Behavioural Brain Research 208 (2010) 473–478

Contents lists available at ScienceDirect

Behavioural Brain Research

journal homepage: www.elsevier.com/locate/bbr

Research report

Tactile roughness discrimination threshold is unrelated to tactile spatial acuity

Xavier Libouton [a,b], Olivier Barbier [b], Leon Plaghki [a], Jean-Louis Thonnard [a,*]

[a] *Rehabilitation and Physical Medicine Unit, Université catholique de Louvain, Brussels, Belgium*
[b] *Department of Orthopaedics, Cliniques universitaires Saint-Luc, Brussels, Belgium*

ARTICLE INFO

Article history:
Received 13 October 2009
Received in revised form
14 December 2009
Accepted 16 December 2009
Available online 24 December 2009

Keywords:
Tactile roughness discrimination
Tactile spatial resolution acuity
Psychophysics
Texture
Threshold

ABSTRACT

The present study examined the relationship between the tactile roughness discrimination threshold (TRDT) and the tactile spatial resolution threshold (TSRT) at the index fingertip in humans. A new device was built for measuring TRDT, allowing pair-wise presentations of two sets of six different sandpaper grits. The smoothest grits ranged from 18 to 40 μm and the roughest grits ranged from 50 to 195 μm particle size. The reference sandpaper had a 46 μm particle size. A two-alternative forced choice paradigm and a double interlaced adaptive staircase procedure yielding a 75% just noticeable difference (75%jnd) was used according to Zwislocki and Relkin [28]. Contact force and scanning velocity were measured at the fingertip with a built-in sensor. The TSRT was assessed with an extended set of grating domes. Fifty-three male and female subjects, spanning a wide age range participated in this study. The JND75% or TRDT was lower for the smoothest sandpapers (15 ± 8.5 μm) compared to the roughest sandpapers (44 ± 32.5 μm). TRDT performance was unrelated to age or gender. Additionally, grit size had no effect on the mean forces (normal and tangential) exerted at the fingertip or the mean scan velocities. In contrast, there was a significant degradation of TSRT performance with age. Lastly, there was no significant correlation between TRDT and TRST performance. Results of this study support the theory that the neural mechanisms underlying the perception of tactile roughness discrimination for fine textures differ from those involved in spatial resolution acuity often associated with the SA1 afferents.

1. Introduction

Early in the twentieth century, Katz [18] argued that coarse texture perception is primarily mediated by spatial encoding while fine texture perception is primarily mediated by temporal encoding (e.g., vibrotaction). This conception has been called the “duplex theory of tactile texture perception” [10,14]. Subsequently, the validity of this theory was questioned on empirical grounds. For instance, Lederman [19], using a series of precisely machined metal gratings as stimuli, found that the spatial parameters of gratings exerted a chief influence on texture perception, while the speed of movement of the fingertip across the grating contributed little to texture discrimination. Connor and Johnson [5] further compared the relative ability of hypothetical spatial and temporal coding mechanisms to account for roughness perception. They examined the neural basis of spatial encoding in monkeys and their findings implicated the involvement of slow adapting type 1 (SA1) mechanosensitive afferents, rather than those mediating vibrotaction. In recent years, however, new experimental evidence has accumulated to support Katz’s view that vibrotaction plays a role in the perception of textures whose elements are too small and closely spaced to be processed spatially [12] and even for the perception of relatively coarse textures [3,7]. Currently, it is assumed that spatial and temporal coding mechanisms can operate in isolation, but that in ecological conditions they work together to enhance the tactile perception of texture.

Texture perception is multidimensional with two orthogonal dimensions: roughness/smoothness and hardness/softness [13]. Most research examining tactile texture perception has focused specifically on the highly prominent perceptual dimension of roughness. The present experiments dealt chiefly with this perception. More precisely, we aimed to determine the just noticeable difference (JND) threshold for roughness discrimination under moving conditions [8]. For this purpose, we designed and built a device that allows pair-wise presentations of sandpapers with different particle sizes in a two-alternative forced choice procedure. Furthermore, to characterize the moving conditions, the sandpapers were mounted on a 3D force plate allowing measurement of the force exerted by the fingertip and the scanning velocity of the lateral movement. We hypothesized that force and scanning velocity may be related to texture discrimination performance, as subjects may spontaneously alter these variables for optimal performance. Finally, to further explore the involvement of spatial and temporal coding mechanisms in the perception of roughness, we

* Corresponding author at: Université catholique de Louvain, Unité de Réadaptation et de Médecine Physique (READ 5375), Tour Pasteur, 53, Av Mounier, 1200 Bruxelles, Belgium. Tel.: +32 2 764 53 67; fax: +32 2 764 53 60.
E-mail address: jean-louis.thonnard@uclouvain.be (J.-L. Thonnard).

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doi:10.1016/j.bbr.2009.12.017

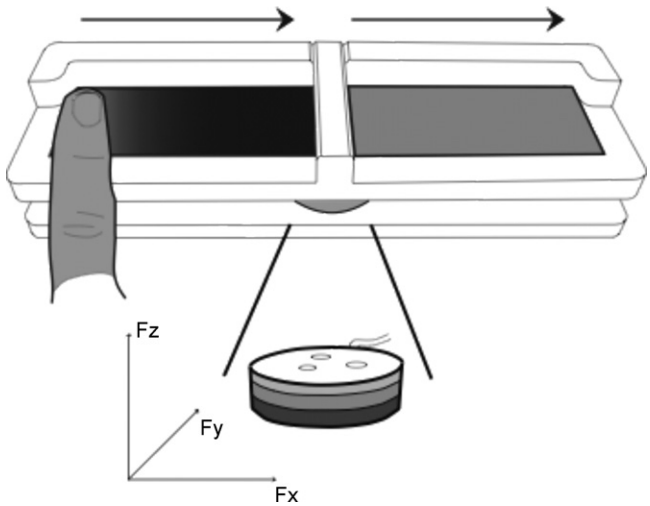

Fig. 1. The device designed and built for the measurement of roughness discrimination threshold. Each test stimulus is located on one side of the upper plate. The focus illustrates the three-dimensional force sensor. F_x and F_y correspond to the tangential force in the scanning direction and F_z to the normal force.

also measured tactile spatial threshold, using the well-known grating orientation task [6,9,23,25].

2. Materials and methods

2.1. Subjects

Fifty-three healthy subjects (28 women and 25 men) participated in the study and were recruited among students of the Université catholique de Louvain and members of their families. All subjects underwent a diagnostic interview by a physician and were included in the study when considered free from diseases or injury that could affect the tactile sensitivity of their hands. Subjects were between 7 and 90 years of age. No inducement was offered for participation. The Ethics Committee of the Université catholique de Louvain approved the experimental procedures, and all subjects, including the parents of child subjects, gave written informed consent.

2.2. Test descriptions

2.2.1. Roughness discrimination task

The subject was comfortably seated at a table facing the experimenter and was requested to position the index of the dominant hand just in front of two textured surfaces, each 7.5 cm × 3.0 cm (Fig. 1). A cardboard screen was placed over the participant's wrist to block the view of their hand. Without further instructions, the participant was asked to slide the fingertip of their index finger on the first stimulus (located on the left side) and then subsequently on the second stimulus (located on the right side). After each trial, the participant was asked to discriminate the textures by reporting which was the rougher surface. Between trials, the subject raised their index finger to allow the experimenter to reposition it on the left side for the presentation of the next stimulus. The subject scanned each stimulus with a single sweep using contact force and scanning velocity that seemed to be most appropriate to them. Headphones were used to muffle any extraneous noise.

Thirteen sandpapers (see Table 1), with average grit sizes varying from 18 μm (grit number P1000—the smoothest stimulus) to 195 μm (grit number P80—the roughest stimulus) were used as stimuli. The set of sandpapers used for this study came from the same manufacturer (SIA abrasives industries®). Grit number and particle size ("micron grade") were according to the Federation of European Producers of Abrasive Products (FEPA) P-grading system.

Two tactile roughness discrimination thresholds (TRDT) were determined using a double interlaced adaptive staircase procedure based on a two-alternative forced choice paradigm (Fig. 2). The stimulus dimension at which static information does not contribute significantly to texture discrimination has been estimated to be ≤100 μm [14]. Therefore we choose P320 sandpaper (average particle size of 46 μm) as our reference stimulus (i.e. about halfway between 100 μm and full smoothness). The reference was present in each trial and randomly located on the left or right side. The first and second staircase started with the P800 (smooth) and P100 (rough) stimuli, respectively. After each trial, we moved from one staircase (smooth or rough) to the other (see Fig. 2). As a result, odd trials were comprised of the staircase in which the smoother textured stimuli (P800 to P360) were compared to the reference (P320) while even trials were comprised of the staircase in which the rougher textured stimuli (P100 to P240) were compared to the reference. We measured the tactile roughness discrimination threshold, which was defined as the amount of change required to produce a 75% just noticeable difference (75%jnd) in sensation. The stimulus difference was defined as the difference in particle size between a given stimulus and the reference stimulus (P320). Using the algorithm proposed by Zwislocki and Relkin [28], the rules for stimulus difference (or intensity variation) were as follow: in each staircase, after every incorrect response, the stimulus difference was increased; after three correct responses, not necessarily in consecutive order, the stimulus difference was reduced (see Fig. 2). The procedure was discontinued when in the same staircase (smooth or rough) the number of up and down stimulus differences after the first mistake was equal. In this way, in each staircase, the stimulus difference was expected to track the 75% correct response threshold, i.e. the 75% just noticeable difference (75%jnd). A few subjects were able to correctly discriminate the smallest difference in particle size (P240 and/or P360 against reference P320). Their discrimination performance exceeded the limit of resolution of the stimuli. For these subjects, we allowed a threshold value of half the smallest difference in particle size.

Table 1
Set of sandpapers.

	Stimulus no.	FEPA[a] P-grade	Average grit size (μm)
Smooth	13	P1000	18
	12	P800	22
	11	P600	25.8
	10	P500	30
	9	P400	35
	8	P360	40
Reference surface	7	P320	46
	6	P240	58
	5	P220	65
	4	P180	78
	3	P120	127
	2	P100	156
Rough	1	P80	195

[a] Federation of European Producers of Abrasives.

2.2.1.1. Apparatus.

Sandpapers were mounted on a platform (Fig. 1) linked to a force–torque sensor (Mini 40 F/T transducer; ATI Industrial Automation, NC, USA). The sensor measured the three force (F_x, F_y, F_z) components exerted by the fingertip on the platform. The sensing ranges for F_x, F_y and F_z were ±40 N, ±40 N and ±120 N with 0.01 N, 0.01 N and 0.02 N nominal resolutions, respectively. The torques and forces measured by the sensors were used to determine the center of pressure (CP)

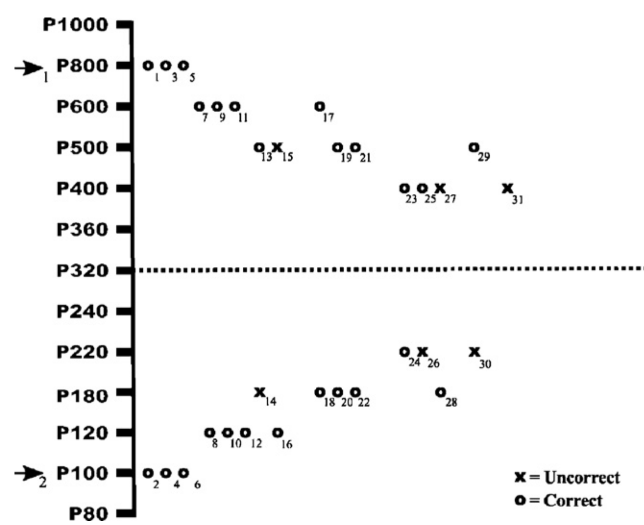

Fig. 2. The double adaptive staircase procedure for both rough and smooth tactile discrimination thresholds. The complete set of stimuli are located on the y-axis. The P320 (average particle size 46 μm) is the reference sandpaper. Numbers above P320 refer to "smooth" textures and below P320 refer to "rough" textures. Arrows indicate the starting points of each staircase. The number below each response corresponds to the order of presentation of each stimulus. A minimum of three presentations, but not necessarily consecutive, of the same sandpaper were necessary before discontinuing the procedure.

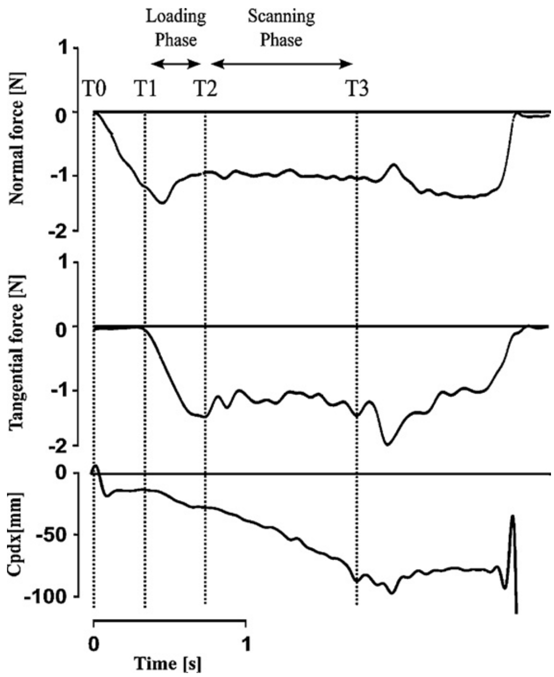

Fig. 3. Example of normal force, tangential force and center of pressure (Cpdx) recorded during the scanning of a given surface. T0 corresponds to the start of the trial, T1 to the onset of the tangential force, T2 to the peak of tangential force and T3 to the offset of scanning. T1–T2 defines the loading phase and T2–T3 the scanning phase.

at the index fingertip with the following equation:

$$CP = \frac{T}{F_z}$$

where T, and F_z correspond to the torque and normal force, respectively. The CP indicates the coordinates of the point at which the resultant F_z should be applied to generate the measured torque (T). The mean scan velocity was calculated on every trial from the CP displacement. The signals from the force transducers were digitized on-line at 200 Hz with a 12-bit 6071E analog-to-digital converter in a PXI chassis (National Instruments, Austin, TX, USA). After analog-to-digital conversion, the signals were further low-pass filtered with a fourth-order, zero phase-lag Butterworth filter having a cut-off frequency of 15 Hz. The following temporal variables were measured (see Fig. 3): (1) the loading phase (T1–T2), defined as the delay between the onset and the peak of the tangential force and (2) the scanning phase (T2–T3). Also measured during the scanning phase were: (1) the mean tangential force; (2) the mean normal force; (3) the mean scanning velocity.

2.2.2. Tactile spatial resolution acuity

Tactile spatial resolution threshold (TSRT) was measured with the Grating Orientation Task (GOT) using JVP Domes (JVP Domes, Stoelting Co., Wood Dale, IL) on the index finger of the dominant hand. This test consists of a set of eleven different hemispherical plastic dome gratings having equidistant bar and groove widths: 0.35, 0.50, 0.75, 1.00, 1.20, 1.50, 2.00, 3.00, 3.50, 4.00 and 4.50 mm. Each dome was applied perpendicularly to the skin for 1–2 s with a skin indentation between 1 and 2 mm. The domes were randomly aligned in one of the two orthogonal directions (i.e. with the grooves parallel or transverse to the long axis of the index finger). Blindfolded subjects were required to identify the stimulus orientation before the stimulus was removed. A procedure adapted from that of Van Boven and Johnson [25] was used [2]. The 3 mm grating was first applied for ten consecutive trials using a randomized orientation of the bars. If the subject succeeded the next smaller grating (2 mm) was applied. If the subject failed, the next larger grating (3.5 mm) was applied. The test was stopped when the probability of correct answers for the grating reached approximately 50%. The tactile spatial resolution threshold was a simple linear interpolation estimate of the 75% correct grating width. A lower tactile acuity grating score (TAG score) signified better tactile spatial resolution acuity.

$$TAG_{score} = g_{below} + \frac{0.75 - p_{below}}{p_{above} - p_{below}}(g_{above} - g_{below})$$

where g = grating width of a probe, p = probability of correct answers, *above* = the grating width that results in a score closest to but above 75% correct, and *below* = the grating width that results in a score closest to but below 75% correct.

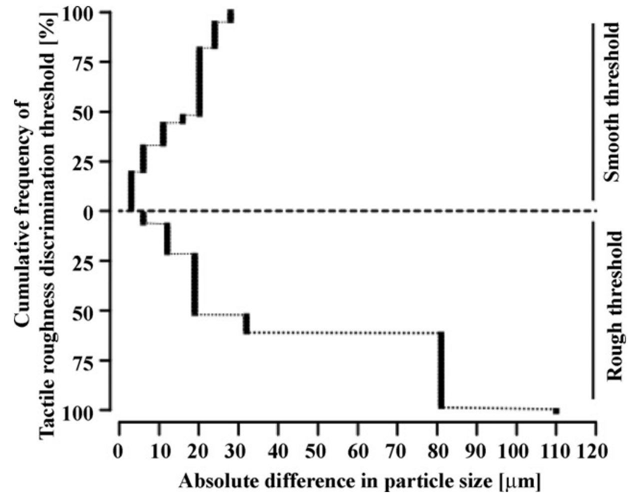

Fig. 4. Cumulative frequency distribution of roughness discrimation thresholds for the set of smooth and the set of rough sandpapers as a function of the absolute difference in particle size between a given sandpaper and the reference sandpaper (particle size of 46 μm). Performance was higher for the set of smooth sandpapers as compared to the performance with the set of rough sandpapers.

2.3. Statistics

Non-parametric statistics were used when normality tests failed or when statistics were performed on ordinal data. Hence a Mann–Whitney U test was used to analyze the effect of sex on the roughness discrimination threshold and a Wilcoxon paired rank test was performed for paired samples. A one-way analysis of variance (ANOVA) was performed on effect of age on the roughness discrimination threshold. For describing the relationship between two variables, Spearman's rank correlation coefficient was computed.

3. Results

Examples of the temporal variation of the normal and tangential forces, as well as the vertical component of the CP during a typical trial are represented in Fig. 3. T0 represents contact with the stimulus. Normal force was increased up to around 1 N. During the loading phase (T1–T2) the tangential force was increased while the CP was slowly altered due to the skin's compliance. At the end of the loading phase, slipping occurred and the scanning phase (T2–T3) started. During this phase the CP changed continuously. The mean scan velocity was calculated as the first time derivative of the CP displacement.

3.1. Roughness discrimination thresholds

The two 75%jnd or TRDTs were measured for each subject: (1) the "smooth threshold", on average 14.7 ± 8.5 μm, expresses the ability to discriminate the smoothest stimuli (S1–S6) against the reference stimulus and (2) the "rough threshold", on average 43.5 ± 32.5 μm, expresses the ability to discriminate the roughest stimuli (R1–R6) against the reference stimulus. Subjects showed a higher performance rate in difference threshold for the set of smooth sandpapers as compared to performance with the set of rough sandpapers (Fig. 4). There was a significant within-subjects correlation between both thresholds (Spearman's rho = 0.43; p = 0.001). There was no effect of age on TRDT for either the rough or smooth staircase (Fig. 5, Spearman's rho = 0.11, p = 0.35 for the rough threshold and rho = 0.13, p = 0.36 for the smooth threshold). Similarly, there was no effect of gender on TRDT (Mann–Whitney U test; p = 0.42 for the rough threshold and p = 0.13 for the smooth threshold, results not shown).

These results were reliably reproduced in eleven participants who were evaluated a second time three months after the first

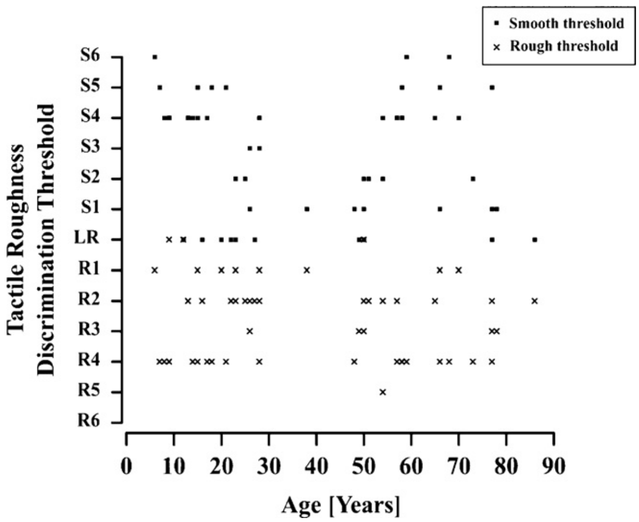

Fig. 5. Effect of age on tactile roughness discrimination threshold for the smooth (S1–S6) and rough (R1–R6) set of sandpapers. LR represents the limit of resolution.

evaluation. There were no significant differences in measurements for the TRDT with the set of smoothest stimuli or with the set of the roughest stimuli (Wilcoxon's paired rank test, $p = 0.42$ and $p = 0.94$, respectively). Patient measures at both assessments were highly correlated with a Spearman coefficient of correlation of respectively 0.725 ($p = 0.0095$) for the rough thresholds and 0.840 ($p = 0.0087$) for the smooth thresholds.

The frequency distributions of mean normal force, mean tangential force and mean scanning velocities for all subjects are shown in Fig. 6. The distributions of the normal and tangential forces are skewed to the right with a median value and interquartile range of 1.1 N [0.7–1.9] and 1.3 N [1.0–2.3] respectively. The scanning velocity was normally distributed with a mean value of 52 ± 40.3 mm/s.

Table 2
Spearman's rank order correlation squared (R^2) for mean scanning velocity and mean forces exerted at the fingertip in relation to the tactile roughness discrimination thresholds for the set of smooth and of rough sandpapers.

	Mean scan velocity	Mean normal force	Mean tangential force
Threshold for smooth sandpaper	0.25 $p = 0.07$	0.17 $p = 0.21$	0.11 $p = 0.43$
Threshold for rough sandpaper	−0.09 $p = 0.53$	−0.13 $p = 0.34$	−0.26 $p = 0.06$

Table 3
Spatial resolution thresholds for different age groups (mean ± SD).

Age groups (years)	*N*	Threshold (mm)
7–15	12	1.3 ± 0.8
16–39	15	1.8 ± 0.7
40–64	15	2.5 ± 0.8
65–90	11	3.5 ± 0.5

There was no significant correlation between age and the normal force ($r = 0.266$; $p > 0.1$), the tangential force ($r = 0.258$; $p > 0.1$) and the mean scanning velocity ($r = 0.033$; $p > 0.1$). Finally, particle size had no effect on any of the measures acquired to characterize the lateral movement of the fingertip against the sandpapers. In addition, particle size did not affect the TRDT for the fine textures or for the coarse textures (Table 2).

3.2. Tactile spatial resolution thresholds

The average tactile spatial resolution thresholds (TSRTs), measured with the Grating Orientation Task (GOT) with respect to age, are presented in Table 3. There was a significant decrease in discrimination performance with age. Subjects above 65 years of age required a grating width about 3 times greater than those in the

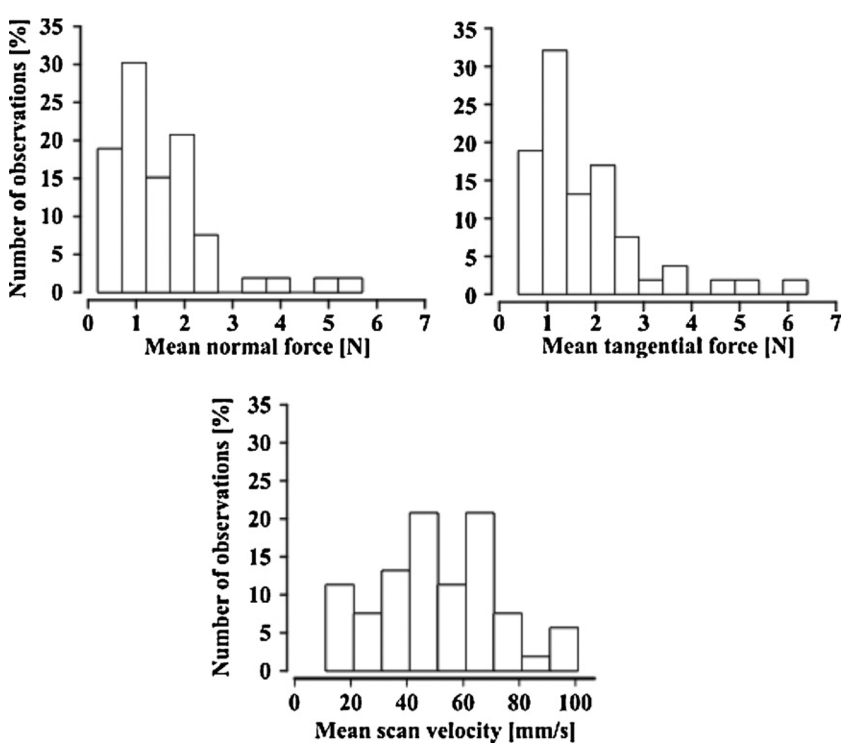

Fig. 6. Relative frequency distributions of the mean normal force, the mean tangential force and the mean scanning velocity used by each subject when exploring the sandpaper surfaces. While normal force and tangential force distributions were skewed to the right, scanning velocity showed a normal distribution.

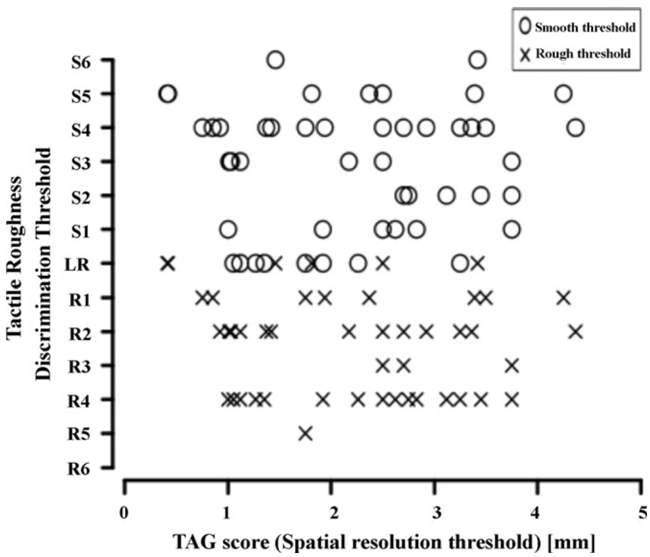

Fig. 7. Spatial resolution threshold plotted against tactile roughness discrimination threshold shows no relationship between the two measures. LR represents the limit of resolution.

youngest age group (7–15 years) in order to perform at threshold ($t = 3.55$; $p < 0.001$).

There was no significant relationship between performance in the GOT and performance in the TRDT (Fig. 7; $r = 0.124$ with $p > 0.4$ for the staircase with the smooth textures and $r = 0.029$ with $p > 0.8$ for the staircase with the rough textures).

4. Discussion

The present results demonstrated that in a two-forced choice paradigm, subjects showed a lower discrimination threshold (TRDT) with a set of smooth sandpapers than with rough sandpapers. Performance on these tasks was independent of movement related variables such as normal force, tangential force and average scanning velocity exerted by the fingertip against the sandpapers. Performance was also unaffected by gender or age. In contrast, we found that tactile spatial resolution acuity deteriorated with age. Lastly, there was no significant within-subjects relationship between roughness discrimination and spatial resolution acuity performance.

One goal of the present study was to investigate a new device enabling the determination of an active tactile roughness discrimination threshold at the index fingertip and to characterize the lateral scanning movement in terms of force and velocity. We chose a two-forced choice procedure implemented in a double interlaced staircase method. This procedure has been demonstrated to be highly effective with little interdependence between series. When questioned, all subjects asserted that they perceived that the stimuli were presented in random order. One disadvantage of the device is maintaining consistency between the steps in particle size. While step-size in sound and light stimuli is easy to determine and control, a constant step-size in roughness is more difficult to obtain. The average size of the abrasive particles in the sandpapers we used in the present study was specified by the manufacturer (i.e., the "micron grade"). However, the mean spacing between particles is approximately 3 times the grit size [4] (54 μm for the finest and 580 μm for the coarsest sandpaper used in the present studies). In other words, spacing is dependent on grit size. Jansson [15] found that the perception of roughness increases with inter-particle spacing. As pointed out by Hollins and Risner [14], sandpapers vary from one another not only in particle size, but also particle shape, the material from which they are made and by attachment to the substrate. As a consequence, the stimulus structure of sandpapers is stochastic in nature, making conclusive interpretations more difficult. In future studies, machine-etched surfaces with well-defined spatial periods may serve as a better alternative to sandpaper.

The scores of the TSRT presented in Table 3 agree with those previously reported [2,21–24,26]. In addition, the age dependent decrease in TSRT found in the present study is also in agreement with previous studies. For instance, Bleyenheuft et al. [2] reported a median and interquartile range for TSRT of 1.2 [1.0–1.8] and 1.1 [0.7–1.4] mm for subjects between 6–9 and 10–16 years of age, respectively. In age groups of 60–71 and 74–95 years of age, Tremblay et al. [23] found a TSRT of 2.7 ± 0.6 and 3.4 ± 0.4 mm, respectively. Psychophysical and neurophysiologic studies [9,17,20,27] have shown that the TSRT is closely related to the density of slow adapting type 1 (SA1) afferent innervation. Additionally, SA1 receptor density decreases with age [1]. Together, these findings readily explain the degradation of TSRT performance with age.

It has been shown repeatedly that humans use the SA1 mechanosensitive afferent system to judge the roughness of textures [16,20,27]. Yoshioka et al. [27] further asserted that spatial variation in SA1 firing rates is the only neural code that accounts for the perceived roughness of surfaces with finely and coarsely spaced elements. However, in an elegant series of experiments, Hollins et al. [11,12,14] demonstrated that the perception of roughness for fine textures with a spatial period of less than 100 μm involves high frequency vibratory cues, likely mediated by Pacinian afferents. These observations have revived an interest in Katz's theory [18] stating that tactile perception of coarse textures depends on a "spatial sense" while tactile perception of finer textures depends on a "vibration sense". Indeed, our results suggest that there is no relationship between TRDT and TSRT performance. In addition, the absence of degradation in TRDT performance with age, while it is clearly present in the TSRT, suggests that these percepts are differently encoded in peripheral afferents. These two facts indicate that the two tactile submodalities rely on different neural mechanisms, i.e. texture discrimination relying more on an intensive coding whereas grating resolution thresholds depend on the spatial structure of afferent signals. The first one requires only minimal peripheral innervation to support perceptual decision, while the second one is critically dependent upon tactile innervation for the resolution of spatial details leading to judgment about groove orientations. Such differences also explain why TRDT was relatively unaffected by age.

In conclusion, the present studies strengthen the theory that the neural mechanisms underlying tactile roughness discrimination for fine textures differ from those involved in spatial resolution acuity at the level of signal transduction and encoding.

Acknowledgements

The authors are grateful to the participants for their kind participation. This work was supported by a grant from the Commission of the European Union under Contract No. EU-FP6-NMP-033287, Nanobiotact.

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