Task and Material Properties Interactively Affect Softness Explorations Along Different Dimensions

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***Abstract*—Haptic research has frequently equated softness with the compliance of elastic objects. However, in a recent study we have suggested that compliance is not the only perceived material dimension underlying what is commonly called softness [1]. Here, we investigate, whether the different perceptual dimensions of softness affect how materials are haptically explored. Specifically, we tested whether also the task, i.e., the attribute that a material is being judged on, might affect how a material is explored. To this end we selected 15 adjectives and 19 materials that each associate with different softness dimensions for the study. In the experiment, while participants freely explored and rated the materials, we recorded their hand movements. These movements were subsequently categorized into distinct exploratory procedures (EPs) and analyzed in a multivariate analysis of variance (MANOVA). The results of this analysis suggest that the pattern of EPs depended not only on the material's softness dimension and the task (i.e., what attributes were rated), but also on an interaction between the two factors. Taken together, our findings support the notion of multiple perceptual dimensions of softness and suggest that participants actively adapt their EPs in a nuanced way when judging a particular softness dimensions for a given material.**

***Index Terms*—active exploration, active touch, compliance, exploratory procedures, haptics, softness, psychophysics.**

I. Introduction

HAPTIC perception factor into many decisions we are facing in daily life. For example, the feel of an object matters when deciding whether the mango is ripe, or whether the chair is comfortable enough to sit on. While the tactual impressions of objects can vary greatly, researchers have shown that these can be characterized by only five main dimensions: warmness (cold/warm), hardness (hard/ soft), micro and macro roughness, and friction (moistness/dryness, stickiness/slipperiness) [2], with softness being one of the most investigated dimensions.

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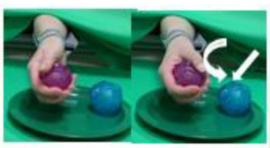
Previous studies on haptic softness typically think of compliance as the physical correlate of softness [2]–[6], which is measured as the deformation of an elastic object in response to an applied force [7]–[9] (see [10] for an exception). In contrast, everyday experiences of soft materials seem to include a much broader range of physical correlates: from squeezing playdough to stroking a rabbit's fur to digging your fingers into the warm sand on the beach. In previous work, we formally followed up on this observation in an experiment were participants haptically explored and rated a wide range of soft (and non-soft) materials. Analyzing the data with the Principal Component Analysis (PCA), we discovered that perceived softness not only covaries with the compliance of the material but also with its viscosity, granularity, and furriness [1]. The idea of a multidimensional construct 'softness' would be consistent with previous work [1], [7], [11]–[13]. But do these softness dimensions also affect how we explore materials? To answer this question, it is necessary to allow participants to freely explore the stimuli in a study, since active haptic exploration of surfaces and objects provides important information that can hardly be achieved from other senses [14]–[15], or passive interactions.

While actively exploring objects and materials, humans use a set of stereotypical movement patterns to perceive different dimensions [10], [16]–[18]. For instance, in order to perceive texture, a repetitive lateral motion is typically generated, or for temperature, stationary contact is used in order to maximize the contact area between object and skin. Individual exploratory procedures are also known to be associated with the perception of specific dimensions. For example, during softness (compliance) judgements *pressure* is usually used, which involves squeezing an object between index finger and thumb or pressing the object with a single finger [17]–[18]. While *pressure* might be optimal for exploring an object's compliance [19], we have recently shown that humans use, in fact, several additional exploratory movements [1], [20], each being associated with a particular type of material. Table I shows examples of these exploratory procedures [1], [19]–[20] for a range of soft and non-soft materials.

In addition to the material properties, i.e., whether a material is granular or furry, previous work has shown that EPs are also influenced by the aim of exploration, i.e., the specific perceptual task [19], and a recent study on texture exploration even suggests that both, the perceptual task *and* the surface properties affect exploratory movements when exploring with a single digit [21].

TABLE I
EXPLORATORY PROCEDURES OBSERVED IN [1] AND IN THE PRESENT STUDY

EP name and example	Definition of the EP	EP name and example	Definition of the EP
 Pressure	Applying normal force to squeeze a material between palm and fingers or using one or more fingers to apply normal force (similar to pressure in [18-19]).	 Stroking	Moving the fingers or the whole hand laterally across objects to get information about the surface while applying only gentle force (not strong enough to deform an object). If the thumb is used it is considered rubbing (rubbing and stroking are linked to lateral motion in [18]).
 Stirring	Immersing one or more fingers into a material and moving its particles (this can be rotational).	 Running through	Picking up some parts/portions of a material and letting them trickle through the fingers.
 Rubbing	Applying torque or lateral force with varied pressure levels, sometimes sweeping a material between index and thumb fingers or forcefully stroking the material with the tumb while balancing an object with the other fingers.	 Rotating	Lifting portions of a material to move and turn its boundaries typically inside the finger(tip)s.
 Pulling	Stretching part of a material by moving fingers or seperating them from each other.	 Tapping	Repeatedly and rapidly hitting a material with knuckles, fingertips [3], or nails.
 Flat-handed pick up	Trying to lift up a portion of a material by maximizing the contact surface with the flat hand.		

First 8 definitions adapted from [*1*], 'flat-handed pick up' obtained from the present study.

Here we ask, whether a similar combined effect of task and material on exploratory movements exists, when participants judge different aspects of softness of every-day materials. To address this question, we employ a large range of soft and non-soft materials in a free exploration paradigm. The experiment builds on our previous work [1], [20] which shows, that perceptual dimensions of softness influence EP patterns. Specifically, we use adjectives and materials that each tap predominantly into one specific perceptual dimension of softness. We verify our selection with a PCA before investigating with a MANOVA the potential effects of- and interactions between the task and material properties on EP patterns.

II. METHODS

A. Participants

30 students (aged 18-38 years; average 23.6 years, 21 women, all right-handed) from Giessen University participated in the study and were compensated with 8 €/hour for their time. All participants were naïve to the purpose of the study and spoke German at a native speaker level. None of them reported sensory, motor, or cutaneous impairments. The two-point discrimination threshold at the index finger of the right (dominant) hand of all participants was 3 mm or better. The study was ethically approved by LEK FB 06 in accordance with the declaration of Helsinki (2008). Participant gave written informed consent.

B. Setups, Materials, and Adjectives

Active noise canceling headphones (Sennheiser HD 4.50 BTNC) were used to eliminate any sounds that might have been caused by the exploration of materials, and to present beeps that signaled the start and end of the exploration period. The experiment was programmed in MATLAB 2017a (MathWorks Inc., 2007) using Psychtoolbox routines [23]–[24]. A standard laptop was placed to the left of the participants to run

Fig. 1. Setup and example material used in the experiment.

TABLE II
MATERIALS SELECTED FOR THE EXPERIMENT AND THEIR ASSOCIATED DIMENSIONS

Deformability	playdough (+), stress balls (+), stone (-);
Viscosity	hand cream (+) and hair gel (+);
Furriness	fur (+), velvet (+)
Granularity	sand (+) and salt (+)
Roughness	sand paper (+), felt (+), aluminum foil (-)
Control	paper balls, wool, linen, lentils, cranberries sponge, cotton balls

Note that sugar was used in [*1*]. However, we replaced it in our study with salt in order to avoid the increasing stickiness of sugar in time after exposure.

TABLE III
ROTATED COMPONENT LOADINGS OF ADJECTIVES FROM [22]

Adjective (English/ German)	**Component I-V: Loadings**				
	I. Furriness	**II. Viscosity**	**III. Granularity**	**IV. Deformability**	**V. Roughness**
Fluffy / flauschig	1,324	-0,407	-0,268	-0,283	0,164
Hairy / haarig	1,051	-0,248	-0,389	0,057	0,481
Soft / weich	0,895	0,360	-0,082	-0,677	-0,131
Velvety / samtig	0,800	-0,179	0,013	-0,318	-0,147
Moist / feucht	-0,119	1,137	-0,025	0,048	-0,249
Sticky / klebrig	-0,260	1,106	0,038	-0,150	-0,085
Wobbly / wabbelig	-0,025	0,947	-0,221	-0,387	-0,050
Sandy / sandig	-0,153	-0,119	1,136	0,288	0,255
Granular / körnig	-0,417	-0,025	1,082	0,692	0,236
Powdery / pulverig	-0,051	-0,052	0,973	0,170	0,098
Hard / hart	-0,613	-0,407	0,159	-0,901	0,101
Inflexible / unbiegsam	-0,234	0,067	0,422	-0,865	-0,054
Elastic / elastisch	0,114	0,273	-0,313	0,780	0,081
Smooth / glatt	-0,271	0,114	-0,202	0,110	-0,949
Rough / rau	-0,383	-0,333	0,373	0,132	0,704

Grayed-out adjectives are the highly loading adjectives per category, which will be used to calculate task dimension scores of the EPs (e.g., fluffy, hairy, soft, and velvety will be averaged for the furriness dimension) in the following analyses.

the experiment and to collect rating responses. During the experiment hand movements were recorded with two identical Sony Digital 4K Video Cameras (recording 28-bit videos at a spatial resolution of 1920 × 1080 pixels). Cameras were placed on tripods to the left and right across the table from the observer (see Fig. 1 for a typical view).

During the experiment, participants were seated in front of a table. A horizontally rotatable armrest on this table ensured that all participants explored the materials from the same distance and position and also reduced potential strain on the arm. A green curtain hid the materials from the participant's view. The experimenter sat behind the curtain and placed plates (diameter 21.5 cm: Fig. 1) that held the materials on the table. Materials that would be substantially altered through exploration (e.g., hand cream) were renewed for each participant. Table II shows the 19 materials that we selected according to material categories (*deformable, fluid, hairy, granular, rough*) that were derived via PCA in earlier work [1], as well as a control condition. For the present study, we wanted to employ only materials that were highly representative of a given perceptual dimension, i.e., those which loaded with an absolute value of 1.5 or larger (which corresponds to 1.5 standard deviation in the z-standard values). An additional selection criterion for materials in one dimension was that they did not have additional high loadings on any of the other dimensions. For each material dimension, we chose 3 materials: two positively and one negatively loaded (indicated by the (+), and (-), respectively in Table II. If no negative loaded material existed, we picked only two positively loaded exemplars. For the roughness dimension we also included sandpaper, as this is a prototypical rough material. Materials for the control category included those that showed high loadings on more than one dimension in [1], like paper balls, linen and sponge.

15 sensory adjectives were selected based on their component scores on deformability, viscosity, furriness, granularity (softness dimensions) as well as roughness (control condition) based on results by [1], [22]. Specifically, for each dimension we choose the two adjectives with the highest positive, and one with the highest negative load. If adjectives with high negative loads were lacking we used three positively loading adjectives (e.g., granularity: sandy, powdery, granular, fluidity: moist, gooey, sticky; hairiness: velvety, hairy, fluffy). For roughness, there was only one positive and one negative adjective that loaded high: rough and smooth. All adjectives were translated from Turkish [1] into German. Both the German version and the English translation of all adjectives can be found in Table. III. Note, that we used the adjective

wobbly instead of gooey because it better captured the property that we intended to convey in the German translation.

C. Design and Procedure

After giving written informed consent, participants completed a questionnaire that assessed any potential sensory, motor, or cutaneous impairments, as well as a two-point discrimination threshold determination task at the dominant hand's index finger. After this, participants were allowed three practice trials in order to get familiarized with the setup and the experiment. During the practice trial, participants rated a wood block on how *woody*, *gracile*, and *structured* it felt to them.

During the experiment each participant rated 15 sensory adjectives for each of the 19 materials. Specifically, they indicated the extent (Likert item 1-5) to which they think an adjective applied to a material: 1 indicated '*not applicable*' and 5 '*applies strongly*'.

On each trial, participants first saw an adjective on the laptop screen. In order to indicate that they were ready to start the exploration of the material they had to press the space button with their left hand. Then, a beep marked the start of the 4-second exploration time, and participants freely explored materials with their right hand. After 4 seconds a second beep signaled the end of the exploration time. Participants were instructed to disengage the exploration when the beep occurs by using the armrest to rotate their hand slightly to the left side (i.e., towards them), and to then indicate their rating of the material by pressing a button on the numpad with the left hand. The procedure of exploring a material and subsequently rating it was repeated 285 times (19 materials x 15 adjectives). Note, that all adjectives were rated independently and in random order during separate explorations. The presentation order of materials was also randomized in order to rule out systematic carry over effects. The experiment was self-paced, participants pressed the space button whenever they felt ready to proceed to the next trial, which usually happened after a couple of seconds. After the end of the adjective list, the experimenter changed the material.

Participants were encouraged to take breaks between materials and allowed to pull their hands back after every trial if needed. However, they were required to do so in order to clean their hand after touching certain materials (e.g., hair gel, sand, hand cream, etc.). The experiment took participants about 1.5 hours (+/-20min, depending on individual speed and break durations).

III. Results

A. PCA on Adjectives

We first calculated Cronbach's alpha between participants for each single adjective across materials in order to estimate the participants' consistency. Standardized Cronbach's α [25] revealed an excellent consistency between participants' ratings for each adjective (each $\alpha \geq .95$). Also, correlations r between participants' ratings for each material and adjective pair (see Fig. 2) were high and statistically significant and ranged between .45 and .82 ($p <.01.$). This degree of consistency is in line with previous studies on sensory ratings [26]–[27].

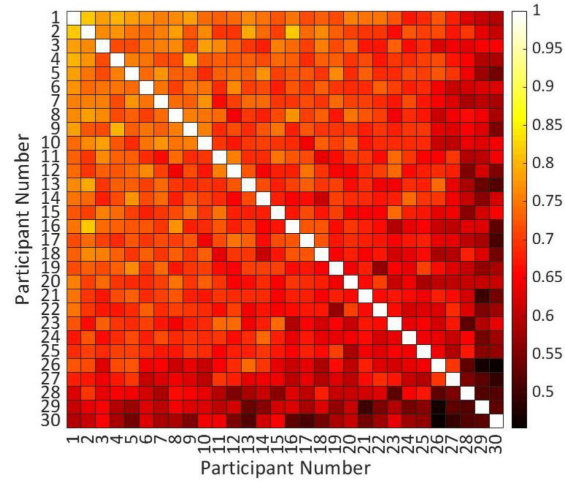


Fig. 2. Pearson's correlation coefficient r for inter-participant correlations (i.e., correlations between each participant and all other participants). Higher correlations plotted in light colors (i.e., white) and lower correlations are plotted in darker colors (i.e., black). The heatmap is ordered by the average correlation per participant.

After this, we averaged responses across participants for each adjective and material, and submitted the averages to a covariance-based PCA in order to verify the different softness dimensions that we found in earlier work [1]. Prior to the PCA we used Bartlett's test of sphericity and the Keyser-Meyer-Olkin (KMO) criterion to assess the suitability of the data for this type of analysis. The KMO criterion of sampling adequacy yielded a score of .48, which is a borderline value. However, Bartlett's test of sphericity was significant, χ 2 (105) = 415.79, $p < .001$, which suggests that the observed correlations were indeed meaningful. The principal components were extracted according to the Kaiser-criterion and rotated using the varimax method.

Five principal components were extracted, explaining 94.3% of the variance (see Fig. 3 for Scree plot). The first rotated component accounted for 25.9% of the variance. It appeared to be related to the material's furriness or fibrousness because adjectives like fluffy, velvety, hairy, and soft loaded high on this component. The second component accounted for 20.6% of the variance in the data. We labeled this component viscosity because sticky, moist, and wobbly were high loading adjectives. Component three explained 20.6% of the variance. High loading adjectives on this component were powdery, sandy, and granular. Thus we labeled it granularity. The fourth component explained 17.8% of the variance, with high loadings of the adjectives inflexible (- = negative load), elastic, and hard (-). Therefore, this component might be linked to deformability. Finally, the fifth component explained 9.4% of the variance, with high loadings of the adjectives smooth (-) and rough, and consequently we labeled it roughness. These five components (4 dimensions of softness and one control dimension) confirm that the adjectives used in our study adequately tap into expected dimensions of softness. Inspecting the materials' component scores (Table IV) confirmed that also the

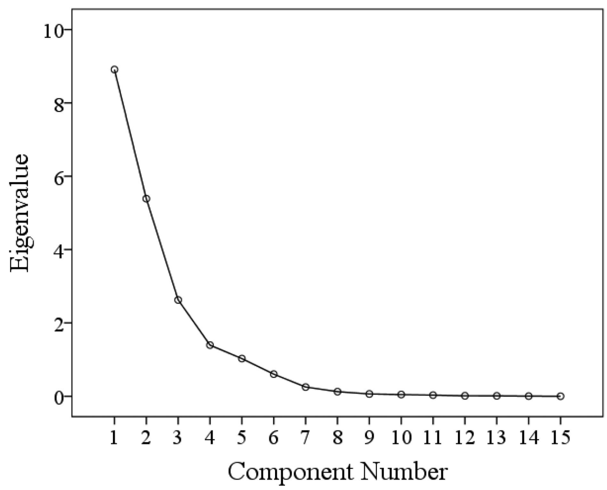


Fig. 3. Scree plot for PCA of sensory adjectives. Shows that five components account for 94.3 percent of the variance.

selected stimuli adequately represent the 4 dimensions of softness & roughness–and in overall agreement with our previous work [1] (cf. Table II). Note, that material categories in the following analyses are based on the scores from Table IV.

TABLE IV
ROTATED COMPONENT SCORES OF MATERIALS

Material	Components				
	Furriness	**Viscosity**	**Granularity**	**Deformability**	**Roughness**
Fur	**1,99**	-0,12	-0,56	-0,38	0,66
Cotton balls	**1,47**	-0,42	-0,28	0,37	-0,02
Velvet	**1.05**	-0.9	0.25	0.95	-1.64
Wool	**1,40**	-0,13	-0,51	-0,15	**1,27**
Paper balls	-1,15	-0,90	-0,76	0,30	-0,09
Hand cream	0,09	**2,22**	-0,43	-0,37	-0,94
Hair gel	0,10	**2,18**	-0,45	-0,37	-0,80
Stress balls	-0,70	**1,27**	-0,17	**1,25**	0,37
Salt	0,04	-0,25	**2,67**	0,12	0,12
Sand	-0,01	0,15	**2,63**	-0,28	0,52
Stone	-0,74	-0,54	-0,67	-2,42	-0,55
Lentil	-0,23	-0,37	0,59	-2,10	-1,59
Sponge	-0,38	-0,63	-0,17	**1,33**	-0,15
Playdough	-0,78	0,17	-0,24	**0,96**	-0,60
Linen	0,37	-0,77	-0,11	0,86	-0,68
Sandpaper	-1,53	-0,63	-0,26	-0,58	**2,14**
Aluminum foil	-1,31	-1,11	-0,73	0,53	-0,78
Cranberries	-0,68	**1,24**	0,07	0,48	**1,37**
Felt	0,51	-0,44	-0,87	-0,49	**1,16**

Larger fonts indicate high loads (absolute value > 1, which corresponds to one standard deviation in the z-standardized values). Bold fonts indicate the high **positive** loads that define the associations with material categories. Only for playdough the defining load marginally failed to exceed 1. Materials in italics load highly positive in two components.

B. Hand Movements

We next analyzed the video recordings of participants' hand movements during the exploration periods. Exploratory procedures were classified according to the list of eight EPs proposed in [1], [20] (see Table I for a detailed description). We also observed one additional hand movement: a "flat-handed pick up" resulting in a total of 9 possible EPs. For each 4-second exploration per individual, material and adjective we coded the frequency of occurrence of each of the 9 EPs, disregarding their duration. These frequencies were normalized to a "percentage value" by dividing 100% by the number of EPs observed in that trial (e.g., if 3 EPs were coded in a trial, each of the three EPs obtained a value of 33.3%).

Due to the extensive amount of labor when manually coding these videos only one rater coded all of the data, which was then used in subsequent analyses. In addition, two raters coded independently the same 50% of all videos (corresponding to 15 participants) in order for us to assess inter-rater reliability [28]–[29]. This was generally high (Cronbach's $\alpha = .89$, $p < .001$), corroborating the main coder's results. Prior to coding the movies, all raters had received training on the EPs. Specifically, they were given detailed explanations on the EPs, and they had practiced coding data from a pilot experiment. These codings were evaluated and compared, and disagreements between raters resolved by discussions. For example, we explained that hand motions that were generated by attempts to clean the hands-off parts of the materials (e.g., sand, playdough) were not to be counted as EPs. When discriminating between the different EPs raters were encouraged to focus on hand movements alone. For example, when differentiating between *pulling* and *pressure*, raters primarily relied on the positioning and movements of the individual fingers. This is a reasonable strategy, since finger dynamics can provide cues about the magnitude and the direction of the applied force: e.g., in *pressure* two fingers approach each other and force is applied towards the object. In contrast, in a typical *pulling* motion two fingers touch and then move apart, indicating that forces direct away from the object. Another example is the distinction of *rotate* from *rubbing* when coding the hand movements for granular materials. Here, raters focused primarily on the motion trajectory, the applied force, and the sliding

TABLE V
UNIVARIATE ANALYSIS OF VARIANCES ACROSS MATERIAL CATEGORY, TASK DIMENSION, AND INTERACTION BETWEEN MATERIAL CATEGORY AND TASK DIMENSION

Material category

Dependent variable	Dfs	*F* value	*p* value	partial η^2
Flat handed pick up	3.08,89.40	15.56	<.01	0.35
Pressure	1.87,54.10	117.1	<.01	0.80
Pull	1.12,32.48	137.75	<.01	0.83
Rotate	1.11,32.04	105.73	<.01	0.79
Rubbing	2.69,77.98	95.96	<.01	0.77
Run through	1.07,30.88	170.97	<.01	0.86
Stroke	1.59,45.97	5.29	=.01	0.15
Stir	1.55,44.85	10.14	<.01	0.26
Tapping	2.67,77.48	8.18	<.01	0.22
Task dimension				
Flat handed pick up	1.03,29.73	56.77	<.01	0.66
Pressure	2.51,72.90	151.20	<.01	0.84
Pull	2.61,75.61	19.96	<.01	0.41
Rotate	3.36,97.31	8.61	<.01	0.23
Rubbing	3.08,89.20	112.75	<.01	0.80
Run through	3.20,92.64	15.64	<.01	0.35
Stroke	2.74,79.31	9.63	<.01	0.25
Stir	2.28,66.10	0.85	>.05	0.03
Tapping	2.91,84.30	7.18	<.01	0.20
Material category*task dimension				
Flat handed pick up	3.55, 102.92	14.29	<.01	0.33
Pressure	6.45, 186.93	54.86	<.01	0.65
Pull	5.46,158.34	9.69	<.01	0.25
Rotate	4.91,142.28	5.96	<.01	0.17
Rubbing	9.57,277.48	18.54	<.01	0.39
Run through	3.55, 102.92	12.20	<.01	0.30
Stroke	5.15, 149.27	1.18	> .05	0.04
Stir	3.70,107.18	0.95	> .05	0.03
Tapping	6.95,201.48	1.70	> .05	0.06

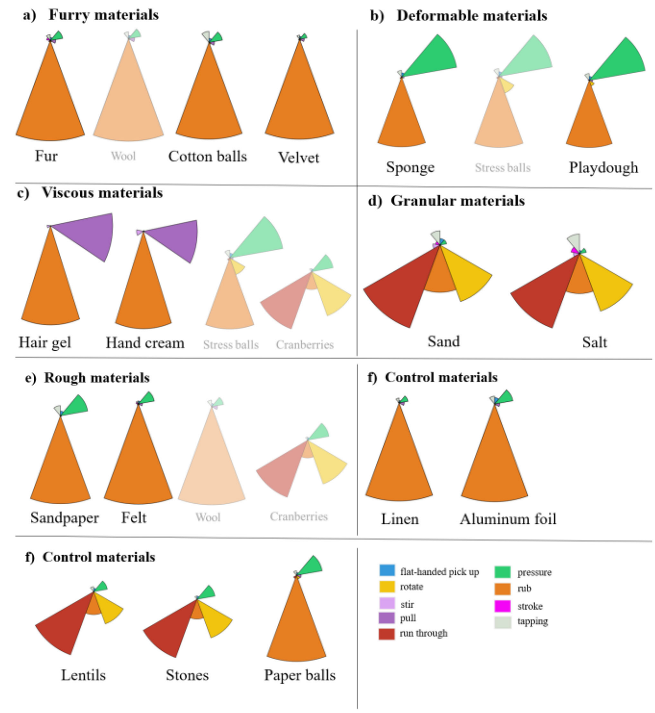


Fig. 4. Mean frequency of occurrence of each EP as a function of material category: *furry* (a), *deformable* (b), *viscous* (c), *granular* (d), *rough* (e), and *control* (f). Individual materials with transparent diagrams loaded high on more than one dimension.

velocity in order to differentiate these two EPs. An EP was classified as *rotate* when the motion trajectory was circular, and the sliding velocity and the applied force appeared relatively low. On the other hand, when the motion trajectory was rather lateral, and the sliding velocity and applied force appeared high, the EP was classified as *rubbing*.

C. Effects of Task Dimension and Material on EPs

After establishing that our choice of rating adjectives and materials adequately represent specific perceptual dimensions of softness (and roughness, as a control dimension), we conducted two-way repeated-measures MANOVAs in order to investigate the individual and combined effects of material properties and task dimension on the patterns of exploratory procedures. To this end, we collapsed the individual frequencies of all EPs across the adjectives that load highest on each of the four different perceptual dimensions and roughness, separately for each material. Specifically, we collapsed EP frequencies for ratings of fluffy, hairy, soft, and velvety for the *furriness dimension*; moist, sticky, and wobbly for *viscosity*; granular, powdery, and sandy for *granularity*; hard, inflexible, and elastic for *deformability*; and smooth and rough for *roughness*. The dependent variables in this MANOVA were the EP frequencies for *flat handed pick up, pressure, pull, rotate, rubbing, run through, stir, stroke*, and *tapping*.

We conducted the first MANOVA with the independent variables of task dimension (5 levels) and individual material (19 levels) in order to test for general effects of *material*. The MANOVA yielded significant main effects of individual material, $V = 2.78$, $F\,(162, 4698) = 12.99$, $p<.01$, partial $\eta^2 = .31$, and task dimension, $V = 2.23$, $F\,(36, 444) = 15.59$ $p<.01$, partial $\eta^2 = .56$, using Pillai's trace (Fig. 4 and Fig. 5a, these plots use the area of circle segments to convey the relative EP frequencies percentages. All segments add up to 100% in total). The interaction between material and task dimension was also statistically significant, $V = 1.13$, $F\,(648, 18792) = 4.18$, $p<.01$, partial $\eta^2 = .13$.

In order to also check for homogenous effects of material type, we conducted a second MANOVA. We organized our 19 materials into separate categories; we agglomerated those that loaded high on the same softness dimension (Table III). Materials that loaded high on two different dimensions (Table IV, italics) were excluded from this analysis. We then investigated how EPs were influenced by both the particular *category* of a given material and the *task dimension* (5 levels). EP frequencies were averaged over each *material category* (*furry, viscous, granular, deformable, and rough [control category]*) and *task dimension* (*furriness, viscosity, granularity, deformability, and roughness [perceptual control dimension]).* As before, the dependent variables were the frequencies of the nine EPs. The (5x5) repeated-measures MANOVA yielded

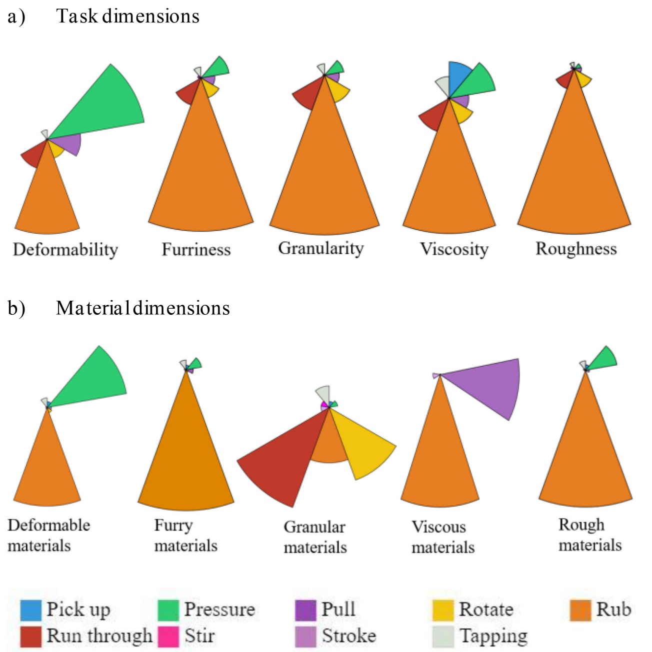


Fig. 5. Mean frequency of occurrence of each EP as a function of task (a) and as a function of material dimension (b).

significant main effects of *material category*, $V = 2.45$, F (36, 444) = 19.5, partial $\eta^2 = .61$, and *task dimension*, $V = 1.98$, F (36, 444) = 12.06 partial $\eta^2 = .49$, as well as a significant interaction between both, $V = 1.67$, F (144, 4176) = 6.61, partial $\eta^2 = .19$ (all $p<.01$, using Pillai's trace, Fig. 6).

To investigate the contribution of each dependent variable to the model we conducted follow-up univariate repeated-measures ANOVAs for each EP. The results indicate, that the frequency of EP occurrence differed significantly across *material categories* for flat handed pick up, pressure, pull, rotate, rubbing, run through, stroke, stir and tapping (Table V). Univariate ANOVAs for each EP showed that most EP frequencies varied significantly also across *task dimensions* for flat handed pick up, pressure, pull, rotate, rubbing, run through, stroke, and tapping, but not for stir (Table V). Following up the interactions with individual ANOVAs we found the following EPs significant: flat handed pick up, pressure, pull, rotate, rubbing, and run through. Interactions were not significant for stroke, stir, and tapping (Table V).

D. Predicting the Material Category From EP Patterns

The analyses above and Fig. 4 & 5 suggest that EPs change as a function of *material category* and the *task dimension*. Next, we wanted to determine whether EP patterns can be used to predict the perceived material categories. To do this, we used a machine learning approach and trained a support vector machine (SVM, with Euclidian distance as error metric) on 90% of the EP data (540 of 600 observations [30 participants x 5 tasks x 4 material categories], 135 per material category [related to salient

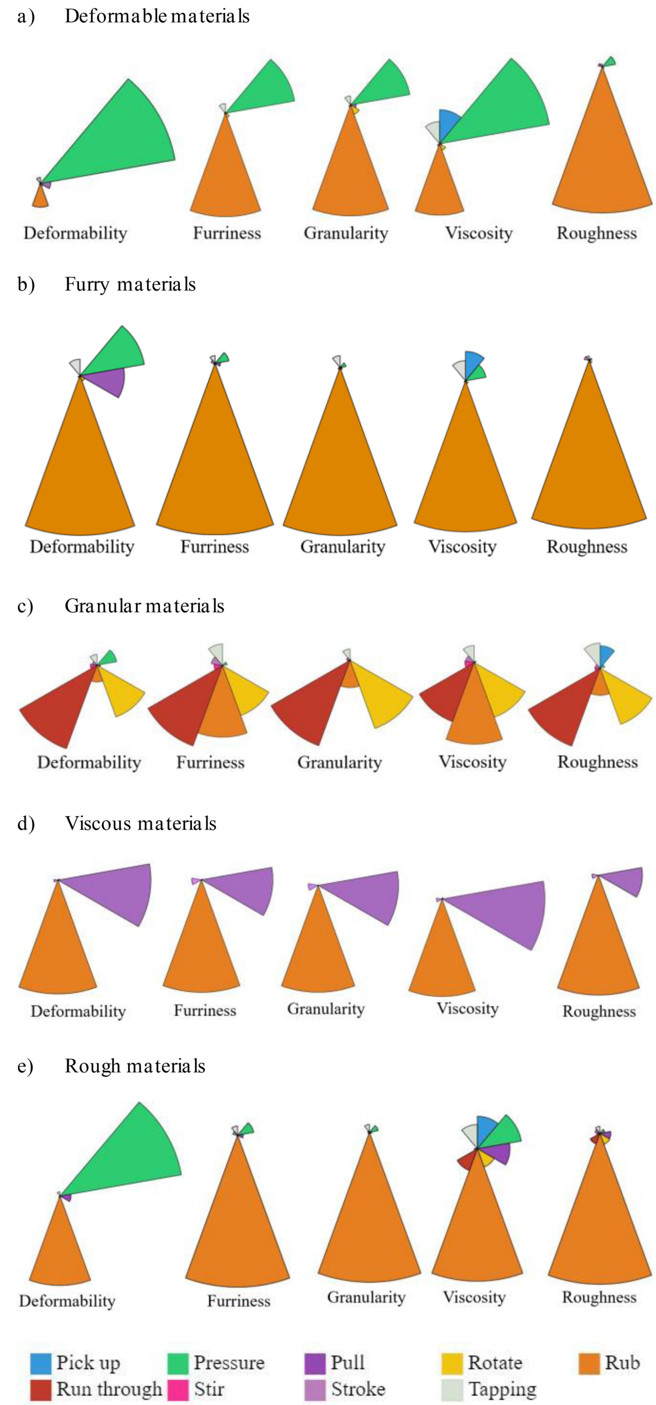


Fig. 6. Mean frequency of each EP as a function of task for different material categories: *deformable* (a), *furry* (b), *granular* (c), *viscous* (d), and *rough* (e).

softness dimension: *viscosity, granularity, furriness, and deformability*]) using the built-in Matlab function *fitcecoc* with a ten-fold cross validation (*crossval* function Matlab). We determined the optimal size of the training data by finding the best parameters to create a hyperplane which divides the data into four categories using a Gaussian kernel. Also, ten-fold cross-validation prevents overfitting and provides a generalized classification error. The goal of the

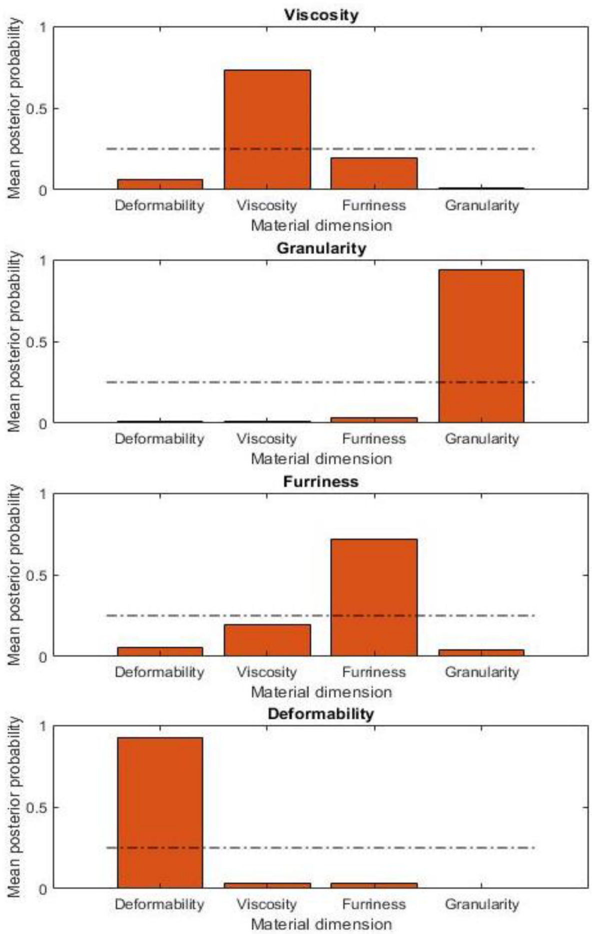


Fig. 7. The performance of a linear support vector machine predicting softness dimensions of the materials from the EP frequencies. Specifically, we plot the mean posterior probability for each material dimensions. The dashed line indicates the chance level (25%).

SVM was to predict the perceived material categories of the remaining data (60 observations). Fig. 7 shows that prediction performance of the SVM was overall very high (86.67%), with best classification for granularity (94%), followed by deformability (92%), viscosity (73%) and furriness (71%). Classification performance was significantly above the chance level (25%) in all conditions.

IV. Discussion

Correctly judging the softness of objects enables us to make critical decisions, such as whether a surface is safe enough to sit on or whether food is edible. We have shown here that, unlike previously thought, soft materials are not just explored by applying pressure, but by using a number of different exploratory procedures. We also found that participants actively adapt how they use these EPs as a function of the perceptual task. Both findings challenge the existing concept of softness as a single dimension. Moreover, interactive effects of task and material category on EP patterns, suggest a very fine-tuned usage of hand movements, which goes beyond the idea that EPs are movement schemes that are closely and heuristically linked exclusively to the task [18].

Some of the results may seem surprising since they go beyond what one's intuition would predict from the daily interactions we have with soft materials. For instance, intuitively, one would think that people primarily stir viscous materials, yet we found that people instead tend to pull viscous substances. Another surprising finding is that participants tended to always rub materials – independent of what it is they are touching and what it is they are judging about a material. However, this EP is flexibly supplemented in different degrees by additional EPs, which are associated with specific material properties, the task, or an interaction of the two. So, instead of the strict specialization of a single movement, we see that people use combinations of movements (e.g., run through followed by rotate for granular materials), which might help them to gather an optimal set of information.

A. *Influence of Individual Material Properties and Material Categories on EPs*

We found that EPs were affected by the individual material properties, which would be consistent with previous research on haptic softness and texture perception [18], [21]. Many of these effects can be explained by the material category: EPs differed between individual materials if the materials loaded high on different softness dimensions. Therefore, we collapsed the data for individual materials that loaded high on a particular dimension. This yielded 5 material categories (4 soft & 1 rough). As can be seen from Fig. 5b, the patterns of EP differed substantially between material categories. This is consistent with previous work [30]–[31] which suggested that perceptual dimensions, that are associated with specific material properties affect the way we explore them. We found the following associations for softness dimensions:

- The most frequently used EPs for highly granular materials (i.e., salt and sand) were run through and rotate (Fig. 4, 5b). It could be that this combination of EPs is particular useful for granular materials: while run through might provide initial coarse information about the density, weight, or viscosity of the grains, rotate provides follow-up, refined information about the size or shape of individual grains. To test this idea, we performed a follow up analysis on the temporal sequence of EPs for granular materials. Briefly, one coder recoded hand movements of 10 random participants with respect to the time sequence of EPs for all granular materials (10 participants x 2 materials, sand & salt, x 15 adjectives = 300 trials), and we analyzed the frequency of combination of the first 2 EPs occurring in a trial—across all trials (with a chance level 1.4%, for 72 ordered combinations of 9 EPs). Only 5 EP combinations were significantly more frequent than chance level (calculated for 300 observation using a Binomial distribution), and results support our idea, showing that the most frequent order of the first two EPs in a trial was indeed run through-rotate (56.3% of trials), followed with quite some distance by the ordered combinations rub-run through (10.0%), rub-tapping (4.3%), rotate-rub (3.67%), and run through-rub (3.3%).

- Participants tended to explore hair gel and hand cream, which are associated with viscosity, mostly by pulling in combination with rubbing. These two EPs may test complimentary aspects of highly viscous materials: Rubbing might provide information particular on stickiness/friction aspects [32] while pulling might estimate tensile ductility.
- Participants frequently used rubbing for cotton balls or fur, which have large values on the furriness dimension. Rubbing is a lateral and forceful EP, and hence probably particularly useful to explore characteristics of deformable surface structures, i.e., furry surfaces.
- For sponge and playdough, materials that score high on the deformability dimension, participants used more frequently pressure than for other material categories. This fits with previous findings showing that pressure is used and well-suited to judge object compliance [14], [17]. In addition, rubbing is frequently used in deformable materials as it is the case for other material categories. We will discuss this point below.
- We also obtained typical uses of EPs for rough materials, namely a high frequency of rubbing. This is consistent with [19] where the roughness-associated EP was lateral motion, which we here differentiated into stroke and rubbing.
- In line with previous work [1], rubbing was used frequently in most material categories: for furry materials (e.g., fur or cotton balls), for viscous materials (e.g., hand cream and hair gel), for deformable materials (e.g., playdough and sponge), for rough materials (sand paper or fur). It was used less likely for granular materials (e.g., sand or salt). Rubbing may be particularly informative compared to other EPs because it can provide force and structural (micro-shape) information at the same time, which may not hold to the same extent for, e.g., stroke, pulling, pressure or tapping [32]. Thus, we speculate that participants might have frequently used this EP because it is highly informative in general.

A limitation of the current study might be that in a few selected cases, a specific EP might be hard to apply to some specific material (e.g., *running through* felt), or conversely a material may allow to apply only a few of the EPs defined in this study. Would this not imply that preferences (and consequently overall frequencies) for an EP might be overemphasized for certain materials? We argue that this argument would only apply if there was a finite fully described number of potential EPs that are possible. If that was the case, then the imposed limitations on the possible types of EP by the properties of the material would lead to an overestimation of the usage of the residual EPs in the set. However, human movement control is quite flexible and adaptive, and a manifold of different EPs is possible, and we did not claim that the list of our 9 EPs is an exhaustive one. Therefore, the baseline for any EP frequency estimate is the (infinite) number of theoretically possible EPs. For this reason, we believe that our interpretation of the results would not change if some of the 9 EPs were not "possible" for some of the materials in our study. Another limitation could be, that the raters' categorization of exploratory procedures might have been influenced by seeing the material. However, given that observers are able to recognize materials by only watching the point-light hand motions of others [30], we believe that the dynamics of the fingers and hand alone might have provided raters with sufficient information to discriminate between different EPs. In a follow up study, we will test this idea formally.

B. *Influence of Task Dimensions on EPs*

EP frequencies also varied as a function of the task dimensions, i.e., which perceptual dimension was rated (Fig. 5a). Specifically, and in line with [17], judging roughness was primarily associated with a *rubbing* motion (would have been categorized as lateral motion in [19]), whereas the deformability judgments were most frequently associated with applying *pressure*. The softness dimensions furriness and granularity were also mainly explored by *rubbing*, and to rate the viscosity of a material caused participants to both *rub* and apply *pressure to the material*, with lower frequencies in-between those for deformability on one side and furriness/granularity on the other side.

The perceptual task modified the usage frequency of EPs less than did the material category. However, we also saw that for each perceptual task not only one EP is dominant, but a number of additional different EPs could occur, potentially providing complementary information to inform the perceptual process. It is quite possible that the order of EPs matters when judging different properties of the materials. For example, it could be that for judging the deformability of a material that the first EP should always be an attempt to compress it, i.e., to apply *pressure*. We tested this idea by investigating whether there were any significant temporal relations between EPs when judging deformability. Specifically, we recoded hand movements of 10 randomly chosen participants with respect to the temporal occurrence of EPs for two representative materials of each material category (*furry*: fur and cotton balls; *granular*: sand and salt; *viscous*: hair gel and hand cream; *deformable*: sponge and playdough; *rough*: sand paper and felt) and all judgments (3 adjectives) pertaining to the deformability of the material. Then, we analysed the frequency of EP-pairs occurring in a certain order for each of the 5 material categories (yielding 60 datapoints per material category). We considered ordered EP pairs that occurred significantly more often than chance (chance level 1.4%, test calculated for 60 observation using a Binomial distribution), and tested for these whether the frequency of one order of the two involved EPs was significantly more frequent than that of the other order (calculated again for 60 observations using a Binomial distribution, using the smaller frequency as a baseline). We found significant temporal relationships between the first two EPs in the following cases: For deformable materials *pressure* was followed by *rub* in 25% of the trials (the other order *rub-pressure* was only observed in 5% of trials); again, for granular materials *run through* was followed by *rotate* in 55% of the trials (vs. 6.67% for *rotate-run through*); finally, for viscous materials *rub* was followed by *pull* in 33% of the trials (vs. 18.3% for pull-rub). These findings support the idea that complementary information is gained successfully from different EPs, at least for some material categories. While the first EP may provide information on more general characteristics of the materials, the second EP may help people gain more detailed information. For example, for deformable materials a first coarser judgment of deformability by applying *pressure* might be fine-tuned by more careful rubbing of the materials between the fingers. However, for furry and rough materials, we did not find temporal relationships in EPs. But this does not render the secondary EPs useless. Regardless of a sequence, using an additional EP is likely still enhancing the information gain, and we plan to test this formally in future work.

C. Interactions

Our results show that the material category effects explained more of the total variance in the EP patterns than the task dimensions. However, we also found an interaction between these two factors (Section C in results). This implies that different combinations of these two factors affected EP frequency differently. This is illustrated in Fig. 6: for granular materials *run through* and *rotate* were used with high frequencies across task dimensions, however, the exact frequency of these EPs and the frequency of additional EPs varied with the *task dimension*: for example, while judging the viscosity of granular materials participants used less *run through* and more *rubbing* compared to other task dimensions. For other material categories *rotate* and *run through* were hardly used for any task. In fact, a similar variation across *task dimensions* was not observed for any other *material category*. This result suggests that EPs are not determined by task or material in isolation, but that instead participants tended to explore materials with a particular set of EPs in order to optimize information apprehension [19]. Specifically, we find in this study that the interaction of *task dimension* and *material category* might influence such an optimization process. We next highlight a few noteworthy interaction effects between the material category and the task dimension (Fig. 6):

- Overall, people frequently use the EP *pull* for viscous materials [1]. *Pulling* is used in similar frequency to judge deformability and viscosity of viscous materials, whereas for furry materials it is used to judge deformability, but not viscosity. This may relate to different effects and information gains in viscous vs. furry materials: By *pulling* the fingers apart in viscous materials participants may try to understand primarily the tensile ductility, which contributes both to deformability and viscosity judgments. However, in furry materials they may mainly gain information on the bending characteristics of textural elements, which is relevant for deformability but less so for viscosity judgments.
- *Pressure* is used across materials and tasks. However, the proportion of applied *pressure* changed across material and task dimension combinations. For example, for deformable, furry or rough materials, it is more frequently used for the deformability tasks than for other tasks, which is not true for granular and viscous materials where it is hardly used at all. This likely reflects that the normal forces that are applied during pressure are quite useful to judge deformation of deformable, rough, and (less so) furry materials, but for granular and viscous materials applying force in varying directions may provide better information.
- While exploring furry or viscous materials people frequently use *rubbing* for any task dimension, whereas its usage depends clearly on the task for rough, deformable and granular materials, e.g., it is used less for deformability judgments as compared to other judgments. This might be the case because deformability judgments in the former, but not in the latter type of materials can be informed by lateral movements during *rubbing*.
- *Rotate* is mainly used for granular materials and hardly for other material categories. Still, for granular materials people adapt the usage of the EP to the task dimension. It is most likely used when the task is to judge granularity and less for furriness, roughness or deformability tasks. Probably, rotation is particularly useful for granularity judgments here, because it gives information about shape and size of grains.
- *Run though* is only used for granular materials, because physically it is not possible to apply this movement to materials that do not have grains. Again, the frequency of the usage is modulated by the task. In particular people applied run through less to granular materials when they judged viscosity as compared to other dimensions. Probably, viscosity judgments manly concern the behavior of the whole material rather than the (sum of) individual behavior of grains. Overall, *run through* and *rotate* seem to be highly specialized EPs in order to gather information about granular materials, and the frequency of using these EPs is further modulated by the task dimension.

Flat-handed pick up is hardly ever used across material categories and task dimensions except for one specific case. When the task is to judge viscosity, it is used in different frequencies for different material categories. People used it for deformable, furry, and rough materials but hardly for viscous materials—maybe because for viscous materials its special functions are already appropriately fulfilled by the EP of *pulling*. Overall, our results show that participants show differentiated patterns of EPs as a function of task dimension as well as of the softness dimension associated with a particular material. This further supports the idea that multiple perceptual dimensions of softness exist. However, how can we ascertain that the observed dimensions are indeed essentially related to perceived softness: In daily life, we often judge the softness of quite diverse materials to guide important decisions about how we should interact with them, for example whether a fruit is edible, the sand on the beach comfortable to sit on, or a garment pleasant to wear. That is in everyday judgments we call various types of materials as being more or less soft as covered by our different softness dimensions. Yet other researchers appear to promote the idea of different softness dimensions: e.g., Di Luca [7] defined haptic softness generally, as the subjective impression of compressibility and deformability characteristics of things and materials, meaning that softness can be interpreted as the perception of a material's response to change through physical interaction. All our softness dimensions would fall under this definition. Previous works by other groups have extended the notion of softness to different dimensions by promoting percepts of firmness, viscosity or surface softness [111-13, Giordano & Avanzini in [7]]. This research together with our results provide strong evidence in support of the notion that perceived softness has multiple dimensions.

V. Conclusion

Results show that participants actively and finely adapt their EPs to combinations of task and material and support the idea of multiple softness dimensions. These findings might be of interest to several applied fields, including robotics, where an understanding of the haptic perceptual space of material qualities could help to optimize the grasping and exploration abilities of autonomous agents [33] or to develop more faithful prosthetics [34].

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