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Perception and Appreciation of Tactile Objects: The Role of Visual Experience and Texture Parameters[†]

A. K. M. Rezaul Karim[1,2,3], **Sanchary Prativa**[3], **Lora T. Likova**[1,2]

[1] *Envision Research Institute, Wichita, KS 67203, USA;* [2] *The Smith-Kettlewell Eye Research Institute, San Francisco, CA 94115, USA;* [3] *Department of Psychology, University of Dhaka, Dhaka 1000, Bangladesh*
E-mail: karim.akmr.monscho06@gmail.com

Abstract. *This exploratory study was designed to examine the effects of visual experience and specific texture parameters on both discriminative and aesthetic aspects of tactile perception. To this end, the authors conducted two experiments using a novel behavioral (ranking) approach in blind and (blindfolded) sighted individuals. Groups of congenitally blind, late blind, and (blindfolded) sighted participants made relative stimulus preference, aesthetic appreciation, and smoothness or softness judgment of two-dimensional (2D) or three-dimensional (3D) tactile surfaces through active touch. In both experiments, the aesthetic judgment was assessed on three affective dimensions, Relaxation, Hedonics, and Arousal, hypothesized to underlie visual aesthetics in a prior study. Results demonstrated that none of these behavioral judgments significantly varied as a function of visual experience in either experiment. However, irrespective of visual experience, significant differences were identified in all these behavioral judgments across the physical levels of smoothness or softness. In general, 2D smoothness or 3D softness discrimination was proportional to the level of physical smoothness or softness. Second, the smoother or softer tactile stimuli were preferred over the rougher or harder tactile stimuli. Third, the 3D affective structure of visual aesthetics appeared to be amodal and applicable to tactile aesthetics. However, analysis of the aesthetic profile across the affective dimensions revealed some striking differences between the forms of appreciation of smoothness and softness, uncovering unanticipated substructures in the nascent field of tactile aesthetics. While the physically softer 3D stimuli received higher ranks on all three affective dimensions, the physically smoother 2D stimuli received higher ranks on the Relaxation and Hedonics but lower ranks on the Arousal dimension. Moreover, the Relaxation and Hedonics ranks accurately overlapped with one another across all the physical levels of softness/hardness, but not across the physical levels of smoothness/roughness. These findings suggest that physical texture parameters not only affect basic tactile discrimination but differentially mediate tactile preferences, and aesthetic appreciation. The theoretical and practical implications of these novel findings are discussed. © 2022 Society for Imaging Science and Technology.*

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1. INTRODUCTION

Our perceptual world comprises a wide variety of objects, arts, and images that are rich in texture. Textures, an essential element of sensory inputs, provide us not only cues to perceptual discrimination [9, 51] but also significant information about the aesthetic qualities of objects, industrial products, or artifacts. Therefore, textures are widely used in product design, art, and architecture to convey specific aesthetic information [110], to evoke aesthetic emotions and set moods in humans [14, 35]. In everyday life, we choose to purchase objects or products, such as clothes or curtains designed with certain textures, while discarding many alternatives designed with different textures. Thus, it is important to understand how people perceive and appreciate the beauty of textured products or objects in the environment.

Surface textures are usually described as smooth or rough, coarse or fine, soft or hard, matt or glossy, and so forth. Depending on the sensory modality we use to sense and perceive them, textures fall into two distinct categories: visual textures and tactile textures. Visual textures give us an implied sense of surface composition related to local spatial variations of simple stimuli like color, orientation, and intensity. Tactile textures, on the contrary, are rendered to provide real information about the physical surface qualities of objects or products, such as sculpture and architecture materials that can not only be seen but felt by touch as well. In the last few decades or so, research has exclusively focused on the perception and aesthetics of visual textures (e.g., texture perception: [16, 22, 41, 48, 53, 54, 71, 76, 90, 95, 109, 111–113, 116, 121]; texture aesthetics: [14, 28, 50, 67, 68, 77, 78, 87, 94, 107, 110]) with scant attention to tactile textures. The intent of this study was to fill this gap by studying the perception and aesthetics of tactilely textured objects in individuals who underwent typical sensory development in comparison with those who experienced deprivation of the visual sense. Perception is the capacity of an individual to detect slight differences in environmental stimulation using a sensory system, whereas aesthetics is defined as the emotional feelings or affective reactions that s/he uses to appraise/appreciate the quality or richness of an object or event in the environment.

Like visual objects or products, tactile objects or products have also discriminative attributes and hedonic attributes that produce pleasant or unpleasant sensations

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[8, 96]. The hedonic attributes of tactile stimulation are important for emotional wellbeing [21, 56, 96], and interpersonal relationships between individuals, such as parents and infants, close friends, and romantic partners [66, 88, 93, 118]. Thus, hedonic touch forms a cornerstone of social, affiliative behavior in humans [85] and is critical in physical and mental development [24, 42]. Prosaically, we encounter the touch of clothing against our bodies every day, and this contact determines the comfort of the garments we wear [18]. Thus hedonic touch likely influences the estimated product quality [39] and guides consumer behavior and attitudes [17, 97–99]. Hedonic tactile stimulations (pleasant or unpleasant) are powerful motivators that facilitate product evaluation, product preferences, and purchase decisions (see [3, 23, 27, 80, 83, 98]). Thus, retailers can directly benefit from allowing customers to touch their products as it positively affects customers' choices (see [2, 3, 23, 39, 100]).

Touch is particularly important for the evaluation of a product's substance/material properties, such as roughness, hardness, temperature, and weight [52, 60, 70, 98], as it provides unique information that cannot be obtained through visual inspection [75]. Among these substance properties, roughness and softness are two prominent dimensions of tactile textures [49, 92] that have received growing amount of interest in recent years. One line of research has investigated the psychophysical relationships between subjective experience of tactile roughness or softness and the physical magnitude of surface roughness or object compliance (a physical correlate of softness) in sighted humans [30, 96, 115]. These studies showed that the perceived roughness of a stimulus surface was approximately a power function of the physical magnitude of roughness [30, 115] and that the perceived magnitude of softness increased monotonically as a function of increasing object compliance, leveling off around the end of the stimulus range [96]. A second line of research investigated how these discriminative texture parameters are related to the implicit hedonic aspects of touch in sighted humans [58, 63, 96, 115]. These studies revealed that the perceived magnitude of pleasantness of tactile sensation was inversely related to the physical or estimated magnitude of surface roughness [58, 63, 115], or increased monotonically with softness estimates or object compliance [96]. Because smooth or soft stimuli likely engender less friction [31, 64, 65], other studies in sighted humans demonstrated that people rate smooth and soft stimuli (e.g., silk material, cosmetic brushes) as more pleasing than rough and hard stimuli (e.g., burlap material, plastic mesh, polyester, sandpaper, sponge, cotton) under both active [32, 79, 102] and passive [29, 31, 32] touch conditions. Thus, it has been shown that stimulus preference increases (proportionally) with increasing magnitude of smoothness or softness [30, 47].

1.1 *The Present Study*

The findings outlined above unequivocally advance our understanding of the discriminative and hedonic components of tactile sensation [92] in people with typical sensory development. However, they do not tell us anything about these components in those who experience atypical sensory development, such as the blind who rely on tactile modality the most. Studies that compared the blind with the sighted on these components give some insights into the impact of visual experience on these components of tactile sensation. In relation to the discriminative component, two prior studies demonstrated that there are no differences between blind (congenitally or early) and blindfolded sighted participants in tactile perception [7, 43]. One of these studies showed that the material representations (e.g., roughness, hardness, orderliness, warmth, elasticity, friction) were highly similar between blind and blindfolded sighted participants [7]. The second study demonstrated that visual experience or imagery is not necessary for tactile texture perception and does not aid such texture discrimination as smoothness [43]. This study further demonstrated that perceptual skill was similar between vision and touch with relatively coarse textures, but touch was superior to vision for much finer surface textures. These studies together suggest that visual experience is not mandatory for shaping tactile perceptual representation. However, the lack of visual experience in the blind can be compensated by heightened tactile experience, resulting in superior skills in tactile grating discrimination [37], tactile letter (Braille) recognition [12], and other forms of tactile acuity tasks [72]. Some studies claimed that both congenitally and late blind participants outperformed their sighted counterparts not only on tactile acuity task but on three-dimensional (3D) tactile shape discrimination task, as well [37, 55, 91].

Data about the role of visual experience on the hedonic component of tactile sensation are scanty as very little research on aesthetics has been conducted with the blind population. One rare exception is work by Rubin [103], who investigated whether blind children have a sense of '*tactile aesthetics*' different from that of their partially sighted and fully sighted peers. The study reported a number of differences. For example, blind children usually prefer 3D scrap wood sculptures made by other blind children, but not by partially sighted and sighted children. Similarly, partially sighted and sighted children preferred objects made by other partially sighted and sighted children, respectively. Second, aesthetic interest as measured by spontaneous responses to objects was greater in the blind than both the partially sighted and sighted children. Third, the visually impaired children showed greater interest in structural features of the sculptures such as enclosures or boundaries and openings or holes, whereas the sighted youngsters appreciated abstract elements such as shape, texture, and overall configuration of the artifacts. Fourth, the visually impaired children tended to be more "subjective" (associating their object choices with life experiences), whereas the sighted children tended to be fairly 'objective' in their responses to the items.

Despite all the above differences, one noticeable similarity between children of the three categories of visual experience was that most of them preferred variety to sameness, such as preferring rounded and flat sculptures to plain ones; it appears that visual experience alone did not impact these tactile preferences. Because this study used sculptures made by visually impaired children, as well as sculptures made by sighted children, it was obvious that those sculptures were tactilely different from one another to a certain extent. The exposure to stimuli with dissimilar properties that give a sense of varying levels of tactile pleasantness might have contributed to dissimilar tactile preferences. Pleasure is considered to be distinct from interest, and is an important route to liking or preference [38]. Pleasure is a positive valence of emotion that involves feelings of enjoyment, happiness, and satisfaction [8], whereas interest is a feeling that motivates someone to focus on or explore an object or event [38]. An object or event can be interesting but not necessarily pleasant; and an unpleasant object or event can nevertheless be interesting [81, 89, 106, 114]. In this context, Rubin's study cannot tell us whether the sculptures that were found to be interesting were also pleasant. Though her study was unique and has some merits for understanding aesthetic sensitivity in the blind, the reasons for the differences/similarities between her participants were not clear due to the lack of strict experimental control.

The first systematic and controlled experimentation on aesthetics in the blind was conducted by Karim and Likova [55], ushering a novel field of experimental aesthetics in the *tactile* domain. Their study on macrospatial properties of tactile objects demonstrated that aesthetic appreciation, as exhibited through felt tactile hedonics and tactile preference, did not require visual experience. This study demonstrated that both blind and blindfolded sighted participants assessed curved/rounded 3D tactile objects as significantly more pleasing than sharp 3D tactile objects and symmetric 3D tactile objects as significantly more pleasing than asymmetric 3D tactile objects. Consistently, irrespective of visual experience, all participants preferred curved/rounded 3D tactile objects over sharp one and symmetric 3D tactile objects over asymmetric ones. However, it is still unclear whether visual experience plays a crucial role in shaping tactile aesthetic preference and affective tones induced by microspatial tactile properties, such as tangible texture. In a study on visual features of paintings, Marković and Radonjić [82] identified a 3-factor structure of affective tone comprising *Hedonics*, *Relaxation*, and *Arousal. Hedonic* tone refers to the hedonic and even erotic aspect of evaluation (e.g., beauty, pleasure); *Relaxation* refers to the more subtle affective aspect (e.g., calming, warmth, serenity); and *Arousal* refers to more intense affective aspect (e.g., interesting, impressive). However, such a structure of affective tone has not yet been tested in the tactile domain. Though few studies have been conducted on texture magnitude–hedonics association in the tactile domain (see above), the role of physical texture magnitude in shaping tactile aesthetic preference and other aspects of aesthetic appreciation such as *Relaxation* and *Arousal* still remains poorly understood. Thus, the current study was exploratory, designed to fill this gap by examining how people perceive textured objects or stimuli through the sense of touch, how they characterize them, and whether the perception and characterization of tactile textures are mediated by visual experience and such texture parameters as two-dimensional (2D) tactile smoothness and 3D tactile softness.

To the above end, we holistically examine both explicit and implicit attributes of immediate perceptual experience of tangible objects of varying levels of 2D tactile smoothness or 3D tactile softness, using a novel behavioral approach in groups of congenitally blind, late blind, and blindfolded sighted individuals, who differ in sensory experience of the visual world. Explicit attributes, the directly perceptible physical compositional properties (e.g., shape, size, position, orientation, texture) of an object/stimulus, are crucial to detect for effective sensory–motor coordination and action control in everyday life (e.g., eating, driving, playing football; [82, 108]). Implicit attributes, the properties imposed to an object/stimulus by perceivers, are mostly affective and motivational (e.g., some objects may look more or less pleasant, interesting, etc.), and reflect the quality of aesthetic experience [82, 107, 108]. In this study, we use tactile textures, such as 2D smoothness and 3D softness as explicit perceptual variables, three affective dimensions, such as *Relaxation*, *Hedonics*, and *Arousal* (identified for visual arts and aesthetics; [82]) as implicit variables, and aesthetic preferences as outcome variables.

2. METHODS

To measure the aforementioned variables, we used a ranking scale approach that allowed respondents to judge a set of 2D tactile surfaces or 3D tactile objects in relation to one another. This would not be possible in other types of scales, such as a Likert type rating scale which asks respondents simply to rate aesthetics of individual objects, and cannot give comparable information about the aesthetic qualities of objects. For example, when someone assigns a score of 4 to an object of certain qualities s/he may assign the same weight to a second object of worse or better qualities as s/he does not have information of the first object while making judgments of the second one. The problem intensifies when respondents are required to rate several objects on a large number of items/questions. Thus, a rating scale technique likely produces inaccurate and unreliable quantitative data about aesthetic preferences. The ranking scale is free from this kind of potential problem. Thus, though a ranking method likely gives qualitative data, they are more accurate and more reliable at least for relative aesthetics of objects. Also, in a real life setting, we prefer products of a particular brand as compared to others, and even within the same preferred brand, we choose a particular product to purchase by comparing its quality with a number of alternatives. Thus, the use of a ranking scale approach was an appropriate and precise choice in this study as it primarily intended to examine relative aesthetics of tactile objects.

Two experiments were conducted, each one using a mixed experimental design, a type of semi-repeated measures design, in which groups of differential visual

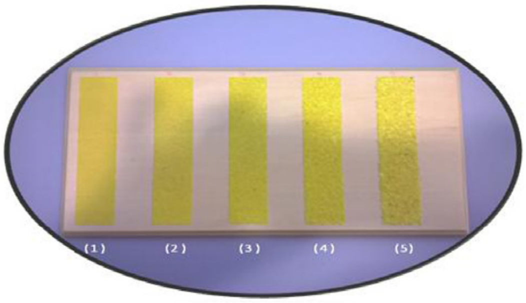


Figure 1. 2D tactile stimuli used in Experiment 1. (1) Smoothest, (2) Smoother, (3) Not-so-smooth–not-so-rough, (4) Rougher, (5) Roughest.

experiences were repeatedly tested under varying levels of smoothness of 2D tactile stimuli or softness of 3D tactile stimuli.

2.1 *Experiment 1: 2D Tactile Smoothness*

2.1.1 *Participants*

A total of 51 individuals, including 18 congenitally blind (10 females, age: 30–75 with Mean = 44.55, SD = 14.64), 14 late blind (7 females, age: 25–46 with Mean = 35.52, SD = 6.04), and 19 blindfolded sighted healthy adults (15 females, age: 22–69 with Mean = 42.09, SD = 16.57), voluntarily participated in this experiment. The congenitally blind group comprised one left-handed and seventeen right-handed participants. The late blind group comprised five left-handed and nine right-handed participants. The sighted group comprised one ambidextrous and eighteen right-handed participants. The visual acuity of the blind participants ranged from <20/500 to no light perception (NLP), and that of the sighted participants was normal or corrected to normal. The late blind participants had a history of full vision for diverse periods since birth, ranging from 7 months to 35 years, whereas the congenitally blind participants never had a record of full vision. Individuals having cognitive impairment, neuropathy of the hands or fingers, and hearing loss were not included in this experiment. All participants signed a Consent Form institutionally approved by the Smith-Kettlewell Internal Review Board (IRB), and all procedures conformed to the Declaration of Helsinki [122].

2.1.2 *Stimuli and Materials*

Tactile Stimuli. Each participant was tested on the smoothness dimension of 2D textured stimuli. We used a set of five textured surfaces composed of arrays of dots of varying height and varying diameter that provided a sense of different levels of smoothness (ranging from very smooth to very rough; Figure 1). These stimuli were numbered as 1, 2, 3, 4, and 5, respectively, and arranged on a wooden board having dimensions of 28.5 cm × 17.5 cm × 1.6 cm. The textured surfaces were of equal size of 11.4 cm × 2.3 cm. The spatial gap between every two adjacent stimulus surfaces was 2.0 cm.

Tactile Preference–Appreciation–Discrimination Questionnaire 1. Based on the relevant literature [1, 34, 40], we designed a behavioral judgment questionnaire comprising a set of 15 items: 1 item to measure 2D *tactile stimulus preference*, 13 items to measure *2D tactile aesthetic appreciation*, and 1 item to measure *smoothness discrimination* of 2D tactile surfaces.

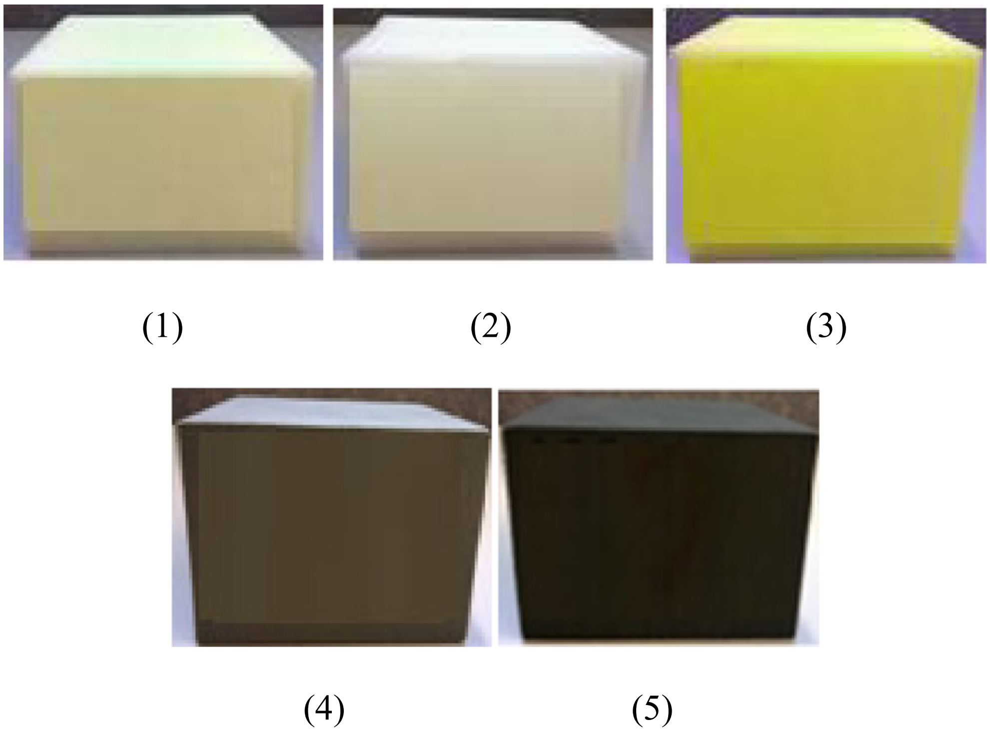
The "*stimulus preference*" section of the questionnaire requires participants to put the selected five 2D tactile surfaces in order of preference by verbally assigning a rank of 5, 4, 3, 2, and 1 to the most preferable, the 2nd most preferable, the 3rd most preferable, the 4th most preferable, and the least preferable surfaces, respectively.

The "*aesthetic appreciation*" section of the questionnaire requires participants to judge the same set of five 2D tactile surfaces in relation to one another on 13 implicit attributes, by verbally and concurrently assigning each tactile surface a rank of 1 (the surface can be least described by the attribute) to 5 (the surface can be most described by the attribute). For example, while judging on *"pleasantness"* each participant verbally assigned a rank of "5" to the most pleasant surface, "4" to the second most, "3" to the 3rd most, "2" to the 4th most, and "1" to the least pleasant surface. The items in this section were arranged in a fixed pseudo-random order: enlivening, calming, comfortable, desirable, enjoyable, exciting, pleasant, relaxing, sensual, appealing, soothing, thrilling, and irritating.

The 13 implicit attributes (items) can be subsumed under the three affective dimensions of aesthetic appreciation, such as *Relaxation, Hedonics*, and *Arousal*, as outlined above [82]. By definition, the "*Relaxation*" dimension comprised 4 attributes, such as *calming, comfortable, relaxing*, and *soothing*; the "*Hedonics*" dimension comprised 5 attributes, such as *desirable, enjoyable, pleasant, sensual*, and *appealing*; and the "*Arousal*" dimension comprised 4 attributes, such as, *enlivening, exciting, thrilling*, and *irritating*. Thus, when the assigned ranks are dimensionwise aggregated, a participant's total "*Relaxation*" score for each stimulus can fall within a range of 4 (if the stimulus is assigned a rank of 1 for all attributes) to 20 (if it is assigned a rank of 5 for all attributes). Similarly, his/her total "*Hedonics*" score for each stimulus can fall within a range of 5–25, and total "*Arousal*" score for each stimulus can fall within a range of 4–20.

The "*smoothness discrimination*" section of the questionnaire requires participants to put the same 2D tactile surfaces in order of felt smoothness magnitude (explicit perceptual property) by verbally assigning a rank of 5, 4, 3, 2, and 1 to the smoothest, the 2nd smoothest, the 3rd smoothest, the 4th smoothest, and the least smoothest surfaces, respectively.

The three sections of the questionnaire were arranged in the order they appeared above. That is, the tactile stimulus preference task appeared first, followed by the tactile aesthetic appreciation and tactile smoothness discrimination tasks. This order was chosen so as to avoid any potential influence of aesthetic appreciation or smoothness discrimination on participant's stimulus preference response.



(1) (2) (3)

(4) (5)

Figure 2. 3D tactile stimuli used in Experiment 2. (1) Softest, (2) Softer, (3) Not-so-soft–not-so-hard, (4) Harder, (5) Hardest.

2.1.3 *Procedure*

Participants were tested individually following standard experimental procedure. Because the stimuli were permanently arranged side by side on a wooden board in an increasing order of roughness, it was not feasible to present them in a random order. However, we presented them in a balanced order of smoothness levels, varying from left to right for half a group of participants, and from right to left for the remaining participants (the two halves were unequal only for the blindfolded sighted group comprising an odd number of individuals). Participant's task was to explore and compare all the five stimulus surfaces with the dominant hand for 100 sec (with an average exploration time of 20 sec/surface, estimated in an initial pilot experiment), followed by 15 separate rank orderings for the set of 15 items described above. To do so, each participant was required to rest his/her dominant hand in a fixed position on each of the five stimuli, and then move it to explore the stimulus surface. Thus, after the exploration and comparison of the five 2D tactile surfaces for 100 sec, each participant performed three forms of behavioral judgments: (i) verbally put the surfaces in order of preference, (ii) judged the surfaces in relation to one another on each of the 13 implicit attributes, and (iii) verbally put the surfaces in order of felt/perceived smoothness magnitude, using the corresponding five-point ranking scales described above. On average, each participant took about 35 min to complete all these judgments following a set of task-specific standard instructions approved by the Smith-Kettlewell IRB.

2.2 *Experiment 2: 3D Tactile Softness*

2.2.1 *Participants*

The three groups of individuals with different levels of visual experience who participated in Experiment 1 also voluntarily served as participants in this experiment as well.

2.2.2 *Stimuli and Materials*

Tactile Stimuli. Each participant was tested on the *softness dimension* of 3D tactile stimuli. All stimuli were of the same size and shape, differing only in softness. The set of stimuli used here comprised of five cube-shaped 3D foam-made tactile objects of different levels of softness (very soft to very hard; Figure 2), each object having dimensions of 5 cm × 5 cm × 5 cm.

Tactile Preference–Appreciation–Discrimination Questionnaire 2. Similar to the aforementioned *Tactile Preference–Appreciation–Discrimination Questionnaire* 1, we designed here a second behavioral judgment questionnaire comprising a set of 14 items: 1 item to measure 3D *tactile stimulus preference*, 12 items to measure 3D *tactile aesthetic appreciation*, and 1 item to measure *softness discrimination* of 3D tangible objects. These behavioral judgment measures were arranged in an order analogous to the order of the behavioral judgment measures in *Questionnaire 1*, and the order of the 12 *aesthetic appreciation* items was determined pseudo-randomly as in Experiment 1.

The "*stimulus preference*" section of this questionnaire allows participants to put the selected five tactile cubes in order of preference by verbally assigning a rank of

1 (the least preferable) to 5 (the most preferable). The "*aesthetic appreciation*" section requires participants to judge the same five tactile cubes in relation to one another on 12 implicit attributes, by verbally and concurrently assigning each tactile cube a rank of 1 (the cube can be least described by the attribute) to 5 (the cube can be most described by the attribute). The "*softness discrimination*" section asks participants to put the same tactile cubes in order of felt softness magnitude (explicit perceptual property) by verbally assigning a rank of 1 (the least soft cube) to 5 (the most soft cube). As in *Questionnaire 1*, the items of the *tactile aesthetic appreciation* measure in this questionnaire can also be subsumed under the three affective dimensions: *Relaxation, Hedonics*, and *Arousal*. Like the "*Relaxation*" and "*Hedonics*" dimensions in that questionnaire, the "*Relaxation*" and "*Hedonics*" dimensions here comprised the same implicit attributes of tactile objects. However, the "*Arousal*" dimension included 3 of the 4 implicit attributes that formed the "*Arousal*" dimension in *Questionnaire 1*. The 13th item ('*irritating*') that was included in the "*Arousal*" dimension of that questionnaire was excluded here as it seemed inappropriate for measuring the aesthetics of 3D tactile softness. Thus, when the assigned ranks are dimensionwise aggregated, a participant's total "*Relaxation*" score for each stimulus can fall within a range of 4 (if the stimulus is assigned a rank of 1 for all attributes) to 20 (if it is assigned a rank of 5 for all attributes). Similarly, his/her total "*Hedonics*" score for each stimulus can fall within a range of 5–25, and total "*Arousal*" score for each stimulus can fall within a range of 3–15.

2.2.3 *Procedure*

As in Experiment 1, participants were tested individually following standard experimental procedure. However, unlike the stimulus presentation in that experiment here the selected five 3D tactile objects of varying softness levels were numbered on the top surface as 1, 2, 3, 4, and 5, respectively and presented to each participant in a pseudo-random order (without repeats). Participant's task was to explore and compare all these objects by pressing on them with the fingers of the two hands for 100 sec (with an average exploration time of 20 sec/object, estimated in an initial pilot experiment), followed by 14 separate rank orderings for the set of 14 items stated above. Thus after the exploration and comparison of all the five 3D objects, each participant performed three forms of behavioral judgments: (i) verbally put the objects in order of preference, (ii) judged the objects in relation to one another on each of the 12 implicit attributes, and (iii) verbally put the objects in order of felt/perceived softness magnitude, using the corresponding five-point ranking scales stated above. On average, each participant took about 35 min to complete all these judgments following a set of task-specific standard instructions approved by the Smith-Kettlewell IRB.

2.3 *Data Analysis*

In Experiment 1, both the 2D *smoothness discrimination task* and 2D *stimulus preference* task comprised only one item. Thus, according to the scoring principle (see above), each participant received a 2D *smoothness discrimination* score or a 2D *stimulus preference* score falling between 1 and 5 for each of the five tactile stimuli. Because the *aesthetic appreciation* task comprised multiple items under three affective dimensions, namely *Relaxation, Hedonics*, and *Arousal*, here, we calculated each participant's mean *Relaxation* score, mean *Hedonics* score, and mean *Arousal* score for each of the five tactile stimuli by averaging the corresponding item ranks in each affective dimension. However, we did not ascertain any composite scores for aesthetic appreciation as it is inappropriate to aggregate the *Relaxation*, *Hedonics*, and *Arousal* scores. Our intention is to understand aesthetic appreciation in terms of these affective dimensions rather than in terms of composite aesthetic scores.

Because the collected data were discontinuous (in rank) and failed to meet normality assumption, we analyzed the data in suitable nonparametric tests as alternatives to standard parametric tests. First, the data for 2D *smoothness discrimination*, 2D *stimulus preference*, and aesthetic appreciation of 2D surfaces on three affective dimensions (*Relaxation Hedonics*, and *Arousal*) were all separately analyzed in a series of Mann–Whitney U tests (as an alternative to standard independent samples t tests) to see whether there were any *sex differences* in each of the five stimuli under the three behavioral judgments. This analysis was motivated by the prior findings that sex differences exist in sensory hedonics [8] and in the use of sensory modalities [46].

Because no sex differences were detected for any of the five stimuli, data were collapsed across the male and female participants. Then, in order to see the effect of *visual experience* on *tactile smoothness discrimination*, *tactile stimulus preference*, and three affective dimensions of aesthetic appreciation, we analyzed the corresponding rank data in a series of Kruskal–Wallis one-way ANOVAs for independent samples (as an alternative to independent samples one-way parametric ANOVAs). Finally, in order to see the effect of *physical smoothness magnitude* on *smoothness discrimination*, *stimulus preference*, and three affective dimensions of *aesthetic appreciation*, we analyzed the corresponding rank data in a series of Friedman's nonparametric ANOVAs for related samples (as an alternative to repeated measures parametric ANOVAs), followed by a series of post hoc analyses of the median of differences using Wilcoxon signed-rank tests with Bonferroni corrected p values.

In Experiment 2, the scoring was done following the same procedure as in Experiment 1. Then, the rank data for 3D *softness discrimination*, 3D *stimulus preference*, and *aesthetic appreciation* of 3D objects on the aforementioned three affective dimensions were analyzed using a series of the same statistical tests used in Experiment 1.

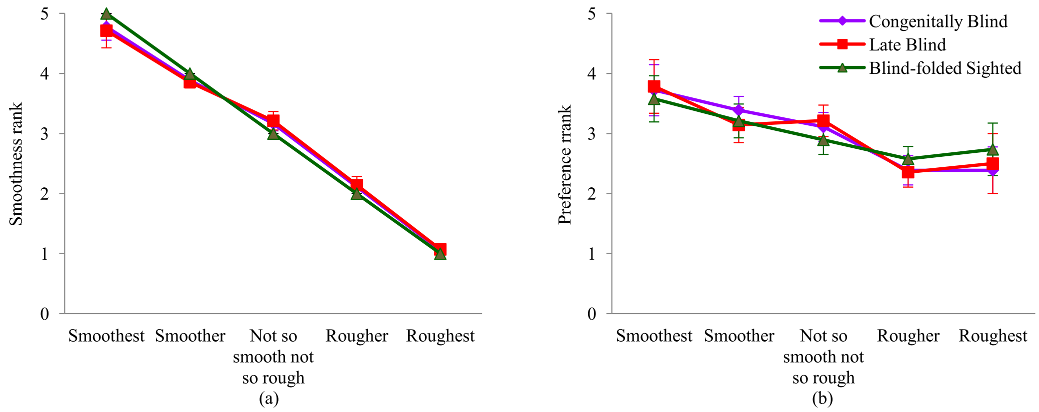


Figure 3. (a) Mean smoothness ranks and (b) mean preference ranks across three visual experience groups in relation to physical smoothness level of 2D tactile stimuli. Error bars represent standard errors of the corresponding group means.

3. RESULTS

3.1 *Experiment 1: 2D Tactile Smoothness*

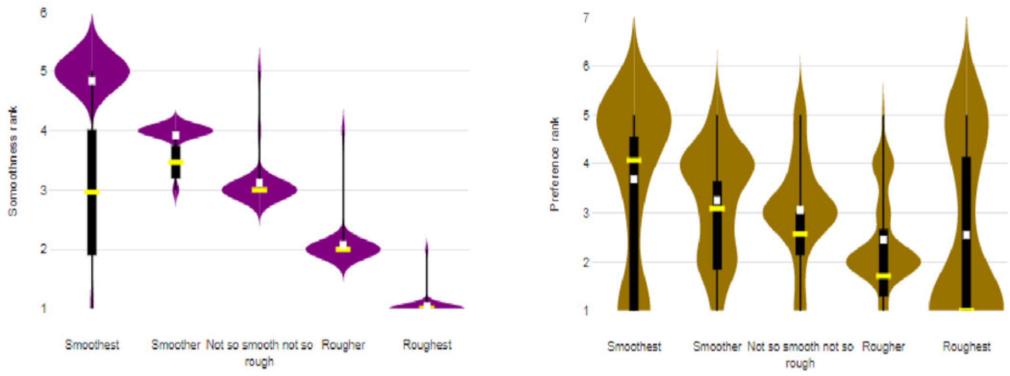
The results of a series of Kruskal–Wallis one-way ANOVAs for independent samples demonstrated visual experience-based no significant differences in 2D *smoothness discrimination, 2D stimulus preference*, and all three affective dimensions (*Relaxation, Hedonics, and Arousal*) assumed to underlie *aesthetic appreciation*. Thus the data were collapsed across visual experience groups (congenitally blind, late blind, and blindfolded sighted), and subjected to a series of Friedman nonparametric ANOVAs for related samples which showed that the effect of physical magnitude of 2D smoothness was significant on *all three behavioral judgments* studied here.

3.1.1 *Smoothness Discrimination as a Function of Physical Magnitude of 2D Smoothness/Roughness*

Figure 3(a) displays visual experience-based group means of *smoothness* ranks for five 2D tactile stimuli of varying physical smoothness levels. It appears that the smoothness rank decreased highly proportionally with increasing *physical magnitude of roughness*, and that on average, all three groups of participants highly conformed to a similar degree of ranking different levels of physical smoothness. Figure 4(a) displays violin plots of smoothness ranks (generated in Displayr) for the same set of five 2D tactile stimuli for all participants combined irrespective of visual experience. This figure shows that the overall shape and distribution of smoothness ranks dramatically differ across the physical smoothness levels of the stimuli. It appears that with the increasing physical smoothness of the stimuli, the distributions tend to comprise higher smoothness ranks. Moreover, the smoothness ranks for the smoother stimuli tend to be highly concentrated around the mean but much further away from the median, whereas the smoothness ranks for the rougher stimuli tend to be highly concentrated around the mean or median. Analysis of rank distributions in a Friedman nonparametric ANOVA demonstrated that the *perceived smoothness* in a 2D tactile stimulus significantly varied across the *physical levels* of *smoothness* ($\chi_r^2(4) = 182.67, p < 0.001, W = 0.895$). Post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected p values as summarized in Table I show that the perceived smoothness was significantly and consistently higher for the physically smoother than the physically rougher stimuli.

3.1.2 *Tactile Preference as a Function of Physical Magnitude of 2D Smoothness/Roughness*

Fig. 3(b) displays visual experience-based group means of *stimulus preference* ranks connected by line charts for five 2D tactile stimuli of varying physical smoothness levels. This figure shows that, on average, all three groups of participants highly conformed to put the set of five 2D tactile stimuli in order of a similar fashion of preference, with the congenitally blind group receiving a preference score of 2.39 (for both the roughest and the rougher) to 3.72 (for the smoothest), the late blind group receiving a preference score of 2.36 (for the rougher) to 3.79 (for the smoothest), and the blindfolded sighted group receiving a preference score of 2.58 (for the rougher) to 3.58 (for the smoothest). The highly overlapping line charts for all three groups of participants indicate that the *stimulus preference* rank has a negative monotonic relationship with the *physical magnitude of roughness*, comprising a Spearman's rank-order $r = -0.98$ for the congenitally blind, -0.80 for the late blind, and -0.90 for the blindfolded sighted. Fig. 4(b) displays violin plots of preference ranks for individual stimuli for all participants combined irrespective of visual experience. This figure shows that the overall shape and distribution of preference ranks dramatically differ across the physical smoothness levels of the stimuli, with some stimuli having much more elongated distributions compared to the other stimuli. It appears that with the increasing physical smoothness of the stimuli, the distributions tend to comprise higher preference ranks that tend to be highly concentrated above the mean or median. Analysis of rank distributions in a Friedman's nonparametric ANOVA demonstrated that participants' *preference* for a 2D tactile stimulus significantly varied across the *physical levels of stimulus smoothness* ($\chi_r^2(4) = 21.30, p < 0.001, W = 0.104$). Post hoc analyses using Wilcoxon signed-rank



(a) (b)

Figure 4. Violin plots showing density distributions of (a) smoothness ranks and (b) preference ranks for five 2D tactile stimuli of varying physical smoothness levels for all participants combined.

Table I. Wilcoxon signed-rank test results of post hoc analysis for pairwise comparison of five 2D tactile stimuli in smoothness discrimination and aesthetic preference.

2D stimulus pair	Smoothness discrimination		Aesthetic preference	
	z	*p*	*z*	*p*
Smoother versus Smoothest	−5.87	<0.001		
Not-so-smooth-not-so-rough versus Smoothest	−5.85	<0.001		
Rougher versus Smoothest	−6.58	<0.001	−3.09	0.02
Roughest versus Smoothest	−6.98	<0.001		
Not-so-smooth-not-so-rough versus Smoother	−5.42	<0.001		
Rougher versus Smoother	−6.85	<0.001	−2.83	0.05
Roughest versus Smoother	−6.91	<0.001		
Rougher versus Not-so-smooth-not-so-rough	−7.02	<0.001		
Roughest versus Not-so-smooth-not-so-rough	−6.91	<0.001		
Roughest versus Rougher	−7.02	<0.001		

Note. The z values are standardized test statistic values, and p values are values with Bonferroni correction. A negative (−) value of z indicates that the second stimulus of the pair received a rank higher than the first stimulus, and a positive (+) value of z (if any) indicates the other way round. Only significant values are shown.

tests with Bonferroni corrected p values as summarized in Table I show that the preference rank was significantly higher for the physically *smoothest and the smoother* stimuli as compared to the physically *rougher* stimuli. The other post hoc comparisons were nonsignificant.

3.1.3 *Tactile Aesthetics as a Function of Physical Magnitude of 2D Smoothness/Roughness*

We plot the data for three affective dimensions (*Relaxation, Hedonics, and Arousal* that underlie *aesthetic appreciation*) in relation to *physical magnitude of 2D smoothness/roughness* in Figures 5 and 6. Fig. 5 displays mean ranks for individual stimuli on each of the three affective dimensions connected by line charts separately for three visual experience groups, as well as for all participants combined. Fig. 6 displays violin plots of rank distributions of the three affective dimensions for individual stimuli for all participants combined irrespective of visual experience. Fig. 5 shows that for all visual experience groups, the physically smoothest and the smoother surfaces received, on average, higher ranks on the *Hedonics* and *Relaxation* dimensions as compared to the *Arousal* dimension, and the *physically* roughest and rougher surfaces received, on average, higher ranks on the *Arousal* dimension as compared to the *Relaxation* and *Hedonics dimensions*, with the *not-so-smooth-not-so-rough* surface receiving a rank closest to the middle of the five-point ranking scale on all three affective dimensions. The line charts indicate that the *Relaxation* rank, *Hedonics* rank, and *Arousal* rank all have a monotonic relationship with the *magnitude of physical roughness*, not only when the data are plotted for all participants combined but for individual groups as well. As demonstrated by Spearman's rank-order correlations, the former two dimensions comprise a perfect negative and the latter one comprises a perfect positive relationship ($r = -1.00$ for *Relaxation*, -1.00 for *Hedonics*, and $+1.00$ for *Arousal*; the same correlation coefficients across the visual groups and the combined group). In addition, the *Relaxation* and *Hedonics* were perfectly positively correlated

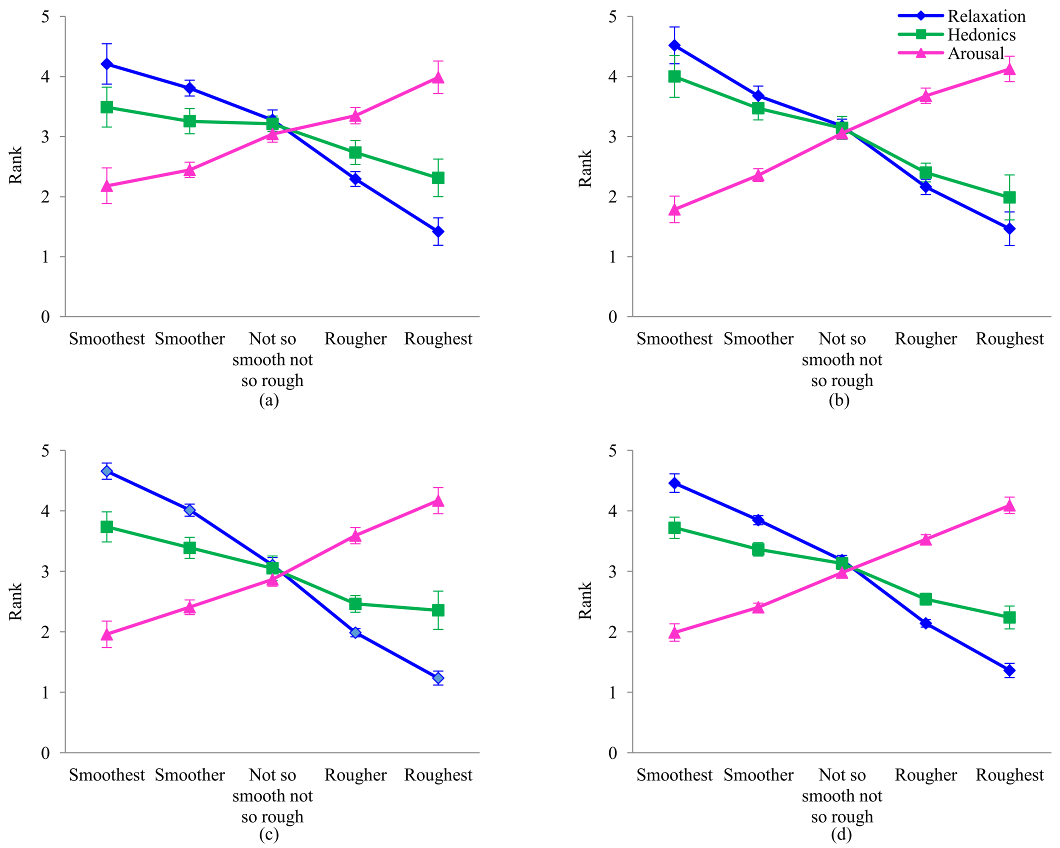
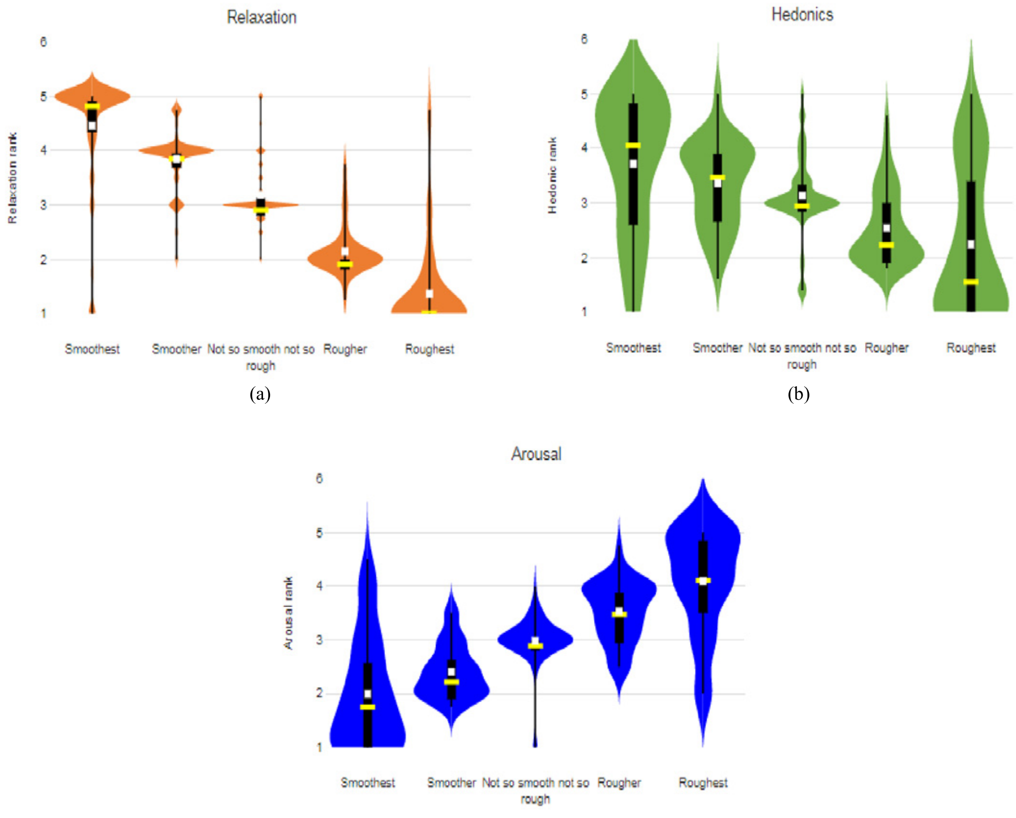


Figure 5. Mean ranks assigned to three affective dimensions of aesthetics: Relaxation, Hedonics, and Arousal in relation to physical smoothness level of 2D tactile stimuli. (a) Congenitally blind, (b) late blind, (c) blindfolded sighted, (d) All participants combined irrespective of visual experience. The *Relaxation, Hedonics*, and *Arousal* scores were determined by averaging the assigned ranks over the corresponding implicit attributes of these affective dimensions. Error bars represent standard errors of the corresponding group means.

(Spearman's rank-order $r = +1.00$), whereas the *Arousal* was perfectly negatively correlated with each of these two affective dimensions (Spearman's rank-order $r = -1.00$). Fig. 6 shows that the overall shape and distribution of ranks for each affective dimension dramatically differ across the physical smoothness levels of the stimuli, with some stimuli having much more elongated distributions compared to the other stimuli. A couple of interesting differences are observed between the rank distributions for these affective dimensions. First, with the increasing physical smoothness, the distributions for both *Relaxation* and *Hedonics* dimensions tend to comprise higher ranks, whereas the distribution for *Arousal* dimension tends to comprise lower ranks. Second, with increasing physical smoothness, the *Relaxation* and *Hedonics* ranks tend to be highly concentrated above the mean or median, whereas the *Arousal* ranks tend to be highly concentrated around or below the mean or median.

Now, analysis of the data for affective dimensions in Friedman's nonparametric ANOVAs demonstrated that the rank distributions for *Relaxation*, *Hedonics*, and *Arousal*, all significantly varied across the *physical levels of 2D surface smoothness* ($\chi_r^2(4) = 140.87$, $p < 0.001$, $W = 0.691$ for *Relaxation*; $\chi_r^2(4) = 29.67$, $p < 0.001$, $W = 0.145$ for *Hedonics*; *and* $\chi_r^2(4) = 93.88$, $p < 0.001$, $W = 0.460$ for *Arousal*). Post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected p values as summarized in Table II show that in most of the cases the *Relaxation* rank and *Hedonics* rank were significantly higher for the physically *smoother* than the physically rougher surfaces. On the contrary, the *Arousal* rank was significantly lower for the physically smoother than the physically rougher surfaces.

Finally, to see whether the differences among the three affective dimensions were significant, comparative analyses were run on the *Relaxation*, *Hedonics*, and *Arousal* data for all participants combined in a series of Friedman's nonparametric ANOVAs for related samples. Results at individual (physical) smoothness levels of the stimuli showed that there were significant differences among the rank distributions for *Relaxation*, *Hedonics*, and *Arousal* at the physically smoothest ($\chi_r^2(2) = 62.40$, $p < 0.001$, $W = 0.612$), the smoother ($\chi_r^2(2) = 69.92$, $p < 0.001$, $W = 0.686$), the rougher ($\chi_r^2(2) = 65.98$, $p < 0.001$, $W = 0.647$), and the roughest ($\chi_r^2(2) = 70.12$, $p < 0.001$, $W = 0.687$) levels, but not at the *not-so-smooth-not-so-rough* level of a stimulus. Post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected p values as summarized in Table III demonstrated that both the physically smoothest



(a) (b)

(c)

Figure 6. Violin plots showing density distributions of affective ranks for five 2D tactile stimuli of varying physical smoothness levels for all participants combined. (a) *Relaxation*, (b) *Hedonics*, and (c) *Arousal*.

Table II. Wilcoxon signed-rank test results of post hoc analysis for pairwise comparison of five 2D tactile stimuli on three affective dimensions of tactile aesthetics.

2D stimulus pair	Relaxation		Hedonics		Arousal	
	z	*p*	*z*	*p*	*z*	*p*
Smoother versus Smoothest	−3.96	<0.001			+3.84	<0.001
Not-so-smooth-not-so-rough versus Smoothest	−4.62	<0.001			+4.45	<0.001
Rougher versus Smoothest	−5.92	<0.001	−3.82	<0.001	+4.96	<0.001
Roughest versus Smoothest	−6.02	<0.001	−3.79	<0.001	+5.21	<0.001
Not-so-smooth-not-so-rough versus Smoother	−3.59	<0.001			+4.78	<0.001
Rougher versus Smoother	−6.09	<0.001	−3.65	<0.001	+5.25	<0.001
Roughest versus Smoother	−6.09	<0.001	−3.58	<0.001	+5.40	<0.001
Rougher versus Not-so-smooth-not-so-rough	−6.10	<0.001	−3.55	<0.001	+4.49	<0.001
Roughest versus Not-so-smooth-not-so-rough	−5.84	<0.001	−3.29	0.01	+4.98	<0.001
Roughest versus Rougher	−5.54	<0.001			+4.72	<0.001

Note. The *z* values are standardized test statistic values, and *p* values are values with Bonferroni correction. A negative (−) value of *z* indicates that the second stimulus of the pair received a rank higher than the first stimulus, and a positive (+) value of *z* indicates the other way round. Only significant values are shown.

and the smoother surfaces received a significantly higher *Relaxation* rank than *Hedonics* and *Arousal* ranks, and a significantly higher *Hedonics* rank than *Arousal* rank. On the contrary, both the physically roughest and the rougher surfaces received a significantly higher *Arousal* rank than *Hedonics* and *Relaxation* ranks, and a significantly higher *Hedonics* rank than *Relaxation* rank.

3.2 *Experiment 2: 3D Tactile Softness*

The results of a series of Kruskal–Wallis one-way ANOVAs for independent samples showed visual experience-based

Table III. Wilcoxon signed-rank test results of post hoc analysis for pairwise comparison of three affective dimensions of aesthetics on stimuli of various smoothness levels.

Affective dimension pair	Smoothest		Smoother		Not-so-smooth-not-so-rough		Rougher		Roughest	
	z	*p*	*z*	*p*	*z*	*p*	*z*	*p*	*z*	*p*
Relaxation versus Hedonics	+4.79	<0.001	+4.30	<0.001			−4.42	<0.001	−4.73	<0.001
Relaxation versus Arousal	+5.78	<0.001	+6.12	<0.001			−6.11	<0.001	−6.18	<0.001
Hedonics versus Arousal	+5.37	<0.001	+5.40	<0.001			−5.27	<0.001	−5.75	<0.001

Note. The *z* values are standardized test statistic values, and *p* values are values with Bonferroni correction. A negative (−) value of *z* indicates that the second affective dimension of the pair received a rank higher than the first affective dimension, and a positive (+) value of *z* indicates the other way round. Only significant values are shown.

no significant differences in 3D *softness discrimination*, *3D stimulus preference*, and all three affective dimensions (*Relaxation, Hedonics, and Arousal*) that underlie *aesthetic appreciation*. Thus, the data were collapsed across visual experience groups (congenitally blind, late blind, and blindfolded sighted), and subjected to a series of Friedman's nonparametric ANOVAs for related samples which showed that the effect of the physical magnitude of 3D softness was significant on *all three behavioral judgments* studied here.

3.2.1 *Softness Discrimination as a Function of Physical Magnitude of 3D Softness/Hardness*

Figure 7(a) displays visual experience-based group means of *softness* ranks for five 3D tactile stimuli of varying levels of (physical) softness. It appears that the softness rank decreased almost perfectly proportionally with increasing *magnitude of physical hardness*, and that on average, all three groups of participants highly conformed to a similar degree of ranking different levels of softness. Figure 8(a) displays violin plots of softness ranks (generated in Displayr) for the same set of 3D tactile stimuli for all participants combined irrespective of visual experience. This figure shows that the overall shape and distribution of softness ranks dramatically differ across the physical softness levels of the stimuli, with the physically softest stimulus having much more elongated distribution compared to the other stimuli. It appears that with increasing physical softness of the stimuli the distributions tend to comprise higher softness ranks that tend to be highly concentrated around the mean. Analysis of rank distributions in a Friedman's nonparametric ANOVA demonstrated that the perceived softness in a 3D tactile stimulus significantly varied across the physical levels of its softness ($\chi_r^2(4) = 202.42$, $p < 0.001$, $W = 0.992$). Post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected p values as summarized in Table IV show that the perceived softness was significantly and consistently higher for the physically softer than the physically harder stimuli.

Table IV. Wilcoxon signed-rank test results of post hoc analysis for pairwise comparison of five 3D stimuli in softness discrimination and aesthetic preference.

3D stimulus (cube) pair	Softness discrimination		Aesthetic preference	
	z	*p*	*z*	*p*
Softer versus Softest	−7.08	<0.001	−3.58	<0.001
Not-so-soft-not-so-hard versus Softest	−7.02	<0.001	−4.73	<0.001
Harder versus Softest	−7.08	<0.001	−5.82	<0.001
Hardest versus Softest	−7.14	<0.001	−6.49	<0.001
Not-so-soft-not-so-hard versus Softer	−6.80	<0.001	−3.99	<0.001
Harder versus Softer	−7.02	<0.001	−5.65	<0.001
Hardest versus Softer	−7.08	<0.001	−6.34	<0.001
Harder versus Not-so-soft-not-so-hard	−6.80	<0.001	−4.18	<0.001
Hardest versus Not-so-soft-not-so-hard	−7.02	<0.001	−6.16	<0.001
Hardest versus Harder	−7.08	<0.001	−6.37	<0.001

Note. The *z* values are standardized test statistic values, and *p* values are values with Bonferroni correction. A negative (−) value of *z* indicates that the second stimulus of the pair received a rank higher than the first stimulus, and a positive (+) value of *z* (if any) indicates the other way round. Only significant values are shown.

3.2.2 *Tactile Preference as a Function of Physical Magnitude of 3D Softness/Hardness*

Fig. 7(b) displays visual experience-based group means of *stimulus preference* connected by line charts for five 3D tactile stimuli of varying physical softness levels. This figure shows that, on average, all three groups of participants highly conformed to put the set of five 3D tactile stimuli in order of a similar fashion of preference, with the congenitally blind group receiving a preference score of 1.22 (for the hardest) to 4.56 (for the softest), the late blind group receiving a preference score of 1.07 (for the hardest) to 4.57 (for the softest), and the blindfolded sighted group receiving a preference score of 1.16 (for the hardest) to 4.58 (for the softest). The highly overlapping line charts for all three groups of participants indicate that the *stimulus preference* rank has a negative monotonic relationship with the *physical magnitude of 3D hardness*, comprising a perfect negative correlation for each of the three visual groups (Spearman's rank-order $r = -1.00$). Fig. 8(b) displays violin plots of preference ranks for individual stimuli for all participants combined irrespective of visual experience. This figure shows that the overall shape and distribution of preference ranks dramatically differ across the physical softness levels of the stimuli. It appears that with increasing physical softness of the stimuli, the distributions tend to comprise higher preference ranks that tend to be highly concentrated above the mean or median. Analysis of rank distributions in a Friedman's nonparametric

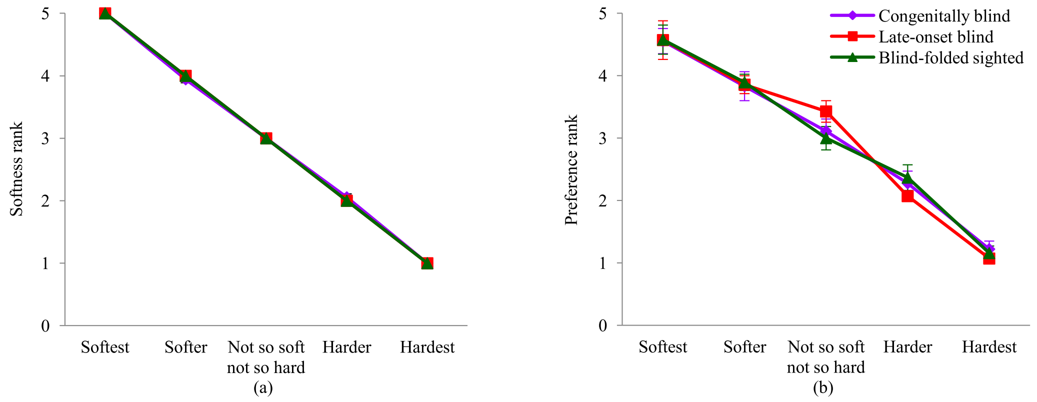


Figure 7. (a) Mean softness ranks, and (b) mean preference ranks across three visual experience groups in relation to physical softness level of 3D tactile stimuli. Error bars represent standard errors of the corresponding group means.

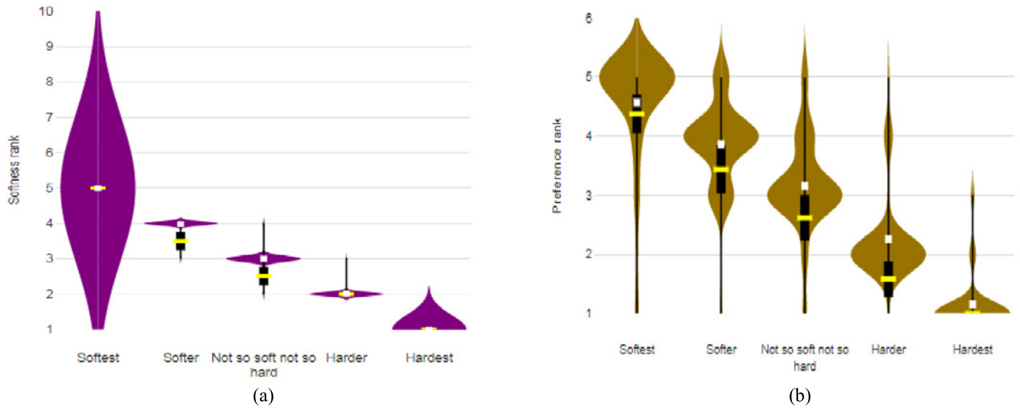


Figure 8. Violin plots showing density distributions of (a) softness ranks and (b) preference ranks for five 3D tactile stimuli of varying physical softness levels for all participants combined.

ANOVA demonstrated that participants' *preference* for a 3D tactile stimulus significantly varied across the *physical levels of stimulus softness* ($\chi_r^2(4) = 146.51$, $p < 0.001$, $W = 0.718$). Post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected p values as summarized in Table IV show that the preference rank was significantly and consistently higher for the *softer* than the harder stimuli.

3.2.3 *Tactile Aesthetics as a Function of Physical Magnitude of 3D Softness/Hardness*

We plot the data for three affective dimensions (*Relaxation, Hedonics, and Arousal* that underlie *aesthetic appreciation*) as a function of *physical magnitude of 3D softness/hardness* in Figures 9 and 10. Fig. 9 displays mean ranks for individual stimuli on each of the three affective dimensions connected by line charts separately for three visual experience groups, as well as for all participants combined. Fig. 10 displays violin plots of rank distributions of the three affective dimensions for individual stimuli for all participants combined irrespective of visual experience. Fig. 9 shows that for the blindfolded sighted group and the combined group, the physically softest and softer stimuli received, on average, considerably higher ranks on the *Relaxation* and *Hedonics* dimensions as compared to the *Arousal* dimension, whereas the physically hardest and harder stimuli received, on average, considerably higher ranks on the *Arousal* dimension as compared to the *Relaxation* and *Hedonics* dimensions, with the *not-so-soft-not-so-hard* stimulus receiving a rank closest to the middle of the five-point ranking scale on all three affective dimensions. The line charts indicate that the *Relaxation* rank, *Hedonics* rank, and *Arousal* rank all have a negative monotonic relationship with the *magnitude of physical hardness*, not only when the data are plotted for all participants combined, but for individual groups as well (Spearman's rank-order $r = -1.00$ for each affective dimension). Here, the *Relaxation, Hedonics*, and *Arousal* dimensions were perfectly positively correlated with each other (Spearman's rank-order $r = +1.00$). Fig. 10 shows that the overall shape and distribution of ranks for each affective dimension dramatically differ across the physical softness levels of the stimuli, with some stimuli having much more elongated distributions compared to the other stimuli. It appears that with increasing physical softness, the distributions for all three affective dimensions tend to comprise higher ranks that tend to be highly concentrated above the mean or median.

Now, analysis of the data for affective dimensions in Friedman's nonparametric ANOVAs demonstrated that the

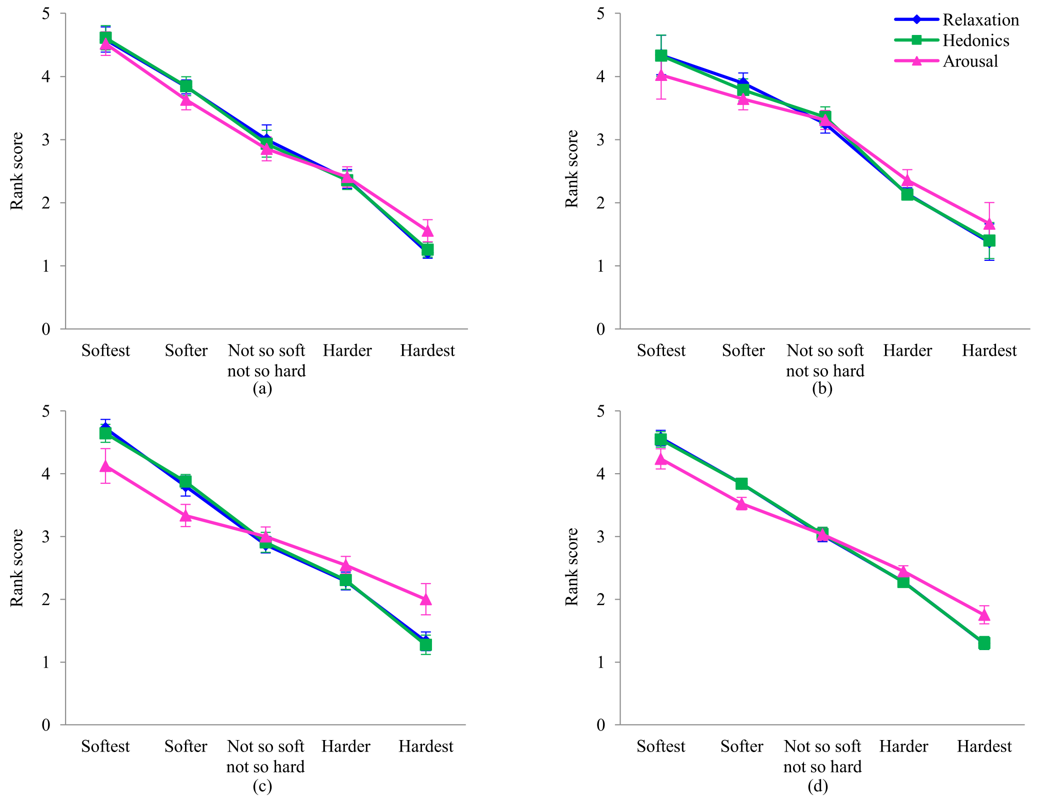


Figure 9. Mean ranks assigned to three affective dimensions of aesthetics: Relaxation, Hedonics, and Arousal in relation to physical softness level of 3D tactile stimuli. (a) Congenitally blind, (b) Late blind, (c) Blindfolded sighted, (d) All participants combined irrespective of visual experience. The *Relaxation*, *Hedonics*, and *Arousal* scores were determined by averaging the assigned ranks over the corresponding implicit attributes of these affective dimensions. Error bars represent standard errors of the corresponding means.

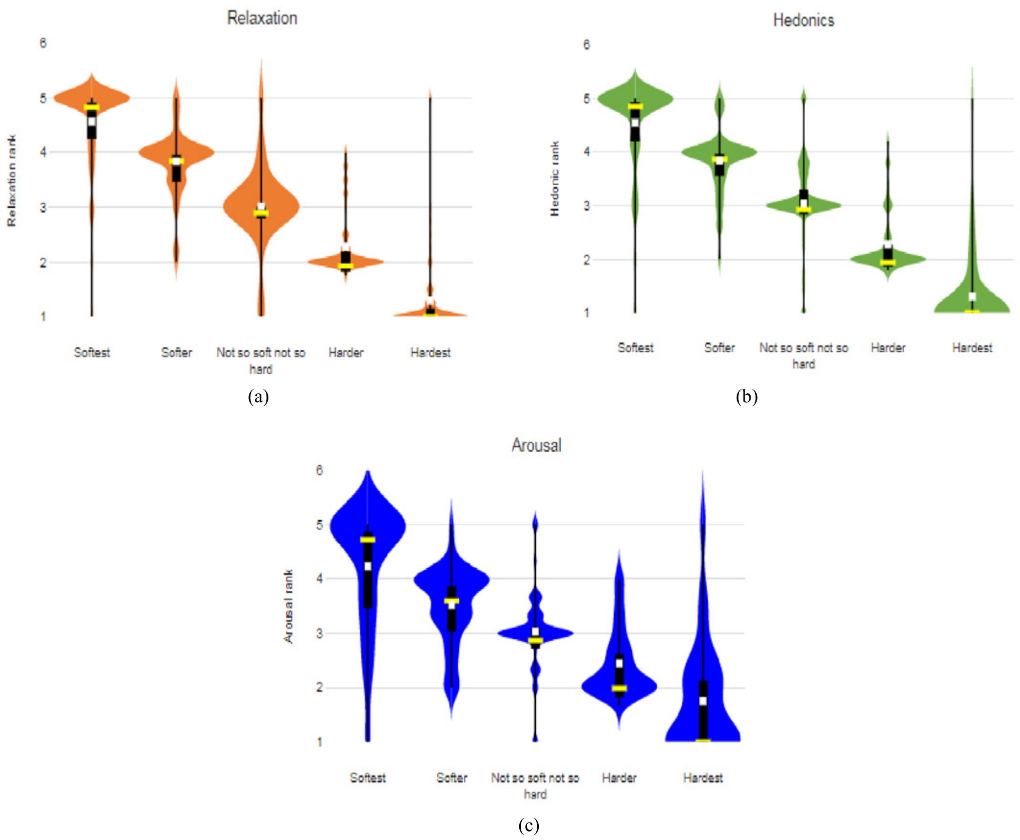
Table V. Wilcoxon signed-rank test results of post hoc analysis for pairwise comparison of five 3D stimuli on three affective dimensions of tactile aesthetics.

3D stimulus (cube) pair	Relaxation		Hedonics		Arousal	
	z	*p*	*z*	*p*	*z*	*p*
Softer versus Softest	−4.03	<0.001	−3.96	<0.001	−3.81	<0.001
Not-so-soft-not-so-hard versus Softest	−5.05	<0.001	−5.00	<0.001	−4.15	<0.001
Harder versus Softest	−6.07	<0.001	−6.05	<0.001	−5.32	<0.001
Hardest versus Softest	−5.99	<0.001	−5.99	<0.001	−5.40	<0.001
Not-so-soft-not-so-hard versus Softer	−4.76	<0.001	−4.99	<0.001	−3.79	<0.001
Harder versus Softer	−5.87	<0.001	−5.94	<0.001	−4.70	<0.001
Hardest versus Softer	−6.01	<0.001	−5.95	<0.001	−5.01	<0.001
Harder versus Not-so-soft-not-so-hard	−4.39	<0.001	−4.26	<0.001	−3.83	<0.001
Hardest versus Not-so-soft-not-so-hard	−6.02	<0.001	−6.00	<0.001	−4.96	<0.001
Hardest versus Harder	−6.03	<0.001	−5.78	<0.001	−5.06	<0.001

Note. The *z* values are standardized test statistic values, and *p* values are values with Bonferroni correction. A negative (−) value of *z* indicates that the second stimulus of the pair received a rank higher than the first stimulus, and a positive (+) value of *z* (if any) indicates the other way round. Only significant values are shown.

rank distributions for *Relaxation*, *Hedonics*, and *Arousal* all significantly varied across the *physical levels of 3D softness* ($\chi_r^2(4) = 143.74$, $p < 0.001$, $W = 0.705$ for *Relaxation*; $\chi_r^2(4) = 139.46$, $p < 0.001$, $W = 0.684$ for *Hedonics*; $\chi_r^2(4) = 98.31$, $p < 0.001$, $W = 0.482$ for *Arousal*). A series of post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected *p* values summarized in Table V show that the *Relaxation* rank, *Hedonics* rank, and *Arousal* rank were all significantly higher for the *softer* than the *harder* stimuli.

Finally, to see whether the differences among the three affective dimensions were significant, comparative analyses



(a) (b)

(c)

Figure 10. Violin plots showing density distributions of affective ranks for five 3D tactile stimuli of varying physical softness levels for all participants combined. (a) *Relaxation*, (b) *Hedonics*, and (c) *Arousal*.

Table VI. Wilcoxon signed-rank test results of post hoc analysis for pairwise comparison of three affective dimensions of aesthetics on stimuli of various softness levels.

Affective dimension pair	Softest		Softer		Not-so-soft-not-so-hard		Harder		Hardest	
	z	p	z	p	z	p	z	p	z	p
Relaxation versus Hedonics										
Relaxation versus Arousal	+2.20	0.084	+3.06	0.006			−2.29	0.066	−3.31	0.003
Hedonics versus Arousal	+2.22	0.081	+3.02	0.009			−2.64	0.024	−3.66	<0.001

Note. The z values are standardized test statistic values, and p values are values with Bonferroni correction. A negative (−) value of z indicates that the second affective dimension of the pair received a rank higher than the first affective dimension, and a positive (+) value of z indicates the other way round. Only significant and nearly significant values are shown.

were done on the *Relaxation, Hedonics*, and *Arousal* data for all participants combined using a series of Friedman's nonparametric ANOVAs for related samples. Results at individual (physical) softness levels of the stimuli showed that there were significant differences among the rank distributions for *Relaxation*, *Hedonics*, and *Arousal* at the softest ($\chi_r^2(2) = 8.35$, $p = 0.015$, $W = 0.082$), the softer ($\chi_r^2(2) = 9.98$, $p = 0.007$, $W = 0.098$), the harder ($\chi_r^2(2) = 9.06$, $p = 0.011$, $W = 0.089$), and the hardest ($\chi_r^2(2) = 17.35$, $p < 0.001$, $W = 0.170$) levels, but not at the *not-so-soft-not-so-hard* level of the stimulus. Post hoc analyses using Wilcoxon signed-rank tests with Bonferroni corrected p values as summarized in Table VI demonstrated that the softest stimulus received a nearly significantly smaller *Arousal* rank than *Relaxation* and *Hedonics* ranks, and the softer stimulus received a significantly smaller *Arousal* rank than *Relaxation* and *Hedonics* ranks. On the contrary, the harder stimulus received a significantly or nearly significantly higher *Arousal* rank than *Relaxation* and *Hedonics* ranks, and the hardest stimulus received a significantly higher *Arousal* rank than *Relaxation* and *Hedonics* ranks.

4. GENERAL DISCUSSION

Using a novel behavioral (rank ordering) approach, we conducted two exploratory experiments to examine for the first time the effects of visual experience and texture parameters on tactile stimulus preference and tactile aesthetic appreciation, in addition to replicating the effects of these factors on basic tactile discrimination.

Analysis of the data in appropriate statistics demonstrated significant effects of textures but no effect of visual experience on all these behavioral judgments. Specifically, it was shown that the basic sensory discrimination of tactile smoothness or softness, smoothness or softness preference, and appreciation of smoothness or softness on three affective dimensions, *Relaxation*, *Hedonics*, and *Arousal*, did not differ between the congenitally blind, late blind, and blindfolded sighted populations. This implies that visual experience is not required for (or does not affect) the emergence of basic, preferred, and aesthetic mental representations of tactile textures. However, specific texture parameters, such as 2D tactile smoothness and 3D tactile softness, were found to have significant impacts on basic tactile discrimination, tactile stimulus preference, and all three affective dimensions of tactile aesthetics. More specifically, we found that tactile stimuli received proportionally higher smoothness or softness ranks with the increasing physical magnitude of 2D smoothness or 3D softness, indicating finer tactile discriminability of humans irrespective of visual experience. Second, physically smoother or softer stimuli were associated with higher ranks in stimulus preference (Figs. 3(b), 4(b), 7(b), 8(b)) and stimulus appraisal on *Relaxation* and *Hedonics* dimensions of aesthetics (Figs. 5, 6, 9, 10). However, in contrast to the 2D smoother stimuli that were associated with lower ranks on *Arousal* (Figs. 5, 6) the 3D softer stimuli were associated with higher ranks on this dimension (Figs. 9, 10).

The demonstration that visual experience plays no significant role in shaping tactile texture perception is consistent with both theoretical views [59, 62, 69] and prior empirical observations [7, 43]. For example, Lederman and Klatzky [69] theorized that the tactile perception of surface structure does not always require mediation by visual imagery. They posit that touch may provide optimal performance when people attempt to identify multidimensional stimuli like common 3D objects that can vary along a number of substance-related dimensions [61]. The sense of touch may perform well in the apprehension of texture (e.g., roughness, hardness), thermal properties and weight, and thus direct tactile encoding likely operates for these qualities, without requiring any visual imagery. In line with this theoretical argument, prior empirical studies showed that visual imagery or experience is not necessary for texture perception as proven by the lack of differences between blind and blindfolded sighted participants in tactile roughness or hardness perception [7, 43]. Though visual experience is not mandatory or advantageous for the development of tactile discriminability, some studies suggested that the lack of visual experience in the blind might lead to superior performance in tactile acuity (e.g., Braille recognition, grating acuity; [12, 37, 72, 91]) and 3D tactile shape discrimination [37, 55, 91] tasks as it is thought to be compensated by heightened tactile experience in their everyday life. Here, we did not find any evidence for this kind of compensatory tactile benefit in the blind. Research has suggested that blind people are able to perform tactile tasks much faster than sighted people [44, 45]. In the present study, we did not test participant's performance speed; instead, we allocated equal amount of time to both the blindfolded sighted and blind groups for stimulus exploration. Thus, we contend that the equal amount of time might have enabled the sighted group to perform to a level equal to the performance level of the blind groups.

As outlined above, visual experience cannot mediate *Relaxation*, *Hedonics*, and *Arousal* dimensions that likely underlie texture preference and aesthetic appraisal of textures. Here, it is important to stress on the limitation of the current literature that neither theoretical views nor empirical findings tell us anything about texture *preference* and texture *aesthetics*. The findings of the present study fill this gap by explicitly demonstrating that visual experience is not necessary for shaping preference for and appreciation of tactile objects with such microspatial property as smoothness and softness. In line with this, one prior study demonstrated that the preference for and appreciation of tactile objects with macrospatial properties (shape, pattern) were not dependent on the level of visual experience [55]. Thus, combining the findings of the present study together with those of that prior study [55], we conclude that visual coding of tactile stimuli or objects is neither necessary nor advantageous for tactile preference and tactile appreciation, and that this notion may equally apply to the stimuli with macrospatial properties (e.g., shape, size, orientation), and those with microspatial properties (e.g., roughness, hardness) as well. This novel notion derived from the findings of our present and prior controlled experimentations challenge the claim of an early uncontrolled experiment that tactile aesthetic preference and appreciation can be associated with visual experience [103]. The present evidence against the role of visual experience in tactile aesthetic preference and appreciation further rules out the prior notion that the visually impaired individuals tend to be more "subjective", and the sighted children tend to be fairly "objective" in tactile aesthetic preference and appreciation [103], and lends direct support to Diderot's philosophical supposition that the blind can be as practical and objective as the sighted in the assessment of tactile objects [25, 86]. However, preclusion of the role of visual experience does not necessarily deny experience-driven tactile aesthetic preference and appreciation (e.g., prior experience associated with emotional valence or aesthetically pleasant/unpleasant tactile objects) as can be speculated from a pool of prior research in visual arts and aesthetics [57, 84, 101, 117, 119, 120].

Analysis of the *effects of texture parameters* reflects some important aspects of our study. One such aspect is that the *basic tactile discrimination* varied highly proportionally as a function of each of the two physical stimulus properties: 2D tactile smoothness/roughness and 3D tactile softness/hardness. Irrespective of visual experience, participants were able to *discriminate* not only between the smoothest and roughest 2D tactile surfaces but between the 2D surfaces with *intermediate* levels of smoothness as well (Figs. 3(a), 4(a), Table I). Similarly, they were able to discriminate not only between the softest and hardest stimuli, but between the stimuli of intermediate levels of softness as well (Figs. 7(a), 8(a), Table IV). These findings are supported by the findings of a number of prior studies. For example, as discussed earlier, some studies demonstrated that the perceived roughness of a stimulus surface varies as an approximate power function of the physical magnitude of roughness [30, 115], while other studies revealed that the perceived magnitude of softness increased monotonically as a function of increasing object compliance, leveling off around the end of the stimulus range [96].

Because touch is the first sense that humans develop and the first sense they use to explore and apprehend the environment [33], the aforementioned findings together with prior research findings [7, 30, 43, 96, 115] suggest that perhaps humans are inherently capable of fine texture detection using the tactile modality alone. This vision-independent high level of texture detection capability can be explained by spatial variations in the firing rate of mechanoreceptive neurons. Although there is no study thus far to interpret neural encoding of tactile softness sensation, studies addressing the neural codes underlying sensation of tactile roughness have shown that the perceived tactile roughness is related to spatial variations in the firing rate of slowly adapting Type I mechanoreceptive neurons [11, 19, 20]. One recent study demonstrated that a surface is felt rough to the extent that the activity varies across nerve fibers and across time within nerve fibers, and this activity variation-based neural code can account not only for magnitude estimates of roughness but for roughness discrimination performance as well [74]. A more recent study in rhesus macaques has shown that a subpopulation of somatosensory neurons preferentially encodes coarse textural features, whereas a second subpopulation of neurons preferentially encodes fine textural features in tactile stimuli [73]. We propose that such type of neural coding might also operate in humans, enabling fine textural discrimination.

A second important aspect of our study is that the tactile *stimulus preference* varied monotonically (not exactly proportionally) as a function of 2D smoothness/roughness or 3D softness/hardness. Irrespective of visual experience, participants preferred 2D *smoother* surfaces over 2D *rougher* surfaces (Figs. 3(b), 4(b), Table I), and *softer cubes* over *harder* cubes (Figs. 7(b), 8(b), Table IV), with strongest preference going for the *softest cube*, and weakest for the *hardest cube* as compared to preferences for all other cubes and 2D stimuli (Figs. 3(b), 4(b), 7(b), 8(b)). In support of the former part of this, prior studies in sighted individuals showed that stimulus preference (proportionally) increased with increasing magnitude of stimulus smoothness or softness [30, 47]. The current literature cannot tell anything about the second part. However, it was typical to exhibit strongest preference for the softest cube because all the roughest surfaces were in fact hard to a certain extent, and here, it has been evident that the preference was weakest for the hardest cube. These findings together suggest two related propositions about sensing tactile aesthetics. First, aesthetic preference for a textured stimulus is inversely related to texture sensitivity, which typically increases with the physical level of roughness or hardness (see [26, 31]). Second, because pleasure and interest are considered as two distinct routes to liking an object/event, the smoother or softer tactile stimuli appear to be more hedonic, that is, more pleasant and/or more interesting [38]. This latter notion has been further corroborated by the findings of our present study as discussed below.

A third important and novel aspect of our study is that it was the first to provide insight into the amodal nature of sensory aesthetics, suggesting that all three affective dimensions, such as *Relaxation*, *Hedonics*, and *Arousal* identified for visual arts and aesthetics ([82]; see also [107]) also likely underlie appreciation of tactile arts and aesthetics. Moreover, as indicated in the aesthetic profile for participants irrespective of visual experience, the *Arousal* dimension appears to be independent (does not mean uncorrelated) of the *Relaxation* and *Hedonics* dimensions in smoothness appreciation (Fig. 5(d)), though it is not clear in softness appreciation (Fig. 9(d)). These findings are partly consistent with the circumplex model, the most widely known dimensional model of emotion [104, 105], which distinguishes hedonic valence (pleasure–displeasure) and arousal (activating–relaxing) as two orthogonal dimensions of an emotional experience, and are inconsistent with Berlyne's psychobiological model of aesthetics which posits an inverted-U shaped relationship between arousal potential of a stimulus and hedonic experience, with an intermediate level of arousal corresponding to maximum pleasure [10]. Thus, we conclude that unlike Berlyne's view [10], the *Hedonics* and *Arousal* dimensions are not always positively associated; rather they might be orthogonal depending on stimulus properties. However, further quantitative studies are warranted to statistically validate these dimensions and their orthogonality in the tactile domain. Because of the ordinal nature of our data such a quantitative analysis (e.g., factor analysis) deemed to the extraction of response dimensions was not feasible in the current study.

A fourth interesting and novel aspect of our study is the demonstration that ranking aesthetic quality on each of the proposed dimensions (the degree to which Relaxational, Hedonic and Arousal attributes are present or absent in a tangible object) varied monotonically, with a negative or positive relationship, as a function of stimulus roughness or hardness. The monotonic functions of the *Relaxation* and *Hedonics* dimensions comprised a negative relationship, indicating that the rank assigned on each of these two dimensions decreased with increasing roughness (Fig. 5) or hardness (Fig. 9). These findings are consistent with prior studies that were limited to examining tactile *Hedonics* only. As discussed earlier, studies of sighted individuals in the tactile domain revealed that the perceived magnitude of pleasantness of tactile sensation was inversely related to the physical or estimated magnitude of surface roughness [58, 63, 115], and positively with softness estimates or object compliance [96]. Because physically smooth or soft stimuli engender less friction [31, 64, 65], other studies in sighted humans demonstrated that people rate physically smooth and soft stimuli as more pleasing than physically rough and hard stimuli under both active [32, 79, 102] and passive [29, 31, 32] touch conditions.

A fifth, more interesting and novel aspect of our study is that the monotonic function of *Arousal* was positive with stimulus roughness in contrast to negative with hardness, which indicates that the felt *Arousal* increased with physical roughness but decreased with physical hardness. This difference between the two *Arousal* trends might be due to the fact that roughness is a source of irritation and pain, but hardness is not much like that. However, there are also some similarities between the smoothness and softness dimensions. As demonstrated for the blindfolded sighted (Figs. 5(c) and 9(c)) and for all participants irrespective of visual experience (Figs. 5(d) and 9(d); Table III), the physically softest and softer 3D stimuli, like the physically smoothest and smoother 2D stimuli, received higher ranks on the *Relaxation* and *Hedonics* dimensions as compared to the *Arousal* dimension, and on the contrary, the physically hardest and harder stimuli, like the physically roughest and rougher stimuli, received higher ranks on the *Arousal* dimension as compared to both the *Relaxation* and *Hedonics* dimensions. However, the differences between the *Arousal* dimension on the one hand and *Relaxation* and *Hedonics* dimensions on the other at the softest, softer, hardest, and harder stimulus levels was substantially apparent in the blindfolded sighted group (Fig. 9(c)), with a little tendency in the late (Fig. 9(b)) but not in the congenitally blind group (Fig. 9(a)). This implies that in 3D softness appreciation task, the blindfolded sighted group differed from both the blind groups on the affective dimensions across the physical levels of 3D softness/hardness; however, this kind of difference was not observed in 2D smoothness appreciation task (Figs. 5(a),(b),(c)). Thus the difference between the sighted and blind individuals on the affective dimensions here cannot be attributed to visual experience but to such stimulus property as texture type.

Inspection of Fig. 9 further indicates that the line charts for *Relaxation* and *Hedonics* dimensions perfectly overlapped with one another across all the physical softness/hardness levels of 3D stimuli; however, such an overlap was not present across the physical smoothness/roughness levels of 2D stimuli (Fig. 5). *Relaxation* is sometimes thought to be a component of hedonic orientation (see [4–6, 13, 15, 36]). Thus, it is likely that what is hedonically pleasant can simultaneously be equally relaxing or calming in a particular context but not in another context as happened in the present study.

It follows from the above findings that irrespective of visual experience, the 2D *smoother* stimuli were more strongly characterized by *Relaxation*-oriented slightly intense affective attributes, such as calming, relaxing, soothing, comfortable, or by *Hedonics*-oriented moderately intense affective attributes, such as pleasant, desirable, enjoyable, sensual, and appealing (Figs. 5(d), 6(a),(b)). On the contrary, the *rougher* tactile stimuli were more strongly characterized by *Arousal*-oriented highly intense affective attributes, such as enlivening, exciting, thrilling, and irritating (Figs. 5(d), 6(c)). However, a different picture was observed for softer–harder comparison in the aesthetic profile. Overall, the physically softer stimuli were characterized more strongly by the *Hedonics*- and *Relaxation*-oriented affective attributes than by the *Arousal*-oriented affective attributes (Figs. 9(d) and 10; Table VI). On the contrary, the physically harder stimuli showed a tendency to be characterized more strongly by the *Arousal*-oriented highly intense affective attributes than by the other two sorts of affective attributes (Figs. 9(d) and 10; Table VI). Thus tactile aesthetic appreciation is determined by physical properties of objects or stimuli.

To summarize, the aforementioned striking differences between the forms of appreciation of 2D smoothness and 3D softness across the affective dimensions of the aesthetic profile suggest unanticipated substructures in the nascent field of tactile aesthetics. We conclude that by examining a variety of implicit attributes encompassing all three affective dimensions and relating each dimension with the physical magnitude of 2D smoothness and 3D softness, the two prominent forms of tactile textures, the present study gives us a full-fledged understanding of the affective structure of tactile aesthetics that apply not only for the sighted but for the blind as well.

5. CONCLUSIONS

To the best of our knowledge, this exploratory study was the first to experimentally investigate aesthetic preference for and aesthetic appreciation of tactile objects as a function of visual experience and tangible texture. This gave us an opportunity to examine for the first time the applicability of three-dimensional affective structure of visual aesthetics (*Relaxation*, *Hedonics*, and *Arousal*; [82]) to the understanding of tactile aesthetics. Studying groups of congenitally blind, late blind, and temporarily blinded (blindfolded) sighted individuals by employing a novel behavioral approach (rank ordering), we revealed that contrary to what might be expected, visual experience is not required for shaping tactile aesthetic preference and tactile aesthetic appreciation, in addition to showing the same for basic tactile discrimination.

We further showed the evidence that tactile texture parameters, such as 2D smoothness and 3D softness, can significantly impact aesthetic preference and the aforementioned three affective dimensions of aesthetic sensation, in addition to impacting basic tactile discrimination. Based on these novel and interesting findings, we conclude that the three-dimensional affective structure of visual arts and aesthetics ([82]; see also [107]) is amodal and applicable to tactile arts and aesthetics not only in the sighted but in the blind as well. However, analysis of the aesthetic profile across the affective dimensions reveals striking differences between the forms of appreciation of 2D smoothness and 3D softness, suggesting unanticipated substructures in the nascent field of tactile aesthetics. Depending on the nature of object textures we experience, the tactile modality differentially senses and perceives environmental objects, making differential affective responses to them. As found in the present study, our felt relaxation and hedonics may highly overlap in sensing and appreciating objects of varying softness levels, but markedly differ in sensing and appreciating objects of varying smoothness levels, with the arousal having an inverse relationship with smoothness level but a positive relationship with softness level.

The novel and interesting findings presented here can have a wide range of theoretical and practical implications. One theoretical implication is that there might be an inherent nature to the coding of tactile perception, tactile preferences, and tactile aesthetics, independent of visual experience. Practically, the findings can inform decisions in future design of tactile arts, tactile objects/products, tools, and technology sensitive to the blind community, yet applicable to the sighted as well. Designing the tactile environments using such a nondifferential approach will strengthen mood and confidence of the blind, enhancing their capability and productivity. The findings also provide novel and highly informative insights to guide the design of future research on the affective structure of tactile aesthetics in relation to a variety of tactile properties. Finally, this study opens the door to expanded experimental investigation of tactile preferences and tactile aesthetics in the blind and the sighted.

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