.[62] Nonetheless, current and future improvements in areas such as wearable electronics should lead to accurate *in situ* measurements of the many ways that people interface with materials.[63–66] With such measures, the core principles of recovery rheology – that viscous and elastic behaviors are transiently separable – are generally applicable and can be used as a philosophy by which to structure experiments.

In summary, human perception of materials relies on the body's sensory inputs. Haptic perception is dependent on the material's rheological properties and over what stresses and timescales the individual probed the material. Our experiments combine *in situ* measurements of people as they perceive materials along with recovery rheology to provide a clear understanding of what factors contribute to perception. Material properties were found to scale logarithmically in the span of a few seconds, which might explain the perceptive differences between individuals found in consumer studies.

Methodology

Materials

The putties used in this work are commercially available and sold as Theraputty Variable Strength Exercise Putty. The product consists of a base putty and a hardener used to modify the rheology. Six putties were prepared with each containing a different hardener concentration (4.7, 14.1, 23.6, 33.3, 42.4, and 51.8 wt%) by mixing the base putty and hardener by hand until the color was homogeneous. The rubber balls were all purchased from the same supplier, had a smooth texture similar to the putty, and were 3.5 cm in diameter.

Sensory data

Sensory tests were performed on a group of 103 human subjects (50 male, 53 female) having an average age of 42.3 years and standard deviation of 9.1 years. Exclusion criteria were dictated by internal company standards and are as follows: pregnant or planning to become pregnant in the next 30 days; is breastfeeding; have participated in any skincare consumer or clinical study in the past 30 days; works in market research, advertising, pharmaceutical industry, or skincare-related field; history of taking medications related to diabetes, skin cancer, or skin conditions such as eczema; self-described as having excessively dry skin; currently have injuries on the fingers or hands, has known allergies or sensitivity to skincare products, has known allergies or sensitivity to polydimethylsiloxane polymers.

In each task, subjects were presented with two samples in an opaque box and asked to determine whether the left or right sample were firmer. The subjects were instructed to press into the left sample first and then the right, then choose which sample was more firm (a two-alternative forced choice test). Subjects were not permitted to return to the left sample after moving to the right sample. An armrest was present in the box to prevent wrist strain. Subjects were asked to self-report any fatigue and allowed to take breaks as needed. Subjects were requested to only apply force normal to the samples. The subjects were told they could use as much time as they desired but could not return to the first sample after touching the second. Sample comparisons were presented in a randomized order in the shape of spheres with a diameter of 3.5 cm. To mitigate training bias, subjects were presented with four excess comparisons in Tasks 1a and 2a and three excess comparisons at the beginning of Tasks 1b and 2b. This data was not used in the analysis. In Tasks 2a and 2b, subjects wore a hard plastic cover on their fingers to restrict cutaneous feedback, which were standard slip-on finger casts with designed to immobilize the index finger in case of injury. Five sizes of finger casts were available, ranging from extra small to extra large; subjects were fitted with an appropriate finger cast by a study administrator prior to testing. Throughout the tests, sensors transiently measured force and position data. Force data was measuring using 5 kg load cells (model TAL220B) connected to control boards (SparkFun Open Scale) set to record force data at a rate of 66.67 Hz. Position data was measured using an optical triangulation position sensor (Micro-Epsilon optoNCDT 1420-50) also set to record at 66.67 Hz. Data was recorded using a custom Python script and the stimulus presentation package PsychoPy.[67] The data analysis was performed in MATLAB using standard functions. Code is available upon request.

Ethics statement

Study protocols were reviewed and approved by Advarra IRB, IRB00000971. Prior to participation, all participants signed a consent form while a study administrator served as witness.

Rheology measurements

Transient recovery rheology experiments were used to characterize the putties. Data was collected using the arbitrary wave function on a stress-controlled rheometer (TA Instruments DHR-3). In recovery tests, a stress is applied for some amount of creep time, the stress is set to zero, and the resulting strain decay is measured for some amount of recovery time. This process is repeated iteratively for increasing creep time until the desired timescale is mapped out. Putties were measured with an 8 mm parallel plate geometry at 25 °C. For reproducibility, putties are given sufficient time to relax on the rheometer so that they reach the same initial state between recovery tests, about 60 seconds. This is confirmed by observing that consecutive recovery tests superimpose graphically. The rheology data was analyzed in MATLAB using standard functions.

Author contributions

E. B. and S. R. designed the rheological tests. J. M. and M. J. designed and performed the sensory tests. E. B. measured the rheology, analyzed the sensory data, and wrote the paper. S. R. supervised the research. All authors contributed to the discussion and evaluation of the research as well as editing and preparation of the final manuscript.

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Conflicts of interest

There are no conflicts to declare.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Supplementary information (SI) is available. The supplementary information contains definitions used in the data analysis and comprehensive behavioral and rheological data sets. See DOI: https://doi.org/10.1039/d5sm01286d.

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An effort was made to be friendly to the color-vision deficient; the rheology plots in this work were made using freely available scientific color maps that prevent visual distortion.[68] We thank the University of Illinois Department of Chemical and Biomolecular Engineering for funding *via* the DuPont Fellowship.

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