Supplementary Information

Feeling Small: Exploring the Tactile Perception Limits

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This PDF file includes Supplementary Methods, Supplementary Figures 1S-4S, Supplementary Table 1S and a reference list.

Supplementary Methods

PDMS specimen preparation

Polydimethylsiloxane (PDMS) (Sylgard 184, Dow Chemical Co., MI, USA) was prepared by hand mixing base monomer and curing agent at a mass ratio of 10:1. The PDMS was cast onto a clean glass plate, placed on a balanced table at room temperature to allow trapped air bubbles to escape, and then cured at 75 °C for 2 h. The cross-linked PDMS with thickness of about 2 mm was cut into 75 mm × 25 mm specimens.

Surface wrinkling and replica moulding

A schematic illustration of the fabrication procedure of wrinkled surfaces is depicted in Fig. 1 in the main text. A PDMS specimen was mounted into a strain stage[1] and strained uniaxially from length L to L + ΔL. In the present study, ΔL was varied to control the amplitude of the resulting wrinkle wavelength[2]. Either ultraviolet ozone (UVO) irradiation or oxygen plasma (OP) treatment was used to oxidize the top surface of the strained PDMS specimen depending on the wrinkle wavelength to be achieved[2]. These treatments create a thin, stiff silicate-like top layer with a higher elastic modulus than the underlying non-oxidized portion of considerably thick PDMS substrate[2,3]. When the strain was subsequently released, surface wrinkles, with a wavelength that minimises the strain energy[4,5], were formed spontaneously perpendicular to the direction of strain due to the difference in elastic moduli between the top layer and the substrate. Stretched and surface-modified PDMS specimens released instantaneously (*i.e.*, strain removed abruptly) in order to avoid possible cracks in the surface[6,7].

Replicas were obtained by moulding a UV-curable adhesive polymer (Norland optical adhesive; NOA81, Norland Products Inc., NJ, USA) against the PDMS. The PDMS was positioned on a cleaned glass slide of dimensions 75 mm × 50 mm (Corning Micro Slide, Corning Inc., NY, USA) with the wrinkles facing upward. Approximately 0.65 g of the polymer was deposited onto the middle of the PDMS surface and a second glass slide was placed on top, which allowed the polymer to spread. Curing was performed for 15 min under ultraviolet light with a wavelength of 365 nm. The top glass slide was then peeled away from the PDMS master, yielding a durable, cleanable replica of the patterned surface.

Characterization of wrinkled surfaces

The replicated wrinkled surfaces produced from the UVO-treated PDMS specimens (coarser structure) were analysed with a contact measurement device (Taylor Hobson Form Talysurf PGI 800). The stylus tip, with a radius of 2 µm, was drawn 1.1 mm perpendicular to the wrinkled surfaces at a speed of 0.1 mm/s and the distance between the sampling points was 0.12 µm. The wrinkle wavelength was estimated from the unfiltered S-parameter, which is the average spacing between local peaks. The wrinkle amplitude (*A*) was obtained from the unfiltered R_z-parameter, which is the average vertical separation of the five highest peaks and the five lowest valleys (ten-point height), *i.e.*, equivalent to 2*A*. The average surface roughness (R_a) was obtained using a cut-off of 0.25 mm. This parameter is included for comparison, since R_a is the parameter that is most often mentioned in the literature.

The replicated surfaces produced from the OP-treated PDMS specimens (finer texture) were analysed with an atomic force microscope[8] (AFM) (Dimension 3100, Digital Instruments, CA, USA) with a Nanoscope III controller. The AFM images were taken in tapping mode using a TAP300Al-G cantilever (BudgetSensors, Innovative Solutions Bulgaria Ltd) with a resonance frequency of 292 kHz and a scanning speed of 1 Hz. The images were further analysed using Gwyddion 2.25 software. The wavelength, amplitude and R_a surface roughness were obtained from profiles drawn over each AFM image, using a cut-off frequency of 0.05 (this corresponds to a cut-off wavelength of 1.5 μm for an image of 10 μm and 256 pixels). Each value was obtained by averaging over 8 independent scans, and the resulting wavelengths, amplitudes and R_a surface roughness are listed in Table 1S.

Participants in the similarity measurement

Twenty naïve participants took part in the experiment. All were women and their average age was 24 years old (range: 21–32 years). They were recruited by advertising at the Royal Institute of Technology as well as the Stockholm University. Every participant received four cinema tickets for their participation.

Stimuli and materials

Table S1 presents the 18 stimulus surfaces used in the experiment on perceived similarity. The dimensions of the surfaces were 50 mm × 25 mm. An 18 × 18 matrix of these stimuli was formed, and the stimulus pairs in the lower half of the matrix were used in the experiment. By including twice every possible pair with the WS1 and WS10 surfaces as well as all pairs of the diagonal adjacent to the main diagonal in the matrix (i.e., 1–2, 2–3, 3–4, …, 17–18), an estimate of the test-retest reliability was made possible. In all, each participant scaled 201 pairs of stimuli. After each comparison, the surfaces were gently cleaned with acetone, using a lint-free tissue paper.

Psychophysical experiments

The experiments started with the participants washing their hands according to a protocol involving a mild detergent and thorough rinsing and drying. After reading the instruction, the participants were encouraged to ask questions about their task. After confirming that the instructions were understood, the participant was asked to put on the blindfold (Tempur sleep mask). The participants were instructed to feel the surface by stroking reciprocally with their preferred index finger (along the axis of the finger) for as long as they wished and at loads and speeds that they established themselves. First, each participant scaled the perceived similarity of a training set of three pairs of surfaces on a scale from 0% similarity (totally different) to 100% similarity (identical). Then, the main similarity experiment commenced.

Each experiment was divided into 25-min sessions. At most five sessions and at least four sessions were required to complete the experiments with a participant. Each session was followed by a 5-min break except after the second session where a 20-min break was inserted. In total, the experiment lasted between 2.5 h and 3 h, depending on the adjustment to a comfortable pace for each participant.

The temperature in the experimental room was 20.5 °C ± 1.3 °C and the relative humidity was 29 % ± 8 %.

Data treatment and analysis

Test-retest reliability was calculated from the subset of 48 duplicate pairs including the diagonal adjacent to the main diagonal in the matrix. Figure 1S presents the averages of the first and the second subsets of these 48 scale values for the first 10 participants of the experiment. Pearson's product-moment correlation (r) between subsets was 0.91, indicating that the test-retest reliability of the perceived similarity scale of the wrinkled surfaces is robust and highly consistent.

Dimensionality and goodness of fit

The similarity data (s) was transformed into dissimilarities (d), where $d = 100 - s$. The resulting symmetric dissimilarity matrices for sets of subjects were analysed with multidimensional scaling. In multidimensional scaling the dissimilarity is treated as distances, the smaller the dissimilarity the smaller the distance. The stimuli are placed in an n-dimensional space where the distance between the stimuli is kept constant. For a set of stimuli with no error, the MDS program would simply measure the distance and place the stimuli in the space accordingly. In psychology measurements however, there is always a certain degree of error. To fit data containing error there are algorithms to reduce stress, the measure of goodness-of-fit. For the present study the S-stress algorithm is used, where both distances (in the solution) and dissimilarities (in the matrix) are squared. The multidimensional scaling method used for the present study was individual differences scaling (INDSCAL), a procedure which delivers a solution calibrated for inter-individual differences[9]. The scree-plot depicted in Fig. 2S shows little improvement of the model fit past three dimensions (zero stress means a perfect correspondence between the similarity data and the INDSCAL configuration whereas a value of one means no fit). Although the stress values of the INDSCAL solutions indicate that both the 2D and 3D solutions represent the dissimilarity data matrices well, the 2D solution described the data better in the present experiment. This outcome was supported by a principal components analysis (PCA) of the similarity matrix of the group, which resulted in two components with eigenvalues larger than one.

For the two-dimensional INDSCAL solution, average stress over matrices was 0.332 (RSQ = 0.476). The high stress value is caused by task difficulty; in this case difficulties to distinguish the perceptual patterns of the stimulus surfaces. The error though is random and the scale values are proportionally over- and underestimated, which is not reflected in the stress value[10]. In fact, the good fit of the two dimensions with the physical measures (wavelength and finger friction) indicate in principle that the INDSCAL solution is indeed delivering two separate perceptual dimensions neatly corresponding to the two physical stimulus quantities varied. This is shown in Fig. 3 and Fig. 4 in the main text.

To assess test-retest variability the INDSCAL solution of the first 10 participants was compared with that of the last 10 participants (Fig. 3S) of the similarity experiment. The results indicate that the general trend remains consistent, although the surfaces are getting more similar during the course of the experiment due to wear of the surfaces (Fig. 4S).

Finger friction measurements

The method of finger friction measurements has been described elsewhere[11,12]. Briefly, a three-component piezoelectric force sensor (Kistler 9251A), together with a charge amplifier (Kistler 5038A3), was used to measure friction between a finger and the wrinkled surfaces that were mounted on the top plate with double-sided adhesive tape. The force sensor was calibrated using dead weights as described in[11].

The index finger of the trained experimenter (a 29-year-old woman) was moved back and forth over the surface, perpendicular to the wrinkle direction (Fig. S5). The finger was inclined at about 30° to the surface and was stroked a distance of 50 mm at a sliding speed of approximately 30 mm/s. When moving the finger over the surface, the loading and frictional forces were recorded versus time with a sampling rate of 100 Hz using a LabVIEW system. Several series of measurements were performed, resulting in six measurements per surface. The average load applied over all measurements was 1.0 N ± 0.10 N. The surfaces were cleaned with acetone and lint free tissue after each measurement to remove any material potentially transferred from the finger[12].

The experimental hand was washed with a commercial detergent and dried with paper towels before each series started. A standard waiting time of 10 min before measurement allowed the finger to equilibrate after cleaning. The relative humidity varied within the range (22 to 33) % and the temperature within the range (23 to 24) °C.

The friction coefficient was calculated as the ratio of the measured frictional force (F) and the applied load (L). The average friction coefficient of the first three stroking cycles was calculated for each surface since the participants tend to make an estimation of the surface feel based on a small number of stroking cycles in the tactile experiments.

Supplementary Figures

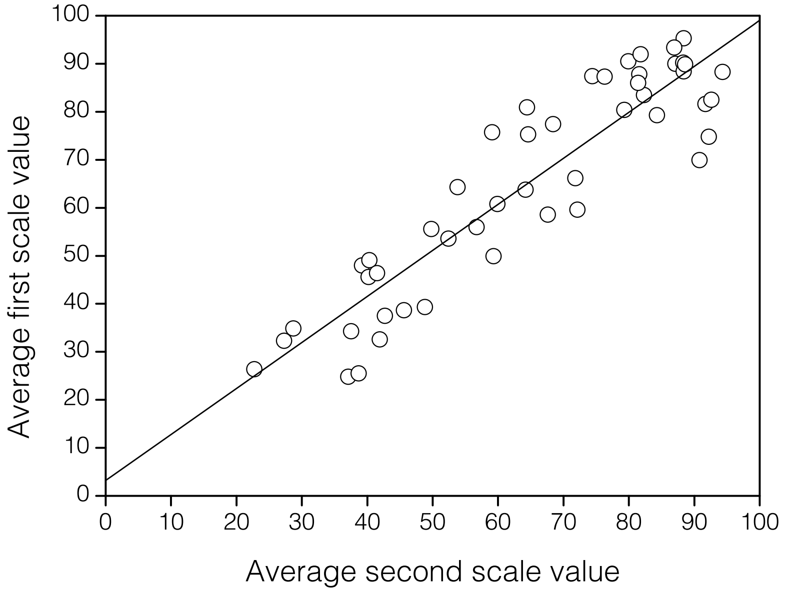

Fig. 1S. Test-retest plot. Average first scale value versus average second scale value for the first 10 participants. The points represent the 48 stimulus surface pairs that were tested twice. The high test-retest reliability (r = 0.91) indicates that participants were very good at scaling perceived similarities on these wrinkled surfaces.

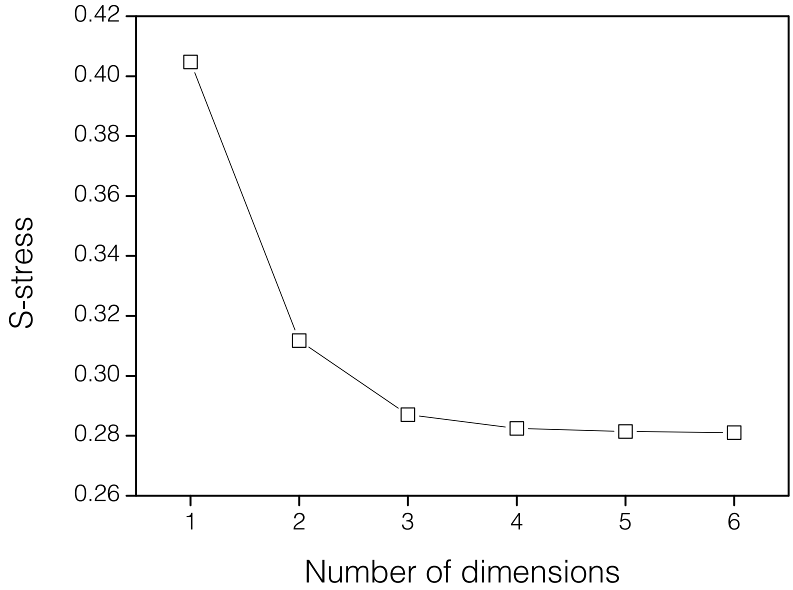

Fig. 2S. Dimensionality. S-stress plot of the tactile space obtained from individual differences scaling (INDSCAL) of perceived similarities, indicating that a 2D space solution, possibly 3D, is the best solution to all dissimilarity data [the similarities (s) were transformed to dissimilarities (ds) by ds = 1 – s].

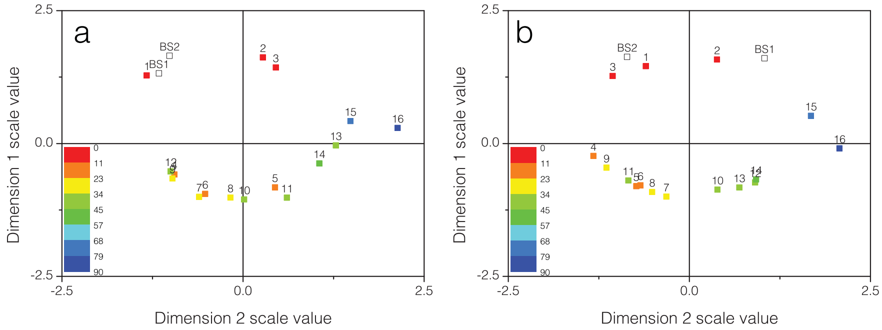

Fig. 3S. Comparison of the 2D INDSCAL solutions between two groups. (**a**) INDSCAL solution for the first 10 participants and (**b**) INDSCAL solution for the last 10 participants. The colour mapping is based on wrinkle wavelength and the stimulus labels represent these wavelengths of the surfaces without the prefix WS (wrinkled surface); thus, larger number indicate longer wavelength. The two blank surfaces (BS1 and BS2) without any systematic pattern are presented as unfilled (white) symbols. Note that one of these blanks (BS1) was damaged by scratching (Subject No. 11); it thereafter is found to be perceptually closer towards the larger wavelengths.

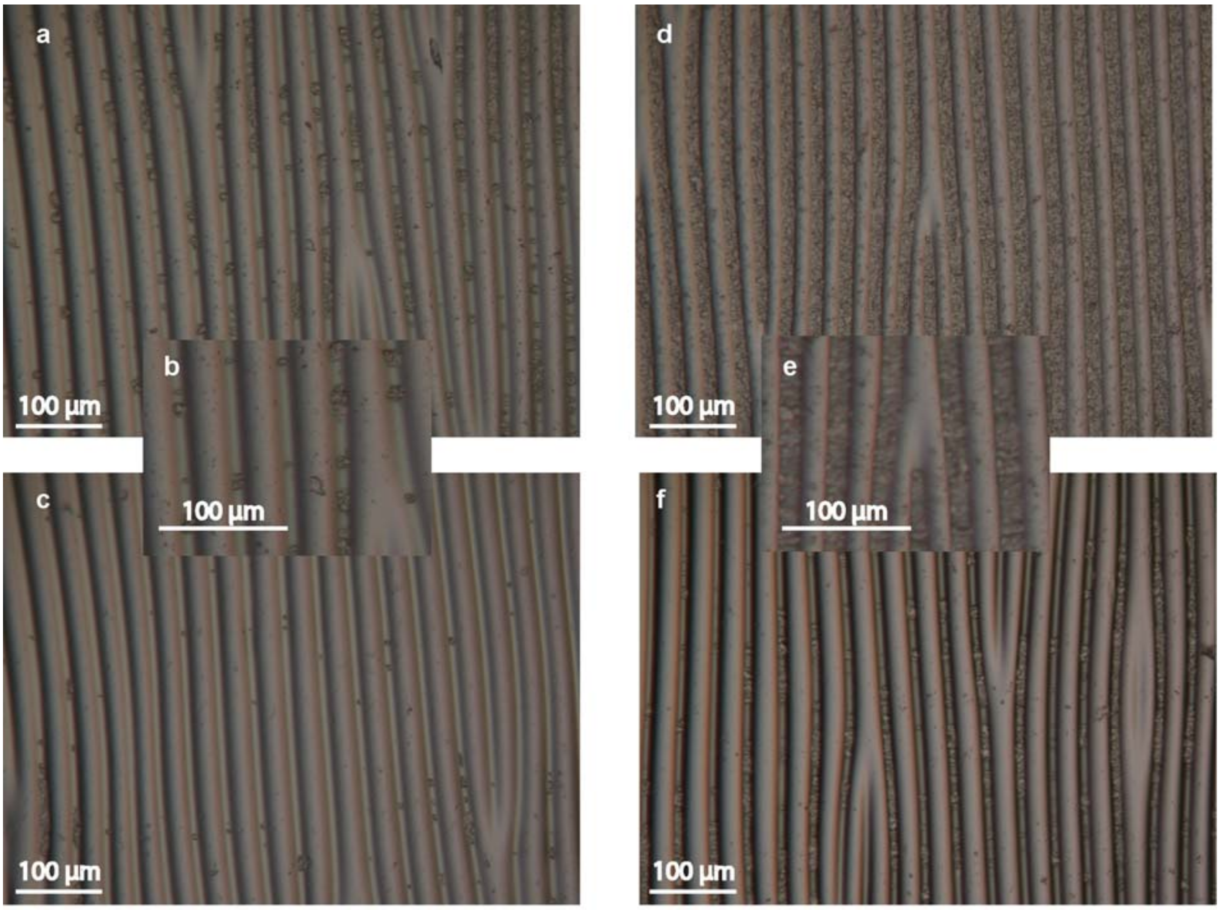

Fig. 4S. Surfaces after use in experiments. Optical microscope images of surfaces WS12 (**a-c**) and WS11 (**d-f**). Debris ends up in the valleys in the centre of the samples (**a,b,d** and **e**) where the majority of the finger contact occurs, as compared to the edges (**c** and **f**). The magnification is 10x and the scale bars are 100 µm. The debris is tare from the surfaces, as concluded from Confocal Raman signal spectra.

Table 1S. Surface characteristics of the 18 stimuli. The measured wavelength, amplitude, finger friction coefficient, and R_a surface roughness, as well as calculated aspect ratio of the replicated wrinkled surfaces. BS stands for blank surfaces without any systematic pattern, replicated from unwrinkled PDMS, while WS stands for wrinkled surface. The stimulus numbering (WS) is from the smallest wavelength to largest wavelength.

Surface	Wavelength (µm)	Amplitude (µm)	Aspect ratio (amplitude/wavelength)	Finger-friction coefficient	R_a surface roughness (µm)
BS1	-	-	-	1.27 ± 0.26	0.001 ± 0.000
BS2	-	-	-	1.41 ± 0.68	0.002 ± 0.001
WS1	0.270 ± 0.040	0.007 ± 0.001	0.025	1.02 ± 0.29	0.003 ± 0.001
WS2	0.760 ± 0.050	0.013 ± 0.003	0.017	1.21 ± 0.31	0.007 ± 0.002
WS3	0.870 ± 0.050	0.022 ± 0.005	0.026	1.09 ± 0.30	0.012 ± 0.003
WS4	17.5 ± 1.0	1.2 ± 0.1	0.067	0.52 ± 0.21	0.48 ± 0.02
WS5	17.6 ± 1.0	1.2 ± 0.1	0.071	0.48 ± 0.11	0.58 ± 0.08
WS6	20.5 ± 0.9	1.6 ± 0.1	0.080	0.31 ± 0.07	0.72 ± 0.07
WS7	25.0 ± 1.1	3.1 ± 0.3	0.123	0.35 ± 0.07	1.64 ± 0.23
WS8	25.1 ± 1.2	2.1 ± 0.2	0.082	0.29 ± 0.08	0.92 ± 0.39
WS9	31.2 ± 1.4	2.4 ± 0.3	0.078	0.59 ± 0.10	1.38 ± 0.15
WS10	34.0 ± 2.4	4.0 ± 0.5	0.119	0.52 ± 0.10	2.21 ± 0.61
WS11	37.4 ± 2.6	4.5 ± 0.4	0.121	0.32 ± 0.06	2.56 ± 0.26
WS12	39.9 ± 2.9	3.3 ± 0.3	0.081	0.54 ± 0.12	1.79 ± 0.20
WS13	42.9 ± 2.6	3.6 ± 0.3	0.084	0.61 ± 0.12	2.09 ± 0.18
WS14	46.5 ± 2.6	4.0 ± 0.2	0.085	0.67 ± 0.17	2.31 ± 0.16
WS15	70.7 ± 2.9	1.9 ± 0.1	0.027	0.90 ± 0.22	1.06 ± 0.06
WS16	90.0 ± 4.3	3.4 ± 0.3	0.038	0.82 ± 0.16	1.79 ± 0.17

REFERENCES

1 Stafford, C. M., Guo, S., Harrison, C. & Chiang, M. Y. M. Combinatorial and high-throughput measurements of the modulus of thin polymer films. *Review Of Scientific Instruments* **76** (2005).

2 Chung, J. Y., Youngblood, J. P. & Stafford, C. M. Anisotropic wetting on tunable micro-wrinkled surfaces. *Soft Matter* **3**, 1163-1169 (2007).

3 Bowden, N., Huck, W. T. S., Paul, K. E. & Whitesides, G. M. The controlled formation of ordered, sinusoidal structures by plasma oxidation of an elastomeric polymer. *Applied Physics Letters* **75**, 2557-2559 (1999).

4 Chung, J. Y., Nolte, A. J. & Stafford, C. M. Surface wrinkling: A versatile platform for measuring thin-film properties. *Advanced Materials* **23**, 349-368 (2011).

5 Volynskii, A. L., Bazhenov, S., Lebedeva, O. V. & Bakeev, N. F. Mechanical buckling instability of thin coatings deposited on soft polymer substrates. *Journal of Materials Science* **35**, 547-554 (2000).

6 Efimenko, K. *et al.* Nested self-similar wrinkling patterns in skins. *Nature Materials* **4**, 293-297 (2005).

7 Chung, J. Y., Lee, J.-H., Beers, K. L. & Stafford, C. M. Stiffness, Strength, and Ductility of Nanoscale Thin Films and Membranes: A Combined Wrinkling-Cracking Methodology. *Nano Letters* **11**, 3361-3365 (2011).

8 Binnig, G., Quate, C. F. & Gerber, C. Atomic Force Microscope. *Physical Review Letters* **56**, 930-933 (1986).

9 Schiffman, S. S., Young, F. W. & Reynolds, M. L. *Introduction to multidimensional scaling: theory, methods, and applications* (Academic Press 1981).

10 Borg, I. & Groenen, P. *Modern multidimensional scaling: Theory and applications*. (Springer Verlag New York 1997).

11 Skedung, L. *et al.* Tactile perception: Finger friction, surface roughness and perceived coarseness. *Tribology International* **44**, 505-512 (2011).

12 Skedung, L. *et al.* Finger friction measurements on coated and uncoated printing papers. *Tribology Letters* **37**, 389-399 (2010).