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Humans Detect Spread Out Size Distribution on Coarse But Not Fine Dotted Surfaces

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Abstract. Surface topography is typically characterized by the mean size or spacing of surface elements, which are known to strongly influence tactile perception. In contrast, it remains unclear how variability around these mean properties, such as the surface element size, influences tactile perception. This study investigated whether differences in dot size variability can be discriminated when mean surface topography is held constant. Participants explored 3D-printed dotted surfaces with identical mean dot size but that differed in the variability of dot diameter. Two mean dot sizes (600 and 1200 µm) were tested, each with three levels of standard deviation in their Gaussian distribution (0%, 40%, 80%). Psychophysical results from a three-alternative forced-choice task revealed that participants reliably discriminated only high variability samples among non-variable ones when dots were large (mean size 1200 µm). Performance remained at chance level for smaller dots (mean size 600 µm). Discrimination was more accurate when one variable surface was presented among two uniform surfaces than in the opposite case. Force measurements showed subtle changes in tangential forces and dynamic friction with increasing variability, but these differences corresponded to Weber fractions below typical perceptual thresholds (10%). These findings demonstrate that tactile sensitivity to variability in dot size is limited to coarse surfaces with high variability, and confirm that mean surface geometry is more critical than small-scale element uniformity for haptic surface perception.

Keywords: surface perception · size variability · tactile discrimination

1 Introduction

When we explore a surface with the fingertips, tactile perception is shaped by its physical properties, such as its material and topography. These properties interact with exploration behaviour that includes the applied force, the scanning speed, and the direction of motion [11]. While surprisingly subtle differences in surface microgeometry can be detected by touch [13, 4], surfaces with marked differences in physical properties can sometimes be perceived as undistinguishable [2]. These observations suggest that tactile perception relies on a selective use of the mechanical information available during exploration.

In scientific studies, surface topography is commonly controlled through the mean size or spacing of surface elements [3, 1], which are known to be primary determinants of tactile surface perception. However, it remains unclear whether variability in elements size beyond the mean also influences tactile surface perception. By contrast, visual surface perception is known to rely strongly on fine variations in local features: observers can perceive synthetic visual surfaces as identical to natural ones when these fine variations are matched [9, 12].

Only a limited number of studies have investigated the role of within-surface variability in tactile surface perception. Ziat et al. [14] examined participants' ability to discriminate between organized and random dot patterns and found that participants were better at detecting increases in randomness than decreases in randomness relative to an intermediate reference level. Kuroki et al. [10] showed that discrimination performance was reduced when carved synthetic surfaces, obtained from pictures of natural surfaces, shared the same lower-order statistics (e.g mean height), suggesting a limited contribution of higher-order statistical features to tactile perception. These studies either used pictures that differed by several parameters or focused on variability in spatial arrangement rather than on feature size. Thus, it remains unclear whether variability in element size alone is perceived when mean surface topography is held constant, and whether the fine and coarse tactile processes suggested by the Duplex theory of touch [6] impact randomness perception.

This study investigated whether local variability in surface topography contributes to tactile discrimination when mean surface topography is held constant. Using dotted surfaces with identical mean dot size but following Gaussian distributions with different standard deviations, we tested whether increasing local variability of the particle size is perceived by humans in conditions of active touch. To that end, a three alternative force choice (3-AFC) or "odd-one-out" task was implemented to enable participants to rely on any useful difference and not only on perceived randomness. Two mean sizes were used, corresponding to relatively small and large surface features. By measuring the forces generated during exploration, we also investigated the relationship between elicited mechanical signals and perceptual differences.

2 Methods

2.1 Participants

Data were collected from eight volunteers (4 female, 4 male, aged 22 to 34). All participants were right-handed and reported no sensory or motor impairment affecting the right hand. The study was conducted in accordance with the Declaration of Helsinki and all participants gave informed consent prior to participation. The study was approved by the ethical committee of Sorbonne University.

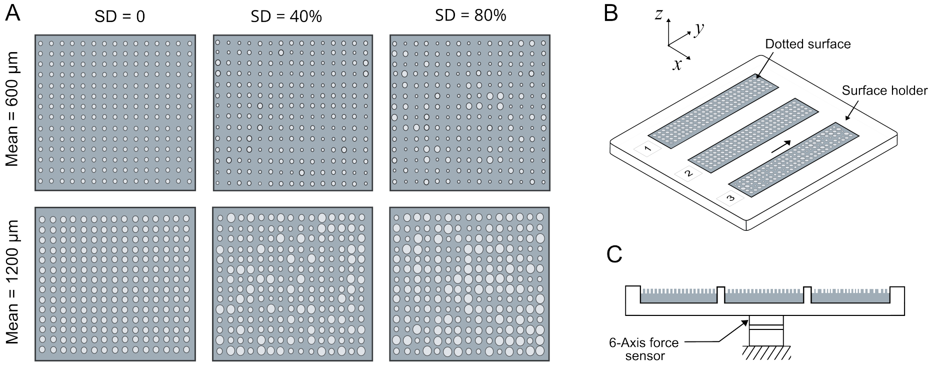

Fig. 1. (A) Sections of the surfaces' two-dimensional models (top view). Each row corresponds to a fixed mean dot diameter, while dot size variability (SD) increases across columns. (B) Experimental setup. The surfaces are mounted on a surface holder and explored sequentially by the participant. The arrow indicates exploration direction. (C) Mounting on a force and torque sensor (side view).

2.2 Stimuli

Stimuli consisted of resin samples (90 x 30 mm^2) with embossed dot patterns. All dots were 0.5 mm in height and arranged on a regular grid, with a constant center-to-center dot spacing of 2 mm across all samples. The only surface parameter that varied between stimuli was dot diameter, which was independently drawn from a truncated Gaussian distribution. Two mean diameters were tested: 600 µm for the first set and 1200 µm for the second set. Within each set, three levels of variability were created by varying the standard deviation of the distribution. The standard deviation was set to 0%, 40% or 80% of the mean, corresponding to uniform, medium and high variability in dot size across the surface. Truncation limits were defined individually for each mean diameter to maintain controlled mean size while avoiding extreme values, which would have compromised 3D printing. The choice of mean diameter was motivated by the range of feature sizes typically associated with spatial coding in tactile surface perception [6]. For the larger mean diameter (1200 µm), all surface elements can be encoded through spatial cues. For the smaller mean diameter set (600 µm), for medium and high variability (SD 40% - 80%) surface elements fall near the lower boundaries of spatial coding.

In total, six distinct surfaces were designed, corresponding to all combinations of the two mean dot diameters and the three levels of variability. The stimuli were generated and translated into printable 3D models using a finite element modelling software (ABAQUS, Dassault Systèmes). The models were printed using a stereolithography 3D printer (Formlabs Form 3+, Grey resin) (Fig.1.A).

2.3 Psychophysics

Participants performed a 3-AFC task. In each trial, three samples were presented: two identical and one that differed in dot diameter variability. The samples were mounted on a Plexiglass holder. Participants explored each sample using the index finger of their dominant hand, performing two left-to-right scanning motions consecutively on the three samples in predefined order. Then, they selected the sample they perceived as different. Visual information was occluded by placing a cardboard screen over the participant's wrist. Contact forces were recorded by a six-axis force sensor (Nano 17, ATI, Industrial Automation) positioned beneath the sample holder (Fig.1.B–C). Participants were instructed to maintain a normal force of 0.5 N during the exploration. Real-time visual feedback of the applied normal force was provided via a force gauge displayed on a screen positioned in front of the participant. Only surfaces from the same set, sharing the same mean dot diameter, were compared in each trial. The uniform surface was compared with each of the two variable surfaces (40% and 80% variability). Each combination was presented eight times in a randomized order. Eight additional catch trials comparing surfaces with different mean dot diameters (600 and 1200 µm, 80% variability) were included, resulting in a total of 72 trials per participant (2 mean diameters × 2 comparisons × 8 repetitions, plus 8 catch trials).

2.4 Mechanical characterization of the finger-surface interaction

Complementary force measurements were conducted to better characterize the finger-surface interaction. One participant (age 30) performed the recordings. The apparatus was identical to that used in the psychophysical experiment. During each trial, the participant explored a single surface positioned in the center of the apparatus using the index finger of the dominant hand. Real-time visual feedback of both the applied normal force (via aforce-gauge) and exploration velocity (via a slider) was provided on a screen to help maintain these parameters as constant as possible during sliding. Measurements were performed under two normal force conditions (0.5 and 1 N) and three exploration velocities (10, 20 and 50 mm/s) for each surface. Each combination was repeated ten times, for a total of 360 trials (2 mean diameters x 3 levels of diameter variability x 2 normal forces x 3 exploration velocities x 10 repetitions).

2.5 Data analysis

Psychophysics Performance of the participants was analysed separately for each set. For each participant and stimulus combination, performance was quantified as the proportion of correct selections across trials. All statistical tests were conducted with a significance level set at $\alpha = 0.05$.

Contact mechanics Force signals were digitised at 114 Hz by a 16-bit acquisition card (NI 6343, National Instruments) and low-pass filtered using a zero-lag Butterworth filter with a 40 Hz cut-off. The slipping phase was identified based on the tangential force, defined as $F_{\text{tangential}} = \sqrt{F_x^2 + F_y^2}$. A baseline period corresponding to the first 200 ms of each trial was used to estimate the noise level. The slipping phase was defined as the time period during which the tangential force exceeded five times the baseline standard deviation for at least 300 ms. The initial and final 10% of the detected slipping phase were discarded to remove transient effects associated with contact onset and release. The root mean square (RMS) of the tangential force was computed over the remaining steady slipping phase. The coefficient of dynamic friction (μ) was calculated as the ratio of the tangential force to the normal force during the steady slipping phase for each trial and then averaged within each condition.

3 Results

3.1 Discrimination performance

Performance was first evaluated relative to chance level using an exact binomial test (p=1/3), given the small number of participants. At the population level, for the 600 µm mean diameter set, none of the combinations differed significantly from chance level (Fig.2A). In contrast, for the 1200 µm mean diameter set, performance was significantly above chance level for combinations with medium and high variability (40–80 %), namely the [0,0,40] and [0,0,80] combinations ($p<$ 0.001; Fig.2B). A significant difference ($p<$0.001) was observed between conditions in which a variable surface was presented among two uniform surface (namely the [0,0,40] and [0,0,80] combinations) and conditions in which a uniform surface was presented among two variable surfaces ([0,40,40] and [0,80,80]) . All catch trials were performed correctly, indicating that participants understood the task and no systematic bias was present.

The effect of stimulus combination on the correct discrimination rate was also evaluated using a Friedman test. No significant effect was found for the 600 µm set. However, a significant effect emerged for the 1200 µm set (χ^2=9.411, p=0.024). Post-hoc pairwise comparisons revealed a significant difference between [0,40,40] and [0,0,80] (Wilcoxon test with Benjamini-Hochberg correction: p=0.04). The pair [0,40,40] and [0,0,80] showed a marginal difference (p=0.05). Overall, these results indicate that discrimination performance increased with diameter variability, but only for the larger mean diameter set. For the smaller set, participants were unable to reliably discriminate surfaces based on variability alone.

3.2 Impact on the root-mean-square of tangential force

The influence of diameter variability on the root mean square of the tangential force (RMS) was analysed separately for each normal force condition and each set. Data were merged across exploration speeds, as scanning velocity did not

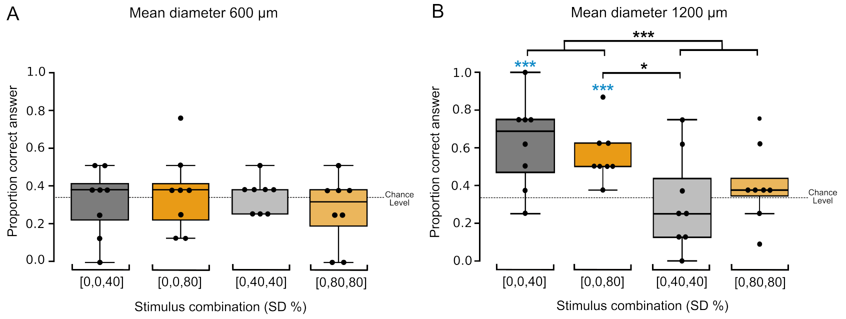

Fig. 2. Discrimination performance as a function of variability level and mean dot diameter size. Box plots showing the proportion of correct answers for both sets of surfaces: (A) 600 µm (B) 1200 µm. Boxplots represent median, 25th and 75th quartiles. Triplets indicate the variability levels of the three samples presented in each trial. Blue asterisks indicate significant differences from chance level and brackets with asterisks indicate significant pairwise comparisons (*$p<0.05$, **$p<0.01$, ***$p<0.001$)

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lead to significant differences in RMS. At 0.5 N, RMS increased with variability for both sets: for the 600 µm mean diameter set, RMS was significantly higher for the medium (40% SD) and high (80%) variability surfaces compared to the uniform surface (Mann-Whitney test with Holm-Bonferroni correction: p=0.002 and p=0.02 respectively) and for the 1200 µm set, RMS for the medium and high variability surfaces was higher than the uniform surface ($p<0.001$ and p=0.001) with a smaller difference between the two non-uniform surfaces (p=0.048) (Fig.3.A). At 1 N, RMS differences were reduced: no significant effect of diameter variability on the RMS were detected for the 600 µm set, and only the comparison between medium and high variability surfaces reached significance for the 1200 µm set (p=0.008) (Fig.3.B).

These results indicate that higher variability in dot diameter slightly increased the tangential force RMS at low normal force for both coarse and fine samples.

3.3 Impact on the coefficient of dynamic friction

The influence of diameter variability on the coefficient of dynamic friction (μ) was analysed separately for each normal force condition and each set. Data were merged across exploration speeds, as scanning velocity did not lead to significant differences in RMS. At 0.5 N, diameter variability had no significant effect on μ for the 600 µm set. In contrast, for the 1200 µm dot set, μ increased with variability: the high variability surface differed significantly from both to medium-variability and uniform surface, and the two variable surfaces also differed significantly (Mann-Whitney test with Holm-Bonferroni correction: all $p<0.001$; Fig.4.A). At 1.0 N, no effect of variability was observed for the 600 µm dot set, only a difference between the two non-uniform surfaces was found

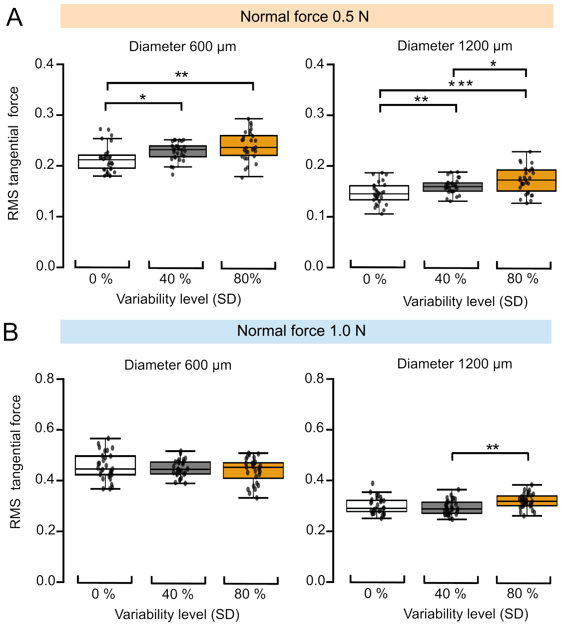

Fig. 3. Root mean square (RMS) of tangential force as a function of variability level for each set for a normal force of 0.5 N (A) and 1.0 N (B). Data are merged across scanning velocities. Boxplots represent median, 25th and 75th quartile. Asterisks indicate significant pairwise differences (*p<0.05, **p<0.01, ***p<0.001)

for the 1200 µm dot set (Mann-Whitney test with Holm-Bonferroni correction: p=0.003; Fig.4.B). For the conditions showing a significant effect of variability (1200 µm at 0.5 N), the magnitude of these mechanically significant differences was quantified by computing relative changes in μ, which were 3.3% (0-40%), 5.4% (0-80%) and 9.0% (40-80%).

These results indicate that the effect of diameter variability on friction occurs only for surfaces with large dots and mostly when low normal force is used.

4 Discussion

This study investigated whether variability in surface feature size can be discriminated when mean surface topography is held constant. Our results indicate that tactile discrimination of elements size variability depends on the scale of the surface elements. Participants were able to distinguish distinct standard deviation in the Gaussian distribution of dot sizes only when the mean dot size was large (1200 µm), and for one variable surface (40% or 80%) among two uniform ones (0%), while performance for the smaller dot set (600 µm) remained at chance level. This size-dependent effect suggests that such local variability can become accessible to touch when surface elements are large enough to be processed using

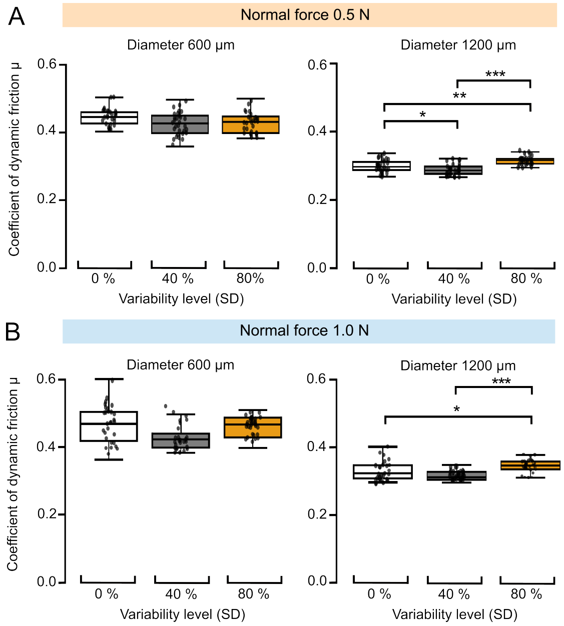

Fig. 4. Coefficient of friction (μ) as a function of variability level for the two sets at normal forces of 0.5 N (A) and 1.0 N (B). Data are merged across scanning velocities. Boxplots represent the median, 25th and 75th quartile. Asterisks indicate significant pairwise differences ($*p<0.05$,$**p<0.01$,$***p<0.001$)

spatial cues. The smaller dot set is closer to fine texture than to coarse ones, but may rely on a combination of spatial and temporal cues [7, 6] since fully fine surfaces could not be tested because smaller dots would have been too fragile to print reliably.

Our findings suggest that tactile perception is shaped by the average size of the surface elements and by the variability in size elements, only when the feature size is large and the variability is pronounced. This interpretation is consistent with the work of Kuroki et al. [10] who highlighted the importance of salient local features for tactile discrimination. Unlike in [10], the coarse textures used in this study could be discriminated, probably due to the higher complexity of the visual patterns translated to carved tactile surfaces used in their task. Our results also confirm that higher randomness is more easily spotted than uniformity [14]. Overall, sensitivity to variability in dot size appears limited in tactile perception compared to visual perception [9], illustrating core differences between the underlying neural mechanisms of vision and touch.

Complementary force measurements were conducted on a participant to test whether clear differences in contact force and friction could be observed between the different surfaces. While the root-mean-square of tangential forces did not show a specific pattern for coarse dotted surfaces, differences in the coefficient of dynamic friction specific to coarse dotted surfaces were observed, especially when low normal force was applied. However, the corresponding Weber fractions were between 3.3% and 9.0%, below typical thresholds of around 10% [5]. Although the mechanical interaction between finger and surface varied with size variability, these changes appear generally too subtle to influence discrimination, highlighting the complex interplay between mechanical changes and perceptual differences [8].

To better understand the mechanical mechanisms underlying perception, future experiments will need to record contact forces during the psychophysical task to relate mechanical differences in successful or unsuccessful trials to participants' decisions. The measurements could be complemented by accelerometer data to capture high-frequency vibrations generated during fingertip-dot interactions. More broadly, these findings contribute to the design of haptic surfaces by suggesting that precise control of mean surface geometry may be more important than uniformity of the individual elements.

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Disclosure of Interests. The authors have no competing interests to declare.

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