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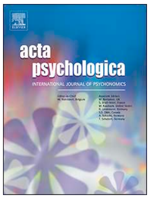

Tactile aesthetics: Textures that we like or hate to touch

Jenny Faucheu[a,*], Benjamin Weiland[b], Mihaela Juganaru-Mathieu[c], Arnaud Witt[d], Pierre-Henri Cornuault[b]

[a] *Mines Saint-Etienne, Univ. Lyon, CNRS, UMR 5307 LGF, Centre SMS, F-42023 Saint-Etienne, France*
[b] *Femto-ST Institute, Department of Applied Mechanics, Univ. Bourgogne Franche-Comté, 24, Chemin de l'Epitaphe, 25000 Besançon, France*
[c] *Mines Saint-Etienne, Institut Henri Fayol, Departement ISI, F - 42023 Saint-Etienne France*
[d] *Laboratory for Research on Learning and Developement, LEAD-CNRS UMR-5022, Univ. Bourgogne Franche-Comté, Dijon, France*

ABSTRACT

Considering object identification and recognition as well as human interaction with objects, texture as a surface property plays a crucial role. A deeper understanding of tactile aesthetics can be useful in the applied field such as in product designs that appeal more to our senses and that are more effective in eliciting certain emotional responses from a potential consumer. In the present study, behavioral experiments were performed using unfamiliar custom-made dot pattern stimuli under two complementary questionings. The first question focused on the tactile perceptive attributes related to topographical characteristics of the textures exhibited by the material surfaces. The second question focused on the texture pleasantness related both to the perceptive attributes and to the topographical characteristics of the textures. The perspective of this work opens on complementary fields of research such as neurosciences to determine the brain mechanisms in the processing of the pleasantness of tactile stimuli.

1. Introduction

In product design, textures can be applied on materials to impact - hopefully positively - the perceptive value of manufactured products. Textures also play a crucial role in object identification (Lacey, Hall, & Sathian, 2010; Lacey & Sathian, 2014). While textures can be perceived visually and haptically, the haptic sense appears to be dominant in perceiving material properties such as textures (Klatzky, Lederman, & Reed, 1987). Multidimensional scaling was used to investigate tactile textures space in terms of perceptual dimensions (Hollins, Faldowski, Rao, & Young, 1993; Yoshida, 1968; Picard, Dacremont, Valentin, & Giboreau, 2003; Ballesteros, Reales, De Leon, & Garcia, 2005), various studied concluded that the smooth–rough and soft–hard scales appear as the basic dimensions of tactile texture perception. Besides, the warm–cold and sticky–slippery scales are other perceptive scale but are often considered as not independent of those for roughness and hardness (Hollins et al., 1993).

At the level of sensory neurons, perception is collected by mechanoreceptors either by sensing pressure or by sensing vibration: the first mechanism is typical of large spaced surface textures, while the second is necessary to perceive finer textures. These different behaviors are well known in the literature as the duplex perception mechanism (Bensmaïa & Hollins, 2005; Fagiani & Barbieri, 2016; Hollins & Risner, 2000; Katz, 1989). Below 100 µm, haptic roughness perception is mainly mediated by a channel sensitive to vibratory information. The interaction between the finger skin and the surface roughness produces a vibration that propagates into the skin causing a space time variation of the skin stress state that induces the response of the mechanoreceptors. Above 100 µm, spatial mechanisms are progressively engaged and gradually become the dominant contributors to texture perception. The switch between spatial and vibrotactile mechanisms in texture perception depends on the geometrical characteristics of the texture. Using gratings with grooves as small as 175 µm, Lederman (1974) found that roughness was independent of movement speed, a result that appears more compatible with spatial coding than with vibrotactile coding. Under conditions of static touch, gratings can be discriminated only if they have ridges or grooves of at least 500 µm wide (Johnson & Phillips, 1981). This means that depending on geometrical arrangement of the texture, the spatial properties of stimulus elements between 100 and 500 µm can contribute to textural judgments.

Among texture parameters, a wide range of studies is dedicated to the roughness/smoothness perception. A review by Bergmann Tiest (2010) concluded that tactual roughness perception is associated with physical surface properties such as height difference, friction, spatial period and dot spacing. More specifically, studies on physical factors influencing pleasant touch have shown a relationship between friction, roughness and pleasantness (Essick et al., 2010; Guest et al., 2011). In particular, pleasant stimuli are those that feel smooth, i.e. not rough (Ekman, Hosman, & Lindstrom, 1965; Etzi, Spence, & Gallace, 2014;

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* Corresponding author.
E-mail address: jenny.faucheu@emse.fr (J. Faucheu).

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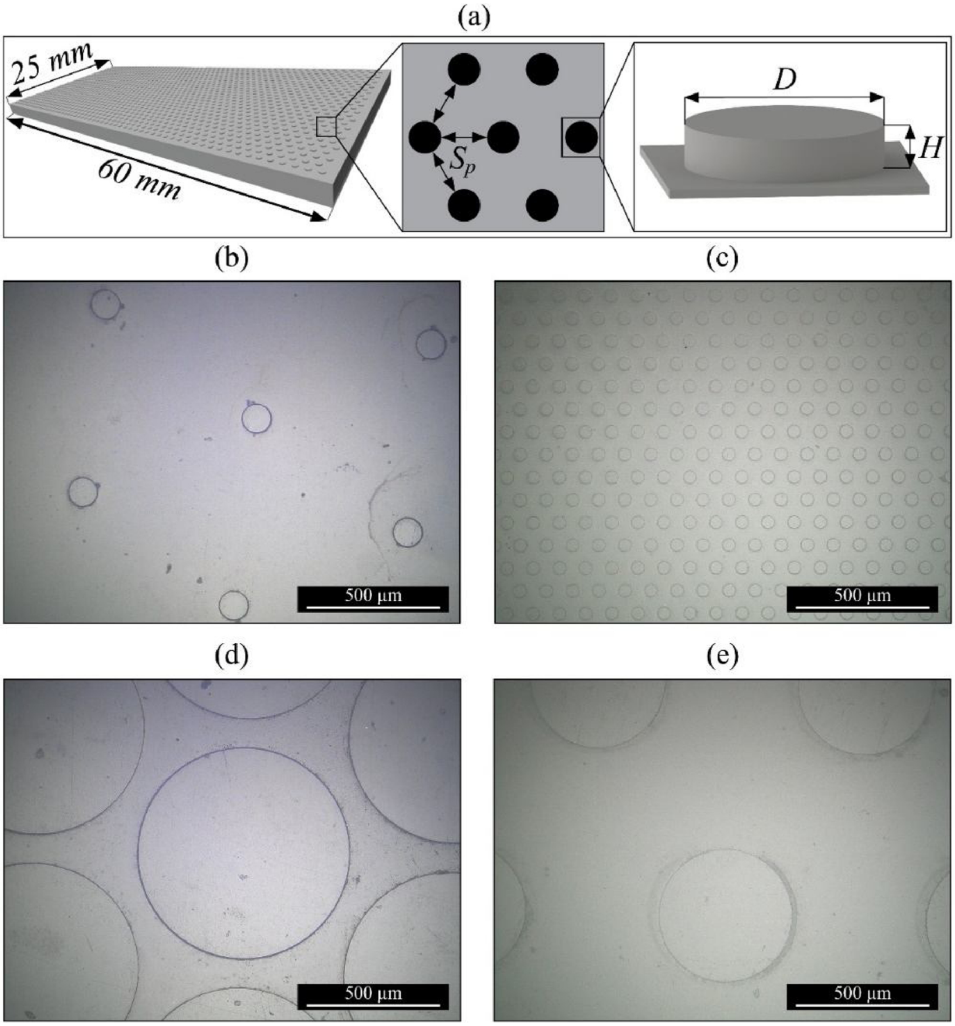

Fig. 1. Geometrical description of the PU textured sursfaces (a) with cylindrical dots in hexagonal array, and typical examples of textures observed in microscopy using the same magnification and showing the diversity of geometrical features: D = 106 µm, H = 18 µm, Sp = 610 µm (b); D = 46 µm, H = 22 µm, Sp = 54 µm (c); D = 797 µm, H = 29 µm, Sp = 116 µm (d); D = 507 µm, H = 18 µm, Sp = 510 µm (e).

Kitada, Sadato, & Lederman, 2012; Verrillo, Bolanowski, & McGlone, 1999). Unpleasant surfaces elicit high friction when a fingertip is actively slipped on them (Klöcker, Wiertlewski, Théate, Hayward, & Thonnard, 2013). Note that pleasantness of textures can be differently perceived in multisensory contexts (Francis et al., 1999; Soranzo, Petrelli, Ciolfi, & Reidy, 2018) or when associated to a tactile identification task (Jehoel, Mccallum, Rowell, & Ungar, 2006). A deeper understanding of tactile aesthetics are certainly not only of theoretical relevance but also extremely useful in the applied field. For instance, information concerning tactile preferences could help designers and engineers to create more appealing objects and materials. Understanding the mechanisms of tactile aesthetics might also be of great use in therapeutic function as well as for helping visually-impaired and sighted individuals, to improve their experience using tactile maps (Gallace & Spence, 2014; Spence, 2008; Spence & Gallace, 2008).

In studies on tactile perception, sourcing or building the appropriate stimuli to be used within an experimental setting is a practical difficulty. Some studies have used everyday textures while others have built custom-made samples. Both natural familiar textures, like fabrics, wood, foams and glass (Bergmann et al., 2006; Yoshioka et al., 2007) and unfamiliar textures like linear gratings (Cascio & Sathian, 2001; Lawrence et al., 2007) and dot pattern stimuli (Dépeault, Meftah, & Chapman, 2009; Kahrimanovic, Bergmann Tiest, & Kappers, 2009) have been used. Zuo pointed out the difference between (physical) texture and perceived texture. The physical texture accounts for both the geometrical configuration of the spatial constructive elements on the object (shape, size, orientation and distribution) and the substance attributes such as mechanical, thermal, optical characteristics. The perceived texture refers to a synthesis of physiological and psychological response to the geometrical configuration and substance attributes of the object (Zuo, Hope, Castle, & Jones, 2001).

In the present study, to ensure that pre-existing differences among participants in the haptic experience with the stimulus material were negligible (Eck et al., 2013), unfamiliar custom-made stimuli based on dot patterns were fabricated. Moreover, custom-made dot patterns have the advantage that one dimension can be varied parametrically while keeping all other dimensions constant. Finally, the dot pattern was rather isotropic so that the percept is independent of the haptic exploration direction. In previous studies, increasing dot diameter resulted in a decreased haptic roughness percept (Blake, Hsiao, & Johnson, 1997; Connor, Hsiao, Phillips, & Johnson, 1990), whereas dot height influenced perceived roughness only for dot patterns with rather small dot diameters (e.g. 0.25–1.60 mm) (Blake et al., 1997). (Ir)regularity of the pattern (Dépeault et al., 2009) as well as scanning speed of the textures (Meftah, Belingard, & Chapman, 2000) did not affect roughness perception with the bare finger. The main factor contributing to roughness perception of these dot patterns appeared to be the mean inter-dot spacing of the textures, with an increased roughness percept for increasing inter-dot spacing (Connor et al., 1990; Dépeault et al., 2009; Gescheider, Bolanowski, Greenfield, & Brunette, 2005; Lederman, Thorne, & Jones, 1986; Meftah et al., 2000; Merabet et al., 2004, 2007). Using behavioral experiments, the aim of this study is to relate the tactile perceptive attributes of textures surfaces to their topographical characteristics (Experiments 1 and 2) and to relate the tactile perceptive attributes to the hedonic judgement (Experiment 3). At the end, insights on the relationships between topographical characteristics of textures and their hedonic judgements are gathered.

2. Experimental procedures

2.1. Description of the stimuli: textured samples

A set of 51 textured and deterministic surfaces in polyurethane resin (PU) were custom-made through a multi-step process. The final textured PU samples have dimensions of 60 x 26 mm^2 and a thickness of 2.9 mm. For all samples, the texture is defined by a flat surface exhibiting a pattern of identical cylindrical dots that are regularly arranged in a hexagonal array. Each texture is defined by the dot diameter D (from 8 to 905 µm) and height H (from 4 to 73 µm), spaced apart by an inter-dot spacing S_p (from 12 to 915 µm) equal along the three main directions of the hexagonal network. Fig. 1 shows an example of surface observed in optical microscopy and the geometric parameters D, H, and S_p defining its texture.

The textured PU samples are manufactured from molding in a silicone mold made from stamping on a silicon stamp. This silicon stamp is made by photolithography and plasma etching in a clean room. This method alternates plasma etching and deposition of a passivation layer to ensure the quality of the vertical side of the cylindrical dots. The silicone (Bluesil RTV 3428) mold is made from that silicon stamp followed by the molding of the PU resin (Rencast FC52) in the silicone mold that finally produces the textured PU sample that are cut using laser cutting to achieve the expected geometric dimensions.

2.2. Experiment 1

In experiment 1, the aim is to relate the tactile perceptive attributes of textures surfaces to their topographical characteristics (D, H, and S_p). To do so, participants are asked to group surfaces that have the same texture to form one or more families of textures where the surfaces differ only in the intensity of this texture. Once the families are formed, the participants are asked to name each family of textures and the relationships between the topographical characteristics and the perceptive attributes are analyzed.

2.2.1. Methods

20 individuals (7 women and 13 men) with an average age of 26.3 ± 1.6 years participated in this experiment. Each participant was asked to clean hands with a hydro-alcoholic gel at the beginning of the experiment. All 51 PU samples, previously cleaned with soap and water, were placed on the table and were hidden under a tablecloth. The participant wore translucent glasses that enabled the participant to manipulate the samples without being able to distinguish the different textures. The inability to visually distinguish the textures with these glasses was confirmed before the experiments on a panel of 5 individuals of the same age of the participants. The participant also wore hearing protection. To begin with, the experimenter explains the experience to the participant by using the following procedure translated from French:

> "*TodayI'm going to ask you to work on about fifty rectangular surfaces such as this one [show a surface]. With the hand that you use to write, you will rub on the surfaces like this holding them between the thumb and forefinger of your other hand. It is not necessary to press excessively on the surfaces. Your goal will be to group surfaces that have the same texture to form one or more families of textures where the surfaces differ only in the intensity of this texture. For example if I asked you to do this exercise with colors, you could get a blue family and a red family with colors ranging from light red to dark red. Once the families are formed, I will ask you to name the texture that you have perceived. Did you understand? I will now ask you to put on these glasses and this helmet so that you focus only on the feeling of touch. It is not very pleasant at first but the inconvenience disappears quickly. Take as much time as you need, you can touch the surfaces as many times as you need.*"

2.2.2. Results and discussion

During experiment 1, each participant created groups of samples according to the tactile perception. At the end of the assignments, the participant provided one or more descriptors for each group that she/he created. In order to visualize the mean perception from all 20 participants, a statistical analysis was performed. In Hierarchical Agglomerative Clustering (HAC) was used (Rokach, 2010), distances between samples and between clusters of samples are defined based on the number of subjects that have classified each sample in the same category. This method helps visualizing distances between samples by applying a stepwise algorithm that merges two groups of samples at each step, the two that are the closest in distance. The final result is a tree or dendogram that visualizes the steps of the merging into clusters from individual objects to one unique cluster containing all samples (Fig. 2).

The HAC method has been run following the Ward's minimum variance method. This resulted in a clustering solution depicted in Fig. 2, with a total within-cluster variance of 34.29% (and a between-clusters variance of 65.71%). The dotted line fixed at a normalized distance between clusters is drawn to split the tree into three groups ($N_{1(\text{vibrating})} = 29$, $N_{2(\text{rough})} = 14$, $N_{3(\text{slippery})} = 8$). In order to verify the cluster tree and to assess that the distances in the tree reflect the original distances between the 51 initial items, we computed the cophenetic correlation. This correlation coefficient reflects the quality of clustering so that the closer the value of the cophenetic correlation is to 1, the more accurately the clustering reflects the data. For the clustering performed in our experiment, the cophenetic correlation was 0.856. Note that a cophenetic correlation above 0.75 is generally considered as very good.

The resulting tree from experiment 1 clearly shows that the 51 samples merge into 3 distinct clusters. A first cluster counts 14 samples and is qualified as *ROUGH* (translated from French "rugueux"). A second cluster counts 8 samples and is qualified as *SLIPPERY* (translated from French "glissant"). A third cluster counts 29 samples and is qualified as *VIBRATING* (translated from French "vibrant").

Hereafter, *in this article*, the samples are named according to the category they belong: samples R1 to R14 for *ROUGH* samples, S1 to S8

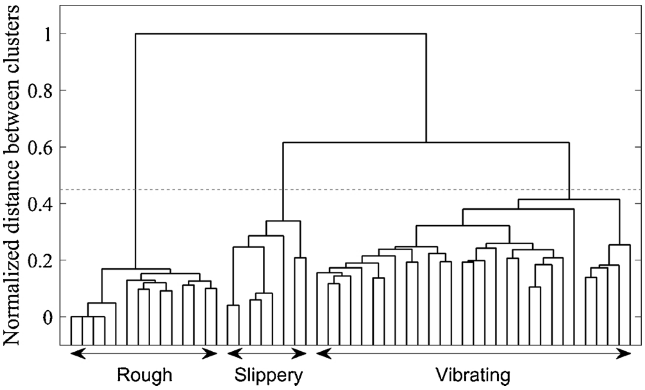

Fig. 2. Hierarchical Agglomerative Clustering from experiment 1 – texture perception. The dotted line fixed at a normalized distance between clusters of 0.45 is drawn to split the tree into three groups.

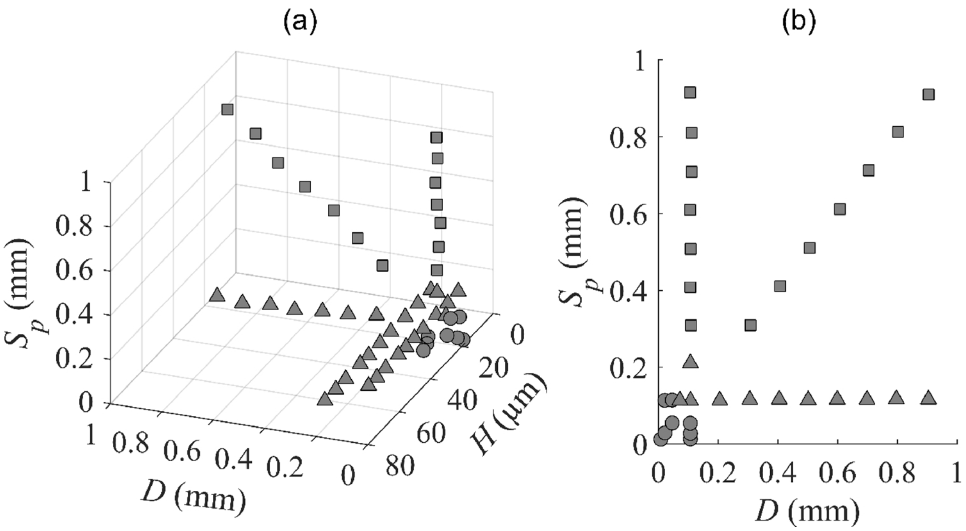

Fig. 3. Perceived textures as a function of their geometrical features (a) for ROUGH samples (squares), VIBRATING samples (triangles), and SLIPPERY samples (circles). Samples exhibiting dots with H = 21 ± 2 μm are plotted in (b).

for *SLIPPERY* samples and V1 to V29 for *VIBRATING* samples.

Fig. 3 shows the relationship between the geometrical characteristics of the textured surfaces and the perceived texture. The parameters D and S_p seem to have a more direct influence on the perceptive categorization than the parameter H. First, it has been noticed that all the samples qualified as *VIBRATING* exhibit an inter-dot spacing S_p equal to 110 μm. Moreover, for diameters D smaller than 100 μm, the samples are qualified *SLIPPERY*. When D increases, the samples become qualified as *VIBRATING*. For inter-dot spacings S_p smaller than 100 μm, the samples are qualified as *SLIPPERY* and when S_p increases, the samples become qualified as *ROUGH*. When both S_p and D increase, the samples become qualified as *ROUGH*.

2.3. Experiment 2 – participants & procedure

In experiment 2, the aim is to further relate the tactile perceptive attributes of textures surfaces to their topographical characteristics. Within each family of textures identified in Experiment 1, the sensation intensity is evaluated. Then the sensation intensity is compared to the topographical characteristics.

2.3.1. Methods

In the psychophysical model (Laming, 1986) for sensation intensity, the idea is simply that an increase in the energy of the physical stimulus should result in an increase in how strong something feels. In experiment 2, the aim is to collect the sensation intensity within each sample categories (*ROUGH*, *SLIPPERY* and *VIBRATING*). 25 individuals (9 women and 17 men) with an average age of 26.9 ± 2.3 years participated in experiment 2. Each participant was asked to clean their hands with a hydroalcoholic gel at the beginning of the experiment and the participant wore translucent glasses that enabled the participant to manipulate the samples without being able to distinguish the different textures. The participant also wore hearing protections. To prevent tiredness, all samples were not evaluated the same day. On a first day, *ROUGH* and *SLIPPERY* samples were evaluated in two separate sequences (22 samples) and a few days later, the *VIBRATING* samples were evaluated in one sequence (29 samples). At the beginning of a sequence, two samples from a given category with clear a sensory intensity difference were proposed to the participant so that he/she can familiarize with the stimulus that he/she will be asked to evaluate. Then, 3 successive trials of samples' evaluation were carried out for each participant. Within a trial, each sample was presented 2 times in a pseudo-random order (different for each trial and each participant). As a result, each participant evaluated 6 times each sample and was asked to evaluate the sensation intensity giving a value between 0 (lowest) and 20 (highest). Finally, within a stimuli category, the arithmetic mean of the 150 evaluations given for each sample (6 evaluations for each of the 25 participants) was calculated to define the sensation intensity (J_R for the *ROUGH* category, J_S for the *SLIPPERY* category and J_V for the *VIBRATING* category).

2.3.2. Results and discussion

Fig. 4 shows that the intensity evaluations (J_R, J_S and J_V) of the 3 samples categories are satisfactorily distributed over the 0–20 scale. Moreover, they exhibit similar ranges: between 7.3 and 13.3 for *ROUGH* samples, between 7.5 and 15.4 for *SLIPPERY* samples, and between 4.6 and 15.2 for *VIBRATING* samples.

Fig. 4 shows that the intensity evaluations (J_R, J_S and J_V) of the 3 samples categories are satisfactorily distributed over the 0–20 scale. Moreover, they exhibit similar ranges: between 7.3 and 13.3 for *ROUGH* samples, between 7.5 and 15.4 for *SLIPPERY* samples, and between 4.6 and 15.2 for *VIBRATING* samples.

Table 1 gathers the topographical features, stimuli category and sensation intensity for all samples. It appears that the *SLIPPERY* samples exhibit small D-features combined with small S_p-features. On the other hand, *ROUGH* samples exhibit large D-features combined with large S_p-features. *VIBRATING* samples seems to lie between with medium to large D-features and medium S_p-features.

Considering the sensation intensity for *SLIPPERY* stimuli, the results show that J_s is related to the D-features in that when D increases J_s decreases. In addition, it seems that for a given D-value, J_s also

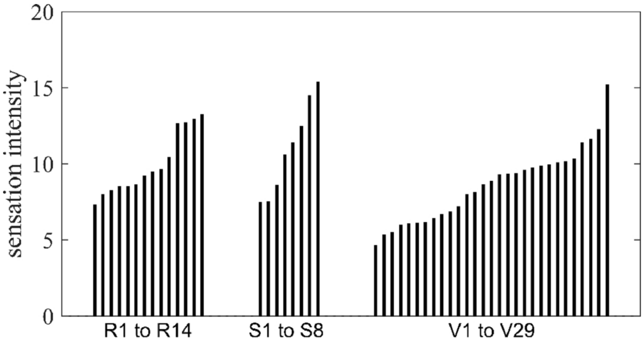

Fig. 4. Sensation intensity obtained for the 3 stimuli categories.

Table 1
Topographical features, stimuli category and sensation intensity of the textured samples.

category	Ref.	H (μm)	D (μm)	S_P (μm)	marker	J_S, J_R or J_V
SLIPPERY	*S1*	21 ± 3	8	12	●	15.4
	S2	21 ± 3	22	28	●	14.5
	S3	21 ± 3	22	113	●	12.5
	S4	21 ± 3	46	54	●	11.4
	S5	21 ± 3	46	114	●	10.6
	S6	21 ± 3	107	13	●	8.6
	S7	21 ± 3	107	27	●	7.5
	S8	21 ± 3	107	53	●	7.5

category	Ref.	H (μm)	D (μm)	S_P (μm)	marker	J_S, J_R or J_V
VIBRATING	*V1*	24 ± 4	72	114 ± 1	△	5.5
	V2	24 ± 4	107	114 ± 1	△ ▷	6.1
	V3	24 ± 4	206	114 ± 1	△ ▶	8.6
	V4	24 ± 4	306	114 ± 1	△	11.6
	V5	24 ± 4	405	114 ± 1	△	12.3
	V6	24 ± 4	502	114 ± 1	△	11.4
	V7	24 ± 4	599	114 ± 1	△	9.6
	V8	24 ± 4	699	114 ± 1	△	9.9
	V9	24 ± 4	797	114 ± 1	△	10.1
	V10	24 ± 4	904	114 ± 1	△	9.3
	V11	24 ± 4	107	210	△	15.2
	V12	4	108 ± 1	111 ± 1	▷	4.6
	V13	11	108 ± 1	111 ± 1	▷	6.0
	V14	27	108 ± 1	111 ± 1	▷	6.1
	V15	33	108 ± 1	111 ± 1	▷	5.3
	V16	38	108 ± 1	111 ± 1	▷	6.8
	V17	43	108 ± 1	111 ± 1	▷	7.2
	V18	51	108 ± 1	111 ± 1	▷	6.1
	V19	57	108 ± 1	111 ± 1	▷	6.4
	V20	62	108 ± 1	111 ± 1	▷	6.7
	V21	5	207 ± 1	111 ± 2	▶	8.0
	V22	14	207 ± 1	111 ± 2	▶	10.0
	V23	31	207 ± 1	111 ± 2	▶	8.9
	V24	38	207 ± 1	111 ± 2	▶	8.1
	V25	46	207 ± 1	111 ± 2	▶	9.4
	V26	51	207 ± 1	111 ± 2	▶	9.3
	V27	60	207 ± 1	111 ± 2	▶	10.3
	V28	67	207 ± 1	111 ± 2	▶	9.8
	V29	73	207 ± 1	111 ± 2	▶	9.7

category	Ref.	H (μm)	D (μm)	S_P (μm)	marker	J_S, J_R or J_V
ROUGH	*R1*	19 ± 1	108 ± 2	309	□	8.5
	R2	19 ± 1	108 ± 2	408	□	9.5
	R3	19 ± 1	108 ± 2	508	□	8.6
	R4	19 ± 1	108 ± 2	610	□	8.5
	R5	19 ± 1	108 ± 2	709	□	8.0
	R6	19 ± 1	108 ± 2	810	□	7.3
	R7	19 ± 1	108 ± 2	915	□	8.3
	R8	19 ± 1	308	309	■	9.2
	R9	19 ± 1	408	411	■	9.6
	R10	19 ± 1	507	510	■	10.4
	R11	19 ± 1	608	611	■	12.7
	R12	19 ± 1	704	712	■	12.7
	R13	19 ± 1	802	812	■	13.0
	R14	19 ± 1	905	909	■	13.3

decreases when S_p increases.

To go deeper in the understanding of the influence of topographical features on stimuli perception, the sensation intensity is compared to the sample topographical features. To examine the relationship between the topographical features (D, H, S_p) and the tactile perception level (*intensity*), we computed correlations and ran multiple regression analyses (Table 2)for the three categories of tactile stimuli (*SLIPPERY*, *ROUGH*, and *VIBRATING*).

First, the *SLIPPERY* stimuli is considered. As the *SLIPPERY* samples exhibit a narrow range of heights H, between 18 and 27 μm (Fig. 3), this topographical parameter has not been considered. Fig. 5 shows that the *SLIPPERY intensity* does not depend on S_P but clearly depends on Dfollowing a linear trend. Pearson correlations revealed that there were significant correlations between H and *Intensity* ($r = -.85$; $p < .01$) and between D and *Intensity* ($r = -.95$; $p < .001$). Hierarchical regression analysis showed that D predicted 90% of the variance of *intensity* perception alone and that S_p predicted 8% of the variance after controlling for D, while H did not account for variance after controlling D and S_p.

Few studies examined the influence of the size or the spatial distribution of texture patterns on the intensity of perceived slipperiness. Arvidsson, Ringstad, Skedung, Duvefelt, and Rutland (2017) studied the slippery sensation provided by surfaces presenting ridges with spatial period (corresponding to $S_p + D$ in the herein study) ranging from 30 to 130 μm. A decrease of the perceived slipperiness when the spatial period increases was observed. However, the width and the spacing of such patterns were not independently controlled, making it impossible to know whether one of these two parameters played a major role on the sensation intensity. In other studies (Li, Yu, & Zhang, 2011; Li, Zhan, Yu, Zhang, & Zhou, 2015; Yu and Li, 2015; Zhang et al., 2017) conducted on surfaces of different roughness, a decrease in the slippery sensation intensity was observed when surface roughness increased. Considering that a higher roughness corresponds to larger topographic patterns, these results are consistent with the decrease observed in Fig. 5(a).

Fig. 6 shows the influence of diameter D and height H on the sensation intensity for *VIBRATING* stimuli. In this case, as seen in Fig. 3, all the samples qualified as *VIBRATING* exhibit an inter-dot spacing S_p equal to 110 μm, except *V11* which exhibits S_p equal to 210 μm and appears in a round dotted box in Fig. 6. Interestingly, samples *V11* ($J_V = 15.2$ with $S_p = 210$ μm) and *V2* ($J_V = 6.1$ with $S_p = 112$ μm) show very different intensities while they exhibit exactly the same H (19 μm) and D (107 μm) values. This observation highlights the huge effect of S_p in the *VIBRATING* sensation intensity although *VIBRATING* surfaces remains limited in S_p ranging from 50 to 250 μm approximately (see Fig. 3). All other surfaces (for which S_p is close to 110 μm) are then considered in the following. Fig. 6b shows that the *VIBRATING* intensity is not clearly related to the height H. In contrast, Fig. 6a exhibits a non-monotonic behavior. For diameter D below 400 μm, the *VIBRATING* intensity increases while for diameter D above 400 μm the VIBRATING intensity slightly decreases. Notwithstanding, it is observed that this decrease versus D is low.

Analyses revealed two significant correlations between D and *Intensity* ($r = .43$; $p < .05$) and between $S_p$and *Intensity* ($r = .57$, $p < .01$). Regression analysis confirmed that S_p explained the main part of the variance (30%) and that D added 19% to the variance after controlling for S_p. After controlling for S_p and D, H added 3% to the variance, which is not significant.

Assuming that inter-dot spaces play the role of grooves interspersed between the dots, this result is consistent with Cesini et al. (2018). They studied textured samples exhibiting periodic parallel linear grooves with spatial periods ranging from 100 μm to 1050 μm using a tribo-tactile device that collects the vibrations induced by the contact between the fingertip dermatoglyphs (spatial period around 400 μm) and the sample surface. It was demonstrated that the final excitation frequency is a function of the combination of the fingertip and surface sample textures leading to the fact that textures with spatial periods below 350 μm were well discriminated contrary to textures with spatial period above 350 μm. The results were consistent with the duplex theory (Bensmaïa & Hollins, 2005; Hollins & Risner, 2000) reporting that tactile texture perception is mediated by vibrational cues for fine textures, which help the texture discrimination and by spatial cues for coarse textures.

Fig. 7 shows the influence of inter-dot spacing S_p on the sensation intensity for *ROUGH* stimuli. As seen in Fig. 3, these samples are organized into 2 sets. A first set of samples exhibit a constant diameter D

Table 2

Hierarchical regression analyses predicting intensity perception from topographical features (D, H, S_p).

Step	SLIPPERY			VIBRATING			Rough		
	Variable	R^2	R^2 modified	Variable	R^2	R^2 modified	Variable	R^2	R^2 modified
Step 1	D	.90	.90***	S_p	.30	.30**	D	.88	.88***
Step 2	S_p	.98	.08***	D	.49	.19***	H	/	/
Step 3	H	/	/	H	.52	.03	S_p	/	/

** $p < .01$.

*** $< .001$.

with different inter-dot spacings S_p (white squares in Fig. 7). For the second set of samples (black squares in Fig. 7), when the diameter D changes, the inter-dot spacing S_p also changes according to the $S_p = D$ relationship. Note that both D and S_p exhibit values above 200 µm. Thus, the textures exhibited by these samples are rather coarse and so, based on the duplex theory, the texture perception is likely to be mediated by spatial cues. Obviously, results highlight that *ROUGH* intensity is independent of S_p but linearly increases with D when S_p keep constant.

Analyses of *ROUGH* stimuli reported two significant correlations between H and Intensity ($r = .73$; $p < .01$) and between D and intensity ($r = .94$; $p < .001$). Regression analysis confirmed that D alone accounted for 88% of the variance, which is significant, while the two other parameters did not account for any % to the variance after controlling for D.

The results obtained for the second set of samples (S_p and D vary together) are consistent with the studies of Hollins and Risner (2000) and Ramananantoandro, Larricq, and Eterradossi (2014) conducted on sandpapers with asperities size below 300 µm. However, the increase of the perceived roughness with D and S_p does not agree with the works carried out by Cascio and Sathian (2001), Sathian, Goodwin, John, and Darian-Smith (1989) and Lawrence et al. (2007) for surfaces exhibiting wrinkles. For inter-wrinkle ranging from 0.1 to 2 mm, the two first studies showed that perceived roughness decreases when wrinkle width increases. The third study concludes in a negligible impact of inter-wrinkle dimension on roughness perception. In the case of the first set of surfaces (constant D and variable S_p), the observed independence of perceived roughness versus S_p is contradictory with the results of the three previous studies which showed that increasing inter-wrinkle dimension causes an increase in the perceived roughness. Similarly, Arvidsson et al. (2017) observed a sharp increase in perceived roughness when inter-wrinkle length exceeds 80 µm. Other studies Connor et al. (1990), Connor and Johnson (1992), Dépeault et al. (2009), Gescheider et al. (2005), Meftah et al. (2000), Merabet et al. (2004), Smith, Chapman, Deslandes, Langlais, and Thibodeau (2002) and Eck et al. (2013) were conducted on surfaces with dots of the same diameter, while more spaced than in the herein study. These works showed that the intensity of the roughness perception increases with dots size for spatial periods (corresponding to $S_p + D$) ranging from 1 to 4 mm.

2.4. *Experiment 3 – participants & procedure*

In experiment 3, the aim is to relate the tactile perceptive attributes of textured surfaces to their hedonic judgement. To do so, the pleasantness of the textures is evaluated using a Likert scale. The hedonic judgement is then analyzed regarding how consensual the judgement is, in order to identify textures that is disliked or liked and textures that induce variety of judgements.

2.4.1. *Methods*

43 individuals (30 women and 13 men) with a mean age of 29.0 years (age range 10–61 years) participated in this experiment. 43 random samplings of 18 PU samples out of the full 50 set of samples were prepared so that each sample was evaluated by 14 or 15 participants.

The participants were seated at a table. On the table, the set of 18 samples was placed right in front of the participant. On the front end of the table, 4 areas were delimited and qualified using a number (1–4) and a sentence as follow (translated from French):

> *1 – Ilike this surface a lot, I would like to have it often on everyday products*
>
> *2 – Ilike this surface, I would like to have it sometimes on everyday products*

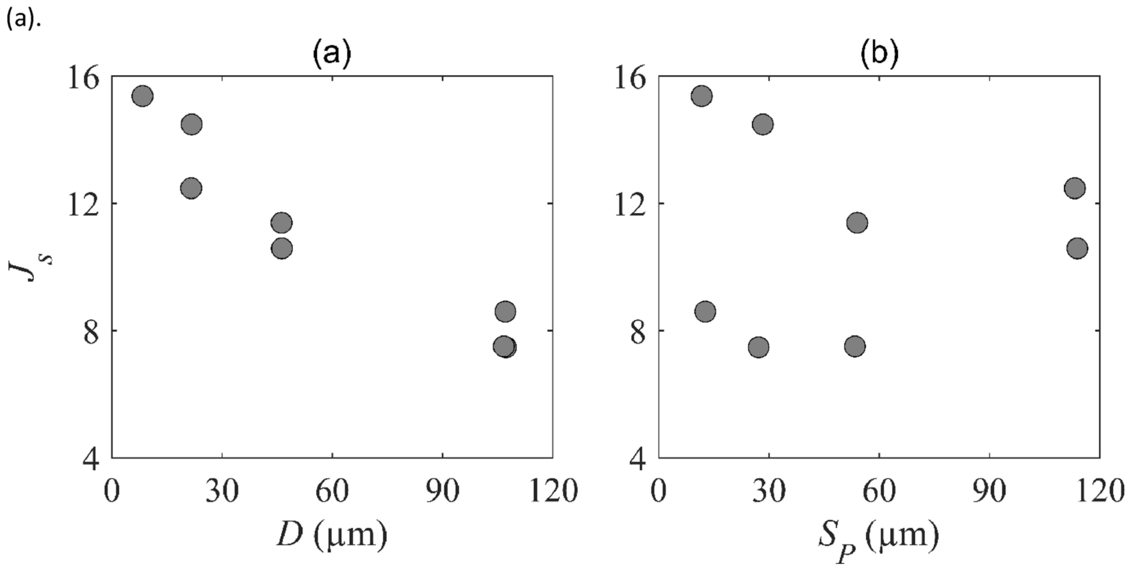

Fig. 5. Influence of dot diameter D (a) and inter-dot spacing S_p (b) on the sensation intensity for SLIPPERY stimuli.

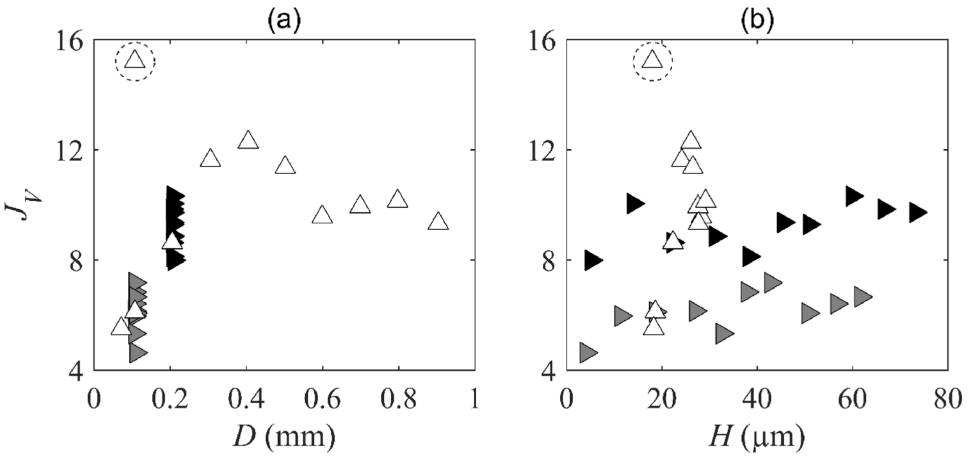

Fig. 6. Influence of dot diameter D (a) and height H (b) on the sensation intensity for *VIBRATING* stimuli. All markers refer to samples exhibiting $S_p = 112 \pm 2\,\mu m$ except the marker surrounded with a dotted encirclement for which $S_p = 210\,\mu m$. White triangles refer to samples that exhibit increasing D but nearly constant $H(24 \pm 4\,\mu m)$ while colored triangles refer to samples that exhibit increasing H with $D = 108 \pm 1\,\mu m$ (grey triangles) or $D = 207 \pm 1\,\mu m$ (black triangles).

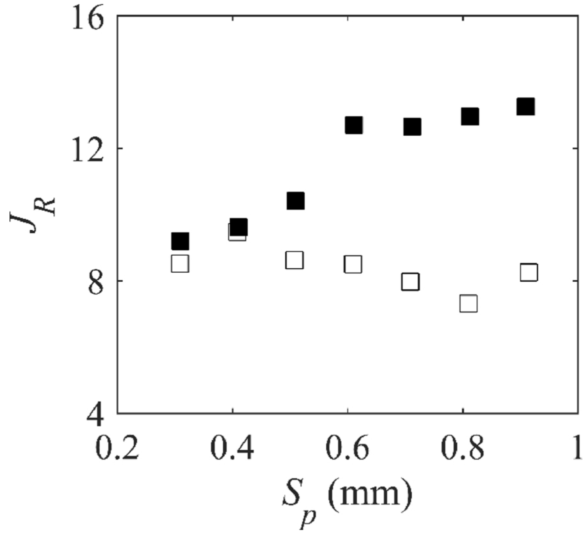

Fig. 7. Influence of dot diameter (D) on the sensation intensity for*ROUGH* stimuli for surfaces with dots exhibiting $D = 108 \pm 2\,\mu m$ (white squares), and surfaces with dots exhibiting $D = S_p$ (black squares).

3 – Idon't like this surface so much, I would like not to have it on everyday products too often
4 – Idon't like this surface at all, I don't want to have it on everyday products.

The participants were instructed to rub on the surfaces with one finger holding them between the thumb and forefinger of the other hand. It was explicitly asked not to limit the sample categorization to categories 2 and 3 only.

2.4.2. Results and discussion

In experiment 3, participants were asked to categorize the samples by associating to each sample a hedonic vote in a 4-level scale from *1-I like it a lot* to *4- I don't like it at all.* To analyze the results, a statistical approach was used based on the total votes in each hedonic level that each sample gathered. Fig. 8 shows the samples that gathered more than 50% votes in one of the four hedonic levels. Samples *S1*, *S8*, *S6* and *S2* gather a lot of *1-I like it a lot votes* and so can be considered as commonly liked textures. In the contrary, samples *R3*, *R12* and *R4* gather a lot of *4-I don't like it* at all votes and so can be considered as commonly disliked textures.

In order to evaluate how consensual the votes are over the participants, the standard deviation of the number of votes per hedonic level was calculated for each sample. If the standard deviation is low, the votes are homogeneously distributed over all four hedonic levels i.e. the samples are evenly liked and disliked. In the contrary, if the standard deviation is high, the votes are preferentially concentrated in one hedonic level i.e. the participants consensually liked (or disliked) the samples. It appears that the ten samples that gather the lowest standard deviations are, in that order, *V6, V9, R14, R9, S3, V15, V13, R5, V25* and *V10* with standard deviation from 4.1 to 7.1, meaning that these samples are appreciated differently by the participants. Note that the standard deviation for samples *V6, V9* and *R14* is lower that 5%. On the other hand, 10 samples (*S1, S8, S6, S2, R4, R6, V1, V16, V22, V27*) exhibit a standard deviation higher than 20%. This might indicate that those samples make consensus in term of participant appreciation. Taking into account that the dataset counts 29 *V*-samples, 14 *R*-samples an 8 *S*-samples, it appears that 50% of the *S*-samples make consensus and 20% of the *R*-samples and *V*-samples do not make consensus. Finally, by comparing the sensation intensities (experiment 2) of samples that make consensus and samples that do not make consensus it appears that the consensual characteristic of the hedonic votes is not linked to the sensation intensity in any of the perceptive category.

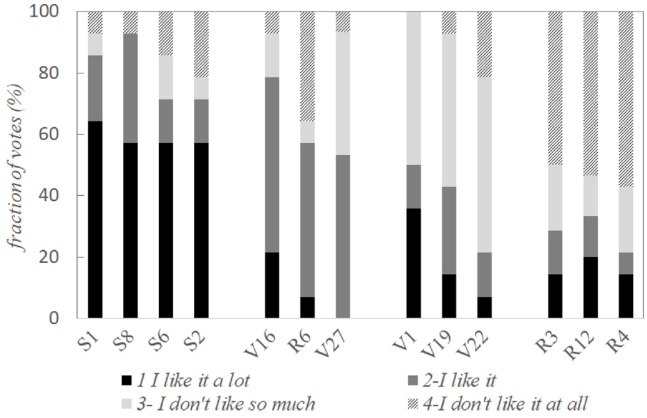

Fig. 8. Samples that gather more than 50% votes in one hedonic level.

To examine the relationship between the topographical features (D, S_p and H) and the hedonic perception level, we computed correlations and ran hierarchical multiple regression analyses (Table 3)for the three categories of tactile stimuli (*SLIPPERY*, *ROUGH*, and *VIBRATING*).

Considering *SLIPPERY* stimuli first, analyses did not reveal any significant correlations between topographical features and hedonic perception ($p_s > .70$). Regression analyses reported that none of the three topographical features significantly predicted hedonic perception.

The same absence of correlations was observed for the*ROUGH* stimuli ($p_s > .10$), except a marginal correlation between D and hedonic perception ($r = -45$; $p = .10$). Regression analyses confirmed that*D*is the only parameter which predicted hedonic perception (14% of the

Table 3
Hierarchical regression analyses predicting Hedonic perception from topographical features (D, S_p and H).

Step	SLIPPERY			VIBRATING			Rough		
	Variable	R^2	R^2 modified	Variable	R^2	R^2 modified	Variable	R^2	R^2 modified
Step 1	D	/	/	D	.20	.20**	D	.14	.14
Step 2	S_p	/	/	S_p	.27	.07	H	.20	.06
Step 3	H	/	/	H	/	/	S_p	.21	.01

** $p < .05$

variance) but marginally ($p = .10$).

However, analyses for *VIBRATING* stimuli showed a significant correlation between D and hedonic perception ($r = .48$, $p < .01$). Regression analyses showed that$D$ accounted for 20% of the variance of hedonic perception, which is significant, while S_p added 7% to the variance after controlling for D, which is not significant, and H did not account for supplementary part of the variance.

In addition, using the *a priori algorithm* (Agrawal and Srikant, 1994) that is one of the most used data mining algorithm (Wu et al., 2008), the relationships between liked and disliked samples have been explored.

The *a priori algorithm* is based on a simple *If/Then* statement which aims to observe frequently occurring patterns, correlations, or associations from datasets found in databases.

For each participant, the association rule mining was applied to highlight four specific statements:

- Statement 1: « *If sample x gets vote #1, then sample y gets vote #1* »
- Statement 2: *« If sample x gets vote #1, then sample y gets vote #4 ».*
- Statement 3: « *If sample x gets vote #4, then sample y gets vote #1* »
- Statement 4: « *If sample x gets vote #4, then sample y gets vote #4* ».

In experiment 3, each sample pairs (x,y) can be evaluated by up to 4 participants. This might be considered as a rather low occurrence, however interesting conclusions can be drawn from samples pairs that are evaluated 3 or 4 times. Then, under association rule mining, a confidence value equal to 0.8–1 shows that the association occurs each time those sample pairs were evaluated in the same sample set. The results obtained for each *If/Then* statements are gathered in Table 2. Taking into account that the following comments cannot be generalized to all samples, it appears that when *VIBRATING* samples are appreciated then other *VIBRATING* samples are also appreciated. On the other hand, when a *SLIPPERY* sample is not appreciated (*S4*) then another *SLIPPERY* sample is also not appreciated (*S1*). Similarly, it appears that samples *R6* and *R4* also share this poor appreciation.

In addition, *VIBRATING* samples seem opposed to *ROUGH* samples in terms of hedonic appreciation (when someone likes *VIBRATING* samples (*V26, V2*), she/he dislikes *ROUGH* samples (*R4, R12*), and so the contrary (*R13* vs. *V8*) (Table 4).

3. General discussion and conclusions

In the present study, behavioral experiments were performed using unfamiliar custom-made dot pattern stimuli under two complementary questionings. The first question focused on the tactile perceptive level related to topographical characteristics of the textures exhibited by the material surfaces. The second question focused on the tactile aesthetics level related both to the perceptive level and to the topographical characteristics of the textures. From the perceptive point of view, the process used to manufacture the samples enables to cover a wide range of topographical characteristics. This wide range of samples in turn evoked three different tactile perception (*SLIPPERY*, *ROUGH* and VIBRATING) that illustrated the perceptive consequence of the duplex theory in that the roughness perception is dependent on vibrotactile cues for fine textures while spatial cues were significant coarse textures.

Since the wide range of topographical characteristics were covered with a large number of samples, small variations of dots geometrical features were achieved. Interestingly, it was shown that the three-abovementioned categories of tactile perception can be precisely defined by specific dots' geometric features and distribution over the surface. Hence, *SLIPPERY* sensation relied on low values of D and Sp not exceeding 120 µm. This sensation relies on the finest textures investigated in the present study for which the *SLIPPERY* intensity is first related to D, and then to S_p. Obviously, the smaller D and S_p are, the higher the *SLIPPERY* intensity is (Table 1). Conversely, coarser textures result to *VIBRATING* and then *ROUGH* sensations. The specific cases of *S4* and *V1* surfaces tend to define the threshold between *SLIPPERY* and *VIBRATING* sensations at D ranging from 50 to 70 µm, when S_p is close to 110 µm. Interestingly, an increase of H does not lead to a shift from *VIBRATING* sensation to *ROUGH* one (Fig. 3 and Table 1) and does not impact the *VIBRATING* sensation intensity (Fig. 6). The VIBRATING intensity is however highly increased when D increases as long as it remains below approximately 400 µm. Results compiled in Table 1 also show that *VIBRATING* sensation is achieved with S_p smaller than 300 µm while higher S_p leads to *ROUGH* sensation. Once again, H and S_p do not really impact the sensation intensity in the case of *ROUGH* sensation. However, a linear relationship between D and *ROUGH* intensity has been highlighted (Fig. 7). These results are of major interest since they provide technical guidelines in terms of texture features definition for the design of products exhibiting specific tactile sensation. However, the relationship between sensation intensities and the fact that textures are liked/unliked is less obvious. Considering *SLIPPERY* sensation, the intensity does not seem to impact the fact that *SLIPPERY* surfaces are consensually liked. Indeed, the results show that SLIPPERY surfaces are largely appreciated and more consensually appreciated than *ROUGH* surfaces that are largely unappreciated. It was also demonstrated that *VIBRATING* surfaces evoke both positive and negative levels of appreciation. These results are consistent with Etzi et al. (2014) conclusions that related pleasurable tactile perception to smoothness of familiar surfaces. Finally Samples that cannot reach a consensus regarding the hedonic perception are samples *R14, V6*, and *V9*. It is noted that *V6* and *V9* exhibit high sensation intensity in *VIBRATING* stimuli ($J_V(V6) = 11.4$, $J_V(V9) = 10.1$) relative to the scale-range reached by all samples, that is [4.6–12.3] if one excepts the particular case of V11 (see Section 2.3.3). Similarly, *R14* exhibit high sensation intensity in *ROUGH* stimuli ($J_R(R14) = 13.3$) relative to the scale-range reached by all samples, that is [7.3–13.3].

The perspective of this work opens on complementary fields of research such as neurosciences to determine the brain mechanisms in the processing of the pleasantness of tactile stimuli. A deeper understanding of tactile aesthetics can be useful in the applied field such as in product designs that appeal more to our senses and that are more effective in eliciting certain emotional responses from a potential consumer.

Guest et al., 2009

Table 4
Results from association rules mining on hedonic results (experiment 3).

If sample x gets vote #1 (If someone likes)		Then samples y gets vote #1 (Then she/he likes)		Occurrence count	Confidence
Sample reference	Perceptive category (Experiment 1)	Sample reference	Perceptive category (Experiment 1)		
V13 and V20	VIBRATING and VIBRATING	V8	VIBRATING	3	1.0
V8 and V20	VIBRATING and VIBRATING	V13	VIBRATING	3	1.0
V8 and V13	VIBRATING and VIBRATING	V20	VIBRATING	3	1.0
If sample x gets vote #1 (If someone likes)		Then sample y gets vote #4 (Then she/he does not like)		Occurrence count	Confidence
Sample reference	Perceptive category (Experiment 1)	Sample reference	Perceptive category (Experiment 1)		
V26	VIBRATING	R4	ROUGH	4	1.0
V2	VIBRATING	R12	ROUGH	4	0.8
R13	ROUGH	V8	VIBRATING	4	0.8
If sample x gets vote #4 (If someone does not like)		Then samples y gets vote #1 (Then she/he likes)		Occurrence count	Confidence
Sample reference	Perceptive category (Experiment 1)	Sample reference	Perceptive category (Experiment 1)		
V8	VIBRATING	R13	ROUGH	4	0.8
If sample x gets vote #4 (If someone does not like)		Then sample y gets vote #4 (Then she/he does not like)		Occurrence count	Confidence
Sample reference	Perceptive category (Experiment 1)	Sample reference	Perceptive category (Experiment 1)		
S4	SLIPPERY	S1	SLIPPERY	3	1.0
R6	ROUGH	R4	ROUGH	4	0.8

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References

Agrawal, R., & Srikant, R. (1994). Fast algorithms for mining association rules. *Proc. 20th int. conf. very large data bases,* 487–499.

Arvidsson, M., Ringstad, L., Skedung, L., Duvefelt, K., & Rutland, M. W. (2017). Feeling fine—The effect of topography and friction on perceived roughness and slipperiness. *Biotribology, 11*, 92–101.

Ballesteros, S., Reales, J. M., De Leon, L. P., & Garcia, B. (2005). The perception of ecological textures by touch: Does the perceptual space change under bimodal visual and haptic exploration? *Proceedings- world haptics conference,* 635–638 (1).

Bensmaïa, S., & Hollins, M. (2005). Pacinian representations of fine surface texture. *Perception & Psychophysics, 67*, 842–854.

Bergmann Tiest, W. M. (2010). Tactual perception of material properties. *Vision Research, 50*, 2775–2782.

Blake, D. T., Hsiao, S. S., & Johnson, K. O. (1997). Neural coding mechanisms in tactile pattern recognition: The relative contributions of slowly and rapidly adapting mechanoreceptors to perceived roughness. *The Journal of Neuroscience, 17*, 7480–7489.

Cascio, C. J., & Sathian, K. (2001). Temporal cues contribute to tactile perception of roughness. *The Journal of Neuroscience, 21*(14), 5289–5296.

Cesini, I., et al. (2018). Correlation between friction-induced vibrations and tactile perception during exploration tasks of isotropic and periodic textures. *Tribology International,* 330–339.

Connor, C. E., Hsiao, S. S., Phillips, J. R., & Johnson, K. O. (1990). Tactile roughness: Neural codes that account for psychophysical magnitude estimates. *The Journal of Neuroscience, 10*, 3823–3836.

Connor, C. E., & Johnson, K. O. (1992). Neural coding of tactile texture: Comparison of spatial and temporal mechanisms for roughness perception. *The Journal of Neuroscience, 12*(9), 3414–3426.

Dépeault, A., Meftah, E.-M., & Chapman, C. E. (2009). Tactile perception of roughness: Raised-dot spacing, density and disposition. *Experimental Brain Research, 197*(3), 235–244.

Eck, J., et al. (2013). Roughness perception of unfamiliar dot pattern textures. *Acta Psychologica, 143*(1), 20–34.

Ekman, G., Hosman, J., & Lindstrom, B. (1965). Roughness, smoothness, and preference: A study of quantitative relations in individual subjects. *Journal of Experimental Psychology, 70*(1), 18–26.

Essick, G. K., McGlone, F., Dancer, C., Fabricant, D., Ragin, Y., Phillips, N., et al. (2010). Quantitative assessment of pleasant touch. *Neuroscience & Biobehavioral Reviews, 34*(2), 192–203.

Etzi, R., Spence, C., & Gallace, A. (2014). Textures that we like to touch: An experimental study of aesthetic preferences for tactile stimuli. *Consciousness and Cognition (Academic Press), 29*, 178–188.

Fagiani, R., & Barbieri, M. (2016). A contact mechanics interpretation of the duplex theory of tactile texture perception. *Tribology International, 101*, 49–58.

Francis, S., Rolls, E. T., Bowtell, R., McGlone, F., Browning, A., Clare, S., et al. (1999). The representation of pleasant touch in the brain and its relationship with taste and olfactory areas. *Neuroreport, 10*, 453–459.

Gallace, A., & Spence, C. (2014). *In touch with the future: The sense of touch from cognitive neuroscience to virtual reality.* Oxford: Oxford University Press.

Gescheider, G. A., Bolanowski, S. J., Greenfield, T. C., & Brunette, K. E. (2005). Perception of the tactile texture of raised-dot patterns: A multidimensional analysis. *Somatosensory and Motor Research, 22*, 127–140.

Guest, S., Dessirier, J. M., Mehrabyan, A., McGlone, F. P., Essick, G., Gescheider, G., et al. (2011). The development and validation of sensory and emotional scales of touch perception. *Attention, Perception & Psychophysics, 73*, 531–550.

Guest, S., Essick, G. K., Dessirier, J. M., Blot, K., Lopetcharat, K., & McGlone, F. P. (2009). Sensory and affective judgments of skin during inter- and interpersonal touch. *Acta Psychologica, 130*, 115–126.

Hollins, M., Faldowski, R., Rao, S., & Young, F. (1993). Perceptual dimensions of tactile surface texture: A multidimensional scaling analysis. *Perception & Psychophysics, 54*, 697–705.

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

Jehoel, S., Mccallum, D., Rowell, J., & Ungar, S. (2006). An empirical approach on the design of tactile maps and diagrams: The cognitive tactualization approach. *British Journal of Visual Impairment, 24*(2), 67–75.

Johnson, K. O., & Phillips, J. R. (1981). Tactile spatial resolution: Two-point discrimination, gap detection, grating resolution, and letter recognition. *Journal ofNeurophysiology, 46*, 1177–1191.

Kahrimanovic, M., Bergmann Tiest, W. M., & Kappers, A. M. L. (2009). Context effects in haptic perception of roughness. *Experimental Brain Research, 194*(2), 287–297.

Katz, D. (1989). *The world of touch.* Hillsdale, England: Lawrence Erlbaum Associates, Inc (Original work published in 1925).

Kitada, R., Sadato, N., & Lederman, S. J. (2012). Tactile perception of nonpainful unpleasantness in relation to perceived roughness: Effects of inter-element spacing and speed of relative motion of rigid 2-D raised-dot patterns at two body loci. *Perception, 41*(2), 204–220.

Klatzky, R. L., Lederman, S. J., & Reed, C. (1987). There's more to touch than meets the eye: The salience of object attributes for haptics with and without vision. *Journal of Experimental Psychology, 116*, 356–369.

Klöcker, A., Wiertlewski, M., Théate, V., Hayward, V., & Thonnard, J.-L. (2013). Physical factors influencing pleasant touch during tactile exploration. *PLoS One, 8*(11), e79085.

Lacey, S., Hall, J., & Sathian, K. (2010). Are surface properties integrated into visuohaptic object representations? *European Journal of Neuroscience, 31*, 1882–1888.

Lacey, S., & Sathian, K. (2014). Visuo-haptic multisensory object recognition, categorization, and representation. *Frontiers in Psychology, 5*, 730.

Laming, D. R. J. (1986). *Sensory analysis.* Academic Press.

Lawrence, M. A., et al. (2007). Haptic roughness perception of linear gratings via bare finger or rigid probe. *Perception (SAGE Publications UK: London, England), 36*(4), 547–557.

Lederman, S. J. (1974). Tactile roughness of grooved surfaces: The touching process and the effects of macro- and microsurface structure. *Perception & Psychophysics, 16*, 385–395.

Lederman, S. J., Thorne, G., & Jones, B. (1986). Perception of texture by vision and touch: Multidimensionality and intersensory integration. *Journal of Experimental Psychology. Human Perception and Performance, 12*, 169–180.

Li, K. W., Yu, R., & Zhang, W. (2011). Roughness and slipperiness of floor surface: Tactile sensation and perception. *Safety Science, 49*, 508–512.

Li, W., Zhan, M. L., Yu, Q. Y., Zhang, B. Y., & Zhou, Z. R. (2015). Quantitative assessment of friction perception for fingertip touching with different roughness surface. *Biosurface and Biotribology, 1*, 278–286.

Meftah, E. M., Belingard, L., & Chapman, C. E. (2000). Relative effects of the spatial and temporal characteristics of scanned surfaces on human perception of tactile roughness using passive touch. *Experimental Brain Research, 132*, 351–361.

Merabet, L. B., Thut, G., Murrayn, B., Andrews, J., Hsiao, S., & Pascual-Leone, A. (2004). Feeling by sight of seeing by touch? *Neuron, 42*, 173–179.

Merabet, L. B., Swisher, J. D., McMains, S. A., Halko, M. A., Amedi, A., & Pascual-Leone, A. (2007). Combined activation and deactivation of visual cortex during tactile sensory processing. *Journal of Neurophysiology, 97*, 1633–1641.

Picard, D., Dacremont, C., Valentin, D., & Giboreau, A. (2003). Perceptual dimensions of tactile textures. *Acta Psychologica, 114*(2), 165–184.

Ramananantoandro, T., Larricq, P., & Eterradossi, O. (2014). Relationships between 3D roughness parameters and visuotactile perception of surfaces of maritime pinewood and MDF. *Holzforschung, 68*(1), 93–101.

Rokach, L. (2010). Clustering methods. In O. Maimon, & L. Rokach (Eds.). *Data mining and knowledge discovery handbook* (pp. 271–298). (2nd ed.). Springer.

Sathian, K., Goodwin, A. W., John, K. T., & Darian-Smith, I. (1989). Perceived roughness of a grating: Correlation with responses of mechanoreceptive afferents innervating the monkey's fingerpad. *The journal of neuroscience, 9*(4), 1273–1279.

Smith, A. M., Chapman, C. E., Deslandes, M., Langlais, J.-S., & Thibodeau, M.-P. (2002). Role of friction and tangential force variation in the subjective scaling of tactile roughness. *Experimental Brain Research, 144*, 211–223.

Soranzo, A., Petrelli, D., Ciolfi, L., & Reidy, J. (2018). On the perceptual aesthetics of interactive objects. *Quarterly Journal of Experimental Psychology, 71*(12), 2586–2602.

Spence, C. (2008). Making sense of touch: A multisensory approach to the perception of objects. In E. Pye (Ed.). *The power of touch: Handling objects in museums and heritage contexts* (pp. 45–61). Walnut Creek, California: Left Coast Press.

Spence, C., & Gallace, A. (2008). Making sense of touch. In E. Chatterjee (Ed.). *Touch in museums: Policy and practice in object handling* (pp. 21–40). London: Berg.

Verrillo, R. T., Bolanowski, S. J., & McGlone, F. P. (1999). Subjective magnitude of tactile roughness. *Somatosensory & Motor Research, 16*(4), 352–360.

Wu, X., et al. (2008). Top 10 algorithms in data mining. *Knowledge and Information Systems (Springer-Verlag), 14*(1), 1–37.

Yoshida, M. (1968). Dimensions of tactual impressions. *Japanese Psychological Research, 10*, 157–173.

Yoshioka, T., et al. (2007). Texture perception through direct and indirect touch: An analysis of perceptual space for tactile textures in two modes of exploration. *Somatosensory & Motor Research, 24*(1–2), 53–70.

Yu, R., & Li, K. W. (2015). Perceived floor slipperiness and floor roughness in a gait experiment. *Work, 50*, 649–657.

Zhang, S., Zeng, X., Matthews, D. T. A., Igartua, A., Rodriguez-Vidal, E., Contreras Fortes, J., et al. (2017). Texture design for light touch perception. *Biosurface and Biotribology, 3*(1), 25–34.

Zuo, H., Hope, T., Castle, P., & Jones, M. (2001). An investigation into the sensory properties of materials. *2nd International conference on affective human factors design,* 500–507.