The Sensation of Pleasantness during Tactile Exploration

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Abstract: Humans constantly explore surfaces with their fingertips, providing information regarding the surfaces' physical attributes and their (un)pleasantness level. It is therefore of interest to investigate whether the perception of pleasantness is related to surfaces' physical attributes. Pleasant touch perception is generally measured indirectly and generates ordinal scores, lacking fundamental psychometric properties which are essential for objective and quantitative measurement. Consequently, probabilistic measurement models have been established to allow transformations of ordinal scores into linear measures.

Accordingly, we first elaborated a solid basis for future investigations in the domain of pleasantness sensation resulting from active surface explorations with index fingertips. The Rasch model was used to develop a unidimensional, linear and invariant *Pleasant Touch Scale*, which classifies 37 different everyday life materials according to their pleasantness levels. The latter seemed to be influenced by the respective surfaces' topographies and by the frictional forces resulting from the tactile surface exploration. These evidences were confirmed in our second study. Indeed, the net values of friction forces, recorded during active fingertip explorations of various material samples of the *Pleasant Touch Scale* could reliably be correlated with their respective pleasantness measures. A further correlation was found between the fluctuations of friction forces and the surfaces' pleasantness measures. Our third study was conducted to determine whether (i) these findings hold true for passive fingertip stimulations and (ii) temperature variations of stimuli impact their pleasantness levels. Frictional forces and surfaces' topographies of stimuli played a crucial role in passive touch pleasantness perception.

Keywords: pleasant touch, surface topography, friction, Rasch model

1. INTRODUCTION

In everyday life, we incessantly explore surfaces with our fingertips.This stimulates the somesthetic senses, described as having 4 different modalities, *i.e.* proprioception, nociception, thermal perception, discriminative touch (Kandel, 2000). However, studies point to the existence of a supplementary *pleasant touch* modality (Johansson et al., 1988; McGlone et al., 2007; McGlone & Reilly 2010; Nordin, 1990). Each of these modalities can be perceived through stimulation of specialized afferent nerve fibers and their specific receptors. The afferent systems are embedded in the skin and vary according to the skin type. For example, C-Tactile nerve fibers, playing a fundamental role in the detection and transmission of pleasant stimuli applied to *hairy* skin, seem to be missing from *glabrous* ones (Johansson et al., 1988; Nordin, 1990). However, as surfaces touched with glabrous skin sites (*e.g.* the fingertips) can be perceived as (un)pleasant, it can be hypothesized that the perception of pleasantness at fingertip level is initiated through stimulation of other sensory modalities, especially discriminative touch. If this would be that case, specific surface physical attributes would probably be related to pleasantness sensation. Finally, it is of interest to investigate whether pleasantness perception is influenced by the exploration strategy (*i.e.* active *vs*. passive).

Information regarding the discriminative modality of touch is captured by thousands of mechanoreceptors, innervated by 4 types of mechanosensitive afferents. Each of these afferent fiber systems responds selectively to specific stimulus features (*e.g.* the spatial image of stimulation, skin vibrations) applied actively or passively to the fingertip. Whether identical stimulus features induce similar percepts during active and passive touch is still debated in the literature (Gibson, 1962; Landrigan et al., 1974; Lederman, 1981; Heller, 1984; Smith et al., 2009; Richardson et al., 1981; Vega-Bermudez et al., 1991).

An essential starting point to investigate in pleasant touch is to be able to measure pleasantness. As pleasant touch is a latent variable it can only be measured indirectly, *e.g.* through a test which (i) is composed of items/questions reflecting increasing levels of pleasantness and (ii) locates people respective to their pleasantness satisfaction level. Typically, the items are rated using either categorical rating (CR) or magnitude estimation (ME) methods. In CR, subjects use a predefined set of categories to rate their perception of pleasantness. This rating can be done using a dichotomous response format, *e.g.* “unpleasant” (scored 0) and “pleasant” (scored 1), or a polytomous one, *e.g.* “unpleasant” (scored 0), “pleasant” (scored 1) and “very pleasant” (scored 2). Usually, the response scores are summed together into a total score, which evaluates the latent variable on an ordinal basis. However, such data are unsuitable for quantitative analyses. In contrast, ME is an unlimited rating procedure, which was originally constructed to overcome the shortcomings of measurement methods generating ordinal data (Stevens, 1975). Nevertheless, it remains unclear whether this aim was really achieved (Wills & Moore, 1994). Consequently, independently of the scaling method used to rate latent variables, modern psychometric methods should be used to assess fundamental scaling properties of the measures prior to any further data interpretation. The Rasch model is a probabilistic measurement model, which can be used to establish linear, unidimensional and invariant scales from ordinal scores (Rasch, 1960). The model enables thus the objective measurement of latent variables and provides an estimate of what our data would be if we were to create a ruler to measure it (Bond & Fox, 2001).

Here, 3 different studies, investigating in pleasant touch perception, are described. Two deal with *active* touch (Study 1 and 2) and 1 with *passive* touch (Study 3). These studies were all approved by the Biomedical Ethical Commission of the Faculty of Medicine of the Université catholique de Louvain (2010/07JUI/174, Belgian registration number: 40320108947).

2. STUDY 1 – RASCH-BUILT MEASURE OF PLEASANT TOUCH TROUGH ACTIVE FINGERTIP EXPLORATION (*adapted* from Klöcker et al., 2012)

2.1. Materials and Methods

2.1.1. Subjects

One hundred and ninety-eight healthy subjects were enrolled for this study.

2.1.2. Stimuli

To elaborate the *Pleasant Touch Scale*, 48 everyday life materials (*e.g.* wax, fabrics, woods, papers) were selected and glued onto an aluminum plate (77 mm x 32 mm).

2.1.3. Procedure

Before each experiment, the index fingertip moisture level of each participant was measured using a Corneometer® CM 825 (CK electronic GmbH, Köln, Germany). Participants were blindfolded and each material was randomly presented to them. Participants explored the material surfaces with their index fingertips through lateral sliding movements, while using a preferred exploration normal force and speed. Each participant then rated the pleasantness level on a 4-level scale: (0) very pleasant, (1) pleasant, (2) unpleasant or (3) very unpleasant. The total score of each material could thus range from 0 (*i.e.* all participants rated it as very pleasant) to 594 (*i.e.* all participants rated it as very unpleasant).

2.1.4. Data Analysis – The Rasch model

Data were analyzed using the Rasch Unidimensional Measurement Models software (RUMM2020).

The Rasch model was originally elaborated to test the "data to model fit" for dichotomous data (Wright & Stone, 1979). Applied to pleasant touch perception, a Rasch analysis of dichotomous data tests for the probability that subject "n" will choose category "x" for surface "i". This probability should be influenced only by the subject's general satisfaction level elicited by surface exploration (β_n) and the surface's pleasantness level (δ_i). In this sense the model is unidimensional as it involves only the pleasant touch dimension of the subjects. The probability that subject "n" perceives surface "i" as pleasant is thus based on the comparison of β_n and δ_i, allowing in turn the calculation of the expected pattern of responses to a set of items (Tennant, 2004). The data to model fit is tested by comparing the expected responses from the model to the observations. The invariance of the scale is thereafter checked to verify that measurements are not influenced by variables other than the measured one (*e.g.* a meter is only sensitive to the length of an object but not its weight). If the data to model fit and the invariance are verified, then the Rasch model has reliably transformed the originally collected ordinal data into linear, unidimensional and invariant measures (Tennant, 2004; Wright & Linacre, 1989). These measures are expressed in logits, the unit of measurement after transformation of the ordinal raw scores into log odds ratios (*i.e.* ratio between the probability of perceiving a surface as pleasant and the probability of perceiving the surface as unpleasant) on a common interval scale (Bond & Fox, 2001). One logit represents the increase in surface pleasantness which is needed to increase the odds ratio by a factor of 2.71. Similarly, one logit represents the increase in person's satisfaction level needed to increase the odds ratio by a factor of 2.71. For illustration, consider Figure 1 where surface A is located at 1 logit and surface B at 2 logits. If person D explores both surfaces, this person will have a e^1=2.71 higher probability of perceiving surface B as pleasant than surface A. If person C is located at 1 logit and person D at 2 logits, person D will have a e^1=2.71 higher probability to rate surface A as pleasant than person C.

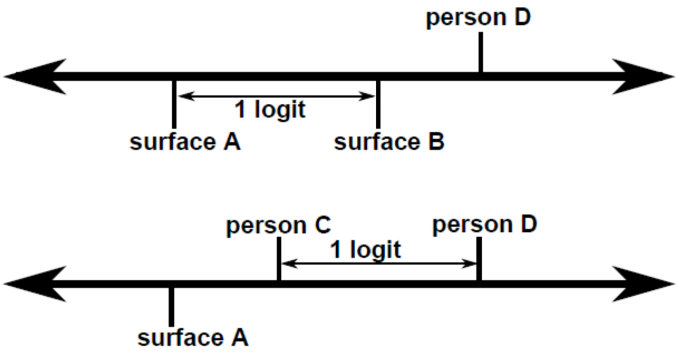

Figure 1: Illustration of the logit

The Rasch model can also be applied to the analysis of polytomous data (Andrich, 1978; Wright & Masters, 1982). In this case, the probability that subject "n" chooses category "x" for item "i", should be influenced only by β_n, δ_i and the threshold[1] (τ_{ij}) location between two successive response categories (Wright & Masters, 1982).

2.1.5. Material selection

Successive analyses were performed to select materials (i) presenting ordered response categories and (ii) fitting a unidimensional scale.

2.1.5.1. Ordered response scale

The subjects were asked to report their pleasantness perception on a 4-level scale: (0) very pleasant, (1) pleasant, (2) unpleasant or (3) very unpleasant. The order of the response categories was verified for each material by checking whether the categories represent decreasing pleasantness levels. If the response categories were ordered, the thresholds were located in the anticipated order, that is, less satisfied subjects should have selected a higher response for any given material, whereas subjects selecting a higher response to a given material should be less satisfied.

2.1.5.2. Unidimensional scale

The item χ^2 fit statistics were used to test the fit of the data to the model requirements. In this method, the squared standardized residuals (*i.e.* the difference between the response expected by the model and the observed response by the subject) of all subjects are summed, leading to a χ^2 value for each material. A significance test is used to evaluate whether the χ^2 is too high to be attributed to random variation (p-value < 0.05 indicates misfitting items) (Tennant & Conaghan 2007).

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[1] Thresholds or boundaries between successive response categories, are the level at which the likelihood of choosing a given response category below the threshold is equal to the likelihood of choosing the response category above the threshold (Bond, 2001). The surfaces difficulty level corresponds to the mean threshold location of the surface.

2.1.6. Differential item functioning

The invariance of the pleasantness hierarchy of the materials within the sample was tested through a "differential item functioning" (DIF) analysis. DIF occurs if subjects of distinct subgroups (*e.g.* males vs. females) with the same satisfaction level perceive any given material differently (Tennant et al. 2004). In this study, DIF was investigated according to (i) gender, (ii) age (<37 vs. ≥37 years, the median age of the subjects) and (iii) fingertip moisture level (<70 vs. ≥70 arbitrary units, or "a.u.", the median moisture level). To investigate DIF, each subgroup was divided into 5 class intervals (CI) of decreasing pleasantness satisfaction, and two-way analysis of variance (ANOVA) was computed on the standardized residuals of the different CIs (Andrich, Sheridan and Luo 2004). Factors analyzed in two-way ANOVA included (i) subject subgroups (*e.g.* males vs. females), and (ii) CIs of decreasing pleasantness satisfaction levels.

2.2. Results

Successive Rasch analyses were performed to construct the final *Pleasant Touch Scale*. The categories "unpleasant" and "very unpleasant" were merged into one category ("unpleasant") as subjects were not able to discriminate between them for eleven material samples. The entire data set was thus reanalyzed using a three-level scale: (0) very pleasant, (1) pleasant and (2) unpleasant. Two items were deleted from further consideration as they still presented disordered thresholds. Furthermore, 9 items did not fit a unidimensional scale. They were also eliminated, resulting in a 37-item scale. The invariance analysis highlighted that 21 material samples presented a DIF according to the participants' fingertip moisture levels. These samples elicited different levels of pleasantness when touched by participants with dry and wet skin and were therefore split into two different items with locations specific to fingertip moisture level (*i.e.* one each for participants with dry and wet skin). Consequently, the final *Pleasant Touch Scale* includes 58 items, of which (i) 16 items share a common location in low and high moisture level subgroups and (ii) 42 items have locations specific to the fingertip moisture level.

2.2.1. Metric properties of the *Pleasant Touch Scale*

The calibration of the 58 items of the *Pleasant Touch Scale* is presented in Table 1, in which the items were ordered from the most unpleasant, at the top, to the most pleasant, at the bottom. Items followed by "_LM" and "_HM" are split items with pleasantness locations specific to subjects with low and high fingertip moisture levels, respectively. The pleasantness levels of the 58 items covered a range of 6.91 logits indicating that the odds of pleasing any particular subject was in a ratio higher than 1000:1 (*i.e.* $e^{6.91}$:1) between the most and least pleasant items. This pleasantness range was arbitrarily centered at 0 logits. Furthermore, the table presents the standard errors (SE) associated with the estimations of the pleasant levels of the different items (mean: 0.18 logits; range: 0.36 logits).

Table 1: Items of the *Pleasant Touch Scale*

Material description	**Pleasantness [logits]**	**SE [logits]**
sandpaper_LM	-4.47	0.48
rough sponge_LM	-4.19	0.40
sandpaper_HM	-2.45	0.30
silicon_LM	-2.44	0.27
silicon_HM	-2.23	0.24
latex	-1.88	0.17
wax	-1.73	0.17
clingfilm	-1.49	0.15
rough sponge_HM	-1.43	0.23
carbon paper_HM	-1.19	0.20
linen	-1.12	0.14
leather chamois_LM	-0.84	0.19
tesa tape_HM	-0.75	0.19
carbon paper_LM	-0.71	0.19
wood_LM	-0.64	0.18
leather chamois_HM	-0.60	0.19
plastic_HM	-0.59	0.19
argil_LM	-0.57	0.18
plexiglass_HM	-0.51	0.17
glass_HM	-0.26	0.16
aluminium_HM	-0.19	0.18
tile_HM	-0.18	0.16
argil_HM	-0.15	0.17
wood_HM	-0.13	0.19
chipboard_LM	-0.10	0.19

cork	0.06	0.13
table cloth_HM	0.20	0.17
plexiglass_LM	0.26	0.15
marble_HM	0.28	0.15
plastic_LM	0.39	0.15
tesa tape_LM	0.40	0.15
glass_LM	0.43	0.15
cast_LM	0.46	0.18
silk	0.52	0.13
transparent paper_HM	0.57	0.15
viscose tissue	0.60	0.12
paper_250g/m²_HM	0.62	0.16
chipboard_HM	0.63	0.17
foam	0.63	0.12
cotton tissue_LM	0.66	0.18
table cloth_LM	0.68	0.16
aluminium_LM	0.70	0.17
tile_LM	0.81	0.17
cast_HM	0.87	0.19
tights	1.07	0.13
paper_250g/m²_LM	1.08	0.17
marble_LM	1.12	0.16
cotton tissue_HM	1.17	0.19
paper_70g/m²	1.22	0.14
paper_120g/m²_LM	1.23	0.19
transparent paper_LM	1.40	0.18
baking paper	1.49	0.13

synthetic tissue	1.50	0.13
velvet	1.74	0.12
cellular rubber	1.83	0.13
paper_120g /m²_HM	1.86	0.20
paper_80g/m²	1.89	0.14
paper_160/g/m²	2.44	0.14

Several material samples of the *Pleasant Touch Scale* were used in the next study to investigate whether any correlation can be detected between the physical properties of the samples and their respective pleasantness levels.

3. STUDY 2 – PHYSICAL FACTORS INFLUENCING PLEASANT TOUCH DURING TACTILE EXPLORATION (*adapted* from Klöcker et al., 2013)

3.1. Materials and Methods

3.1.1. Participants

Eight healthy participants were enrolled for this study.

3.1.2. Apparatus

The measurement apparatus (Figure 2) included a sample holder which was rigidly connected to a high-resolution piezoelectric force sensor (9217a, Kistler Instrumente AG, Winterthur, Switzerland) connected to a charge amplifier (5015A, Kistler Instrumente AG, Winterthur, Switzerland). The piezoelectric force sensor measures fluctuations of friction forces. The force sensor has a 500 Hz exploitable frequency bandwidth and a theoretical noise floor of 10 µN. Two parallel leaf springs provided a high rigidity support for the sample holder in the normal and radial directions, and optimal transmission of the interaction force in the lateral direction. The entire structure was connected to a 6-axis, strain-gauge force-torque sensor (Mini 40, ATI Industrial Automation, Inc., Apex, NC, USA) that allowed us to gain access to the complete interaction force vector in the low frequencies and with a resolution of 20 mN. The finger position was measured by an optical motion tracking system (Optotrak, Northern Digital Inc., Waterloo, Ontario, Canada) that located a light-emitting fiducial marker attached to the scanning finger nail at a rate of 400 Hz. Acquisition of sensor signals have been made using a 12 bits analog to digital converter at a sampling rate of 20 kHz.

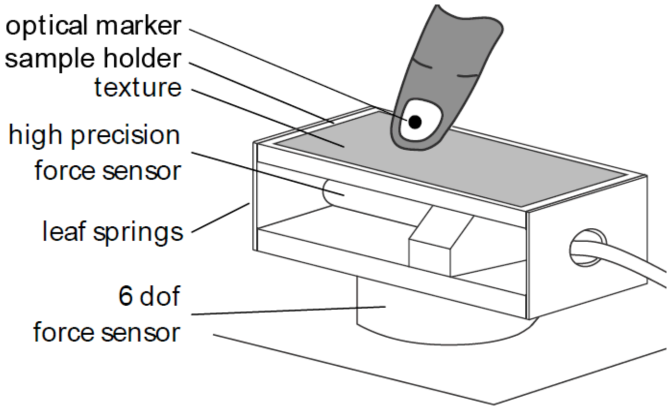

Figure 2: Measurement apparatus of "Study 2"

The participants' fingertip moisture levels were evaluated using the Corneometer® CM 825 (CK electronic GmbH, Köln, Germany).

3.1.3. Stimuli

Twelve surfaces, of the *Pleasant Touch Scale* (Klöcker et al., 2012) were selected for this study. These surfaces ranged from the most unpleasant to the most pleasant surface of the scale.

3.1.4. Protocol

Participants were blindfolded and the moisture level of their right index fingertip was measured using the Corneometer® CM 825. The materials were mounted in a randomized order on the measurement device and the participants were instructed to position their right index fingertip just above the selected material before spontaneously exploring the sample through ten successive lateral sliding movements. During surface exploration the high-frequency tangential force fluctuations were recorded, along with the net interaction force, and the fingertip position. The fingertip moisture level was recorded immediately after the last exploration trial of each surface.

3.1.5. Data processing

All analyses focused on 20 mm (*i.e.* between 40 and 60 mm of each material) of the active steady-state fingertip slip phase. The software package Matlab® (version 7.10) was used to process force and fingertip position data. Force data were numerically low-pass filtered (butterworth 4th order filter) at 800 Hz and the fingertip position signal was used to estimate the exploration velocity.

Firstly, mean values of exploration velocity (v), tangential (f_T) and normal (f_N) forces were computed per sample exploration and per participant. The dynamic coefficients of friction (μ) were determined by dividing f_T by f_N. Secondly, mean values for all parameters were computed over the 10 explorations.

To investigate the effect of surface topography, analyses focused on the rapid fluctuations of the friction force (f_T). Indeed, following the analysis detailed in Wiertlewski et al. (2011), the raw friction force data of each participant and each exploration was resampled with respect to space, using the corresponding fingertip positions. This signal was fast Fourier transformed, generating a spatial spectrum. Consequently, the rapid force fluctuations of each surface could be analyzed in terms of spatial frequencies. To quantify the decay of the friction force with respect to spatial frequency, a regression line was fitted to the spatial spectrum of each sample situated between 0.1 mm^{-1} and 10 mm^{-1},

$$f_T = \beta\eta^{\alpha}$$

where η represents the spatial frequency, $\alpha < 0$ the slope of the regression line and β its offset. Consequently, α and β could be estimated for each sample and each participant (except for one of them who scanned the samples too quickly to be reliably processed).

3.1.6. Statistical analyses

All statistical analyses were conducted using IBM® SPSS® Statistics (version 20).

To investigate whether the participants' fingertip moisture levels remained constant during exploration of each surface, a Repeated Measure Analyses of Variance (RM-ANOVA) was conducted, where "surfaces" and "time" were defined as "within-participant factors" and the two fingertip moisture levels measured per surface exploration as "within participant variables". Further RM-ANOVAs were conducted to determine whether the exploration kinematics, friction and surface topography changed significantly according to the surface being explored. For each of these RM-ANOVAs, "surfaces" were defined as a "within-participant factor" and "within-participant variables" were respectively v, f_N, f_T, μ, α and β.

The correlations between the surfaces' pleasantness levels (independent variable) and respectively v, f_N, f_T, μ, α and β (dependent variables) were estimated using a Spearman correlation analyses.

For all analyses, effects were considered significant for $p<0.05$.

3.2. Results

The participants' fingertip moisture levels did not vary significantly between first and last exploration of each material ($F_{(1,7)} = 1.70$; $p = 0.23$).

The range and the mean values of the participants' spontaneous exploration kinematics and f_T are indicated in Table 2.

Table 2: Summary of exploration kinematics

Variable	Mean (mean±std)	Range (min-max)
v	104.0 ± 56.4 mm/s	42.0 – 321.0 mm/s
f_N	0.7 ± 0.3 N	0.2 – 1.6 N
f_T	0.5 ± 0.3 N	0.1 – 1.5 N

RM-ANOVAs and correlation analyses suggested both that participants adopted a preferred exploration strategy. Indeed, v and f_N were neither significantly adapted according to the surfaces being explored, nor significantly correlated with pleasantness (Table 3). In contrast, f_T, μ, α and β varied significantly according to the scanned surface (Figures 3-4; Table 3).

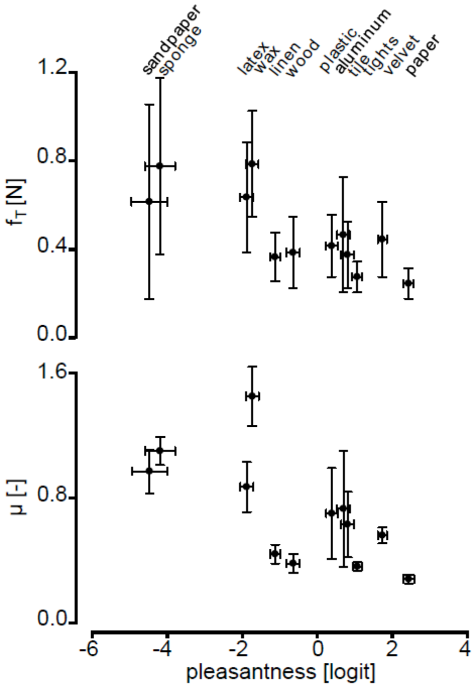

Figure 3: Correlation f_T - *pleasantness* (top) and μ - *pleasantness* (bottom)

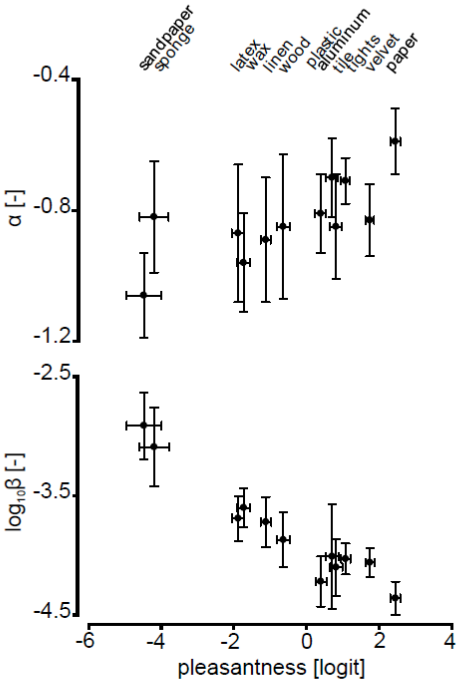

Figure 4: Correlation α - *pleasantness* (top) and β - *pleasantness* (bottom)

f_T and μ were both negatively correlated with pleasantness (Table 3), suggesting that higher friction, occurring during surface exploration, induces lower pleasantness perception. Finally, the statistical analyses of the character of the motion-induced vibrations during surface exploration showed that (i) surfaces were perceived to be more pleasant if the spectrum of the friction force fluctuations was evenly distributed in the low and high spatial frequencies (*i.e.* significant positive correlation between α and pleasantness; Table 3) and (ii) the resulting vibration strength was low (significant negative correlation between β and pleasantness; Table 3).

Table 3: Results of RM-ANOVA and Correlation analysis

Variable	**n**	**RM-ANOVA**		**Correlation**	
v	8	$F_{(11,77)}$=1.66	p=0.99	ρ=0.16	p=0.130
f_N	8	$F_{(11,77)}$=1.82	p=0.65	ρ=0.14	p=0.187
f_T	8	$F_{(11,77)}$=5.99	p<0.001	ρ=-0.45	p<0.001
μ	8	$F_{(11,77)}$=38.80	p<0.001	ρ=-0.65	p<0.001
α	7	$F_{(11,66)}$=9.13	p<0.001	ρ=0.46	p<0.001
$log_{10}\beta$	7	$F_{(11,66)}$=33.09	p<0.001	ρ=-0.80	p<0.001

This observation is illustrated in Figure 5, where the friction induced vibrations of ‘paper’ are evenly distributed in the low and high frequencies. This is not observed for those of the ‘sandpaper’.

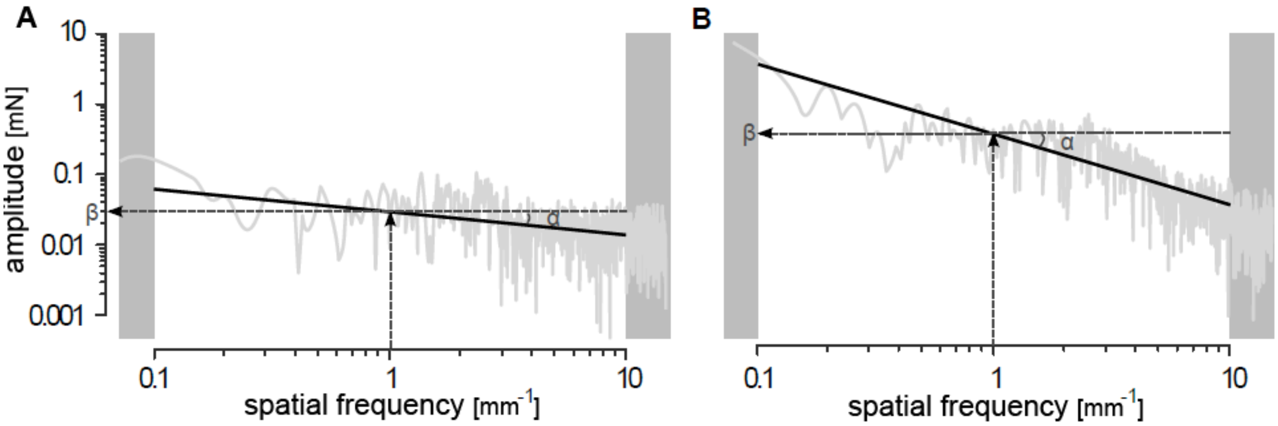

Figure 5: Illustration of the friction induced vibrations by A “paper” and B “sandpaper”.

The next study was conducted to investigate whether pleasantness perception induced through *passive* fingertip stimulation was influenced by the surfaces’ topographies and the friction forces occurring during stimulation. Furthermore, the effect of normal force with which the stimuli are applied and the stimulus temperature on pleasantness perception have been investigated.

4. STUDY 3 – PHYSICAL FACTORS INFLUENCING PLEASANT TOUCH DURING PASSIVE FINGERTIP STIMULATION (*adapted* from Klöcker et al., 2014)

4.1. Materials and Methods

4.1.1. Participants

Twenty-two healthy subjects were enrolled for this third study.

4.1.2. Experimental apparatus

The experimental apparatus consisted of 3 thermal stimulation modules (TSM), on the top of which aluminum plates could be fixed (Figure 6). Every TSM (Figure 6) allowed to regulate the surface temperature of the aluminum plates in a range between 10°C and 50°C by using two high performance Peltier cells (HP-127-1.0-1.3-71P, TE Technology, Inc., MI, USA), a heat sink (MBF35003-24W/2.6, Malico, Inc., Taiwan) and exhaust fans (GM1203PFV1-8 F-GN, Sunonwealth Electric Machine Industry Co., Ltd, Taiwan) that contributed to remove the amount of exceeding heat from Peltier cells. Two NTC thermistors (TCS-610, Wavelength Electronics, Inc., MT, USA), embedded in the aluminum plates, allowed thermal feedback together with 2 linear Proportional-Integral temperature controllers (HTC3000, Wavelength Electronics, Inc., MT, USA) and also allowed the stimulation temperature (TS) to be measured. The 3 TSM were rigidly fixed on an aluminum frame. This structure was installed on the top of two 6-axis, strain-gauge force-torque sensors (Mini 40 and Nano 43, ATI Industrial Automation, Inc., Apex, NC, USA) which were positioned on a 4-axis robot (4-axis SCARA HS series 4535G, DENSO Products and Services Americas, Inc., CA, USA). The robot could be controlled in the normal, tangential and rotational directions with predefined velocities. Acquisitions of the force sensor signals, the position of the robot as well as the temperature of the stimuli have been made at a sampling rate of 1 kHz. Furthermore, to control the participants' fingertip moisture levels (M), the room temperature (T_R) and the relative humidity (H) during the experiment, a Corneometer® CM 825 (CK electronic GmbH, Köln, Germany) was fixed on the measurement experimental apparatus. The fingertip temperature (T_F) could be measured through an infrared thermometer Raytek MI3 (Raytek Corporation, Santa Cruz, CA, USA) which was also fixed on the apparatus. The measurement experimental apparatus was equipped with a hand-arm support which allowed the participant to rest its arm and hand in a way that only the right index fingertip could be stimulated (Figure 6).

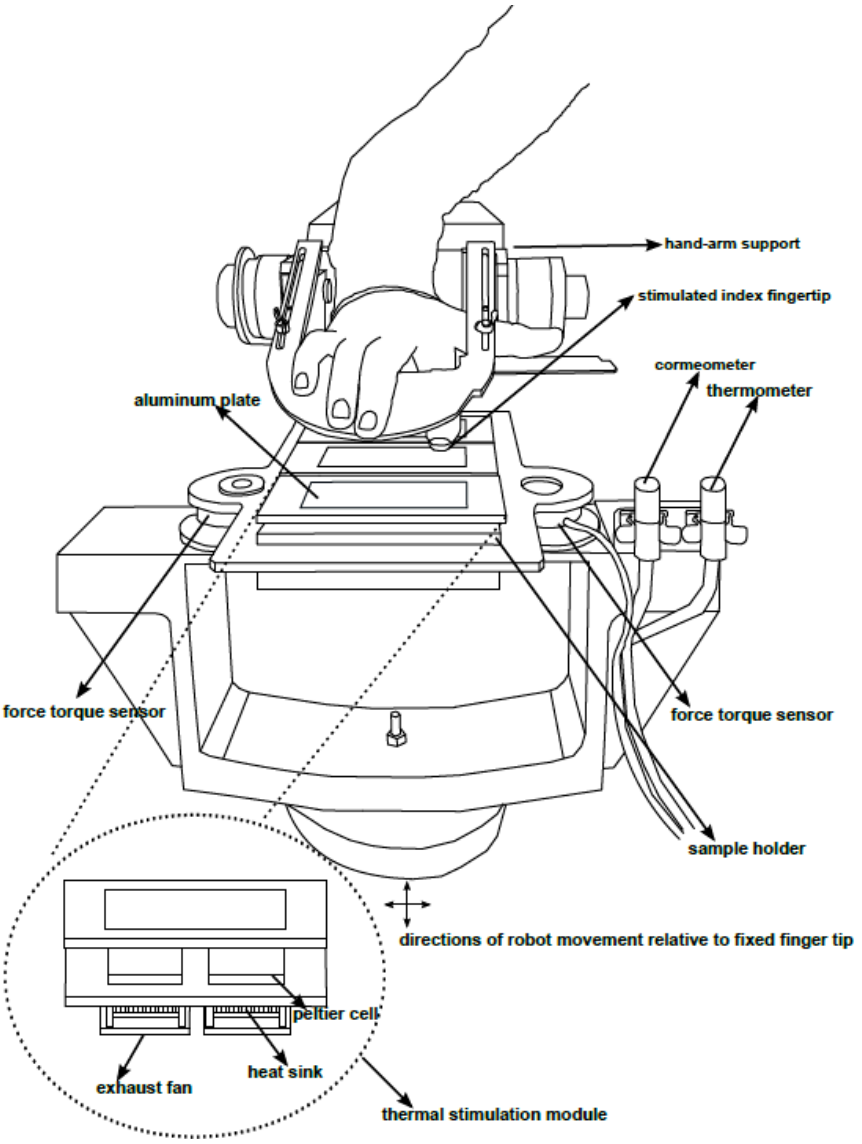

Figure 6: Measurement apparatus of “Study 3”

Three aluminum plates with different average roughness levels (*Ra*) were obtained through controlled electric discharge machining of their surfaces. Their *Ra* was characterized by surface contact profilometry (DektakTM 150 profiler, Veeco Instruments Inc., Arizona, USA). Three profilometry measures were taken per aluminum plate following the long axis of the plate. Mean *Ra* of (i) the smooth plate was 1.4±0.1 µm, (ii) the medium plate was 13.1±1.1 µm and (iii) the rough plate was 40±3 µm.

Each aluminum plate was applied to the index fingertip with 3 different normal forces (f_N) of 0.5N, 1N and 2N and 3 different temperatures (T_S) of 15°C, 30°C and 40°C. As a consequence, we used 27 different stimuli during the experiment (*i.e.* combination of three roughness levels, normal forces and temperatures).

4.1.3. Experimental procedure

Each participant was installed next to the measurement apparatus and the right upper limb was comfortably positioned for stimulation (Figure 6).

After blindfolding the participant, T_R and H were measured. Before fingertip stimulation, M and T_F were controlled. The initial stimulation was then applied in three phases: (i) the robot moved vertically to bring the index fingertip in contact with the stimulus, (ii) the robot was maintained stationary in contact with the fingertip during five seconds to achieve a stable f_N, (iii) the robot applied the stimulus to the participant's index fingertip, by a horizontal movement (from left to right) at 35 mm/s. Participants had to rate the pleasantness of the third phase of each stimulation as very pleasant (scored 0), pleasant (scored 1) or unpleasant (scored 2). The same procedure was repeated for the remaining 26 stimuli. During fingertip stimulation, f_T and f_N were recorded, along with T_S and the robot's position. Figure 7 illustrates a typical trial of the signals recorded during the stimulation phase.

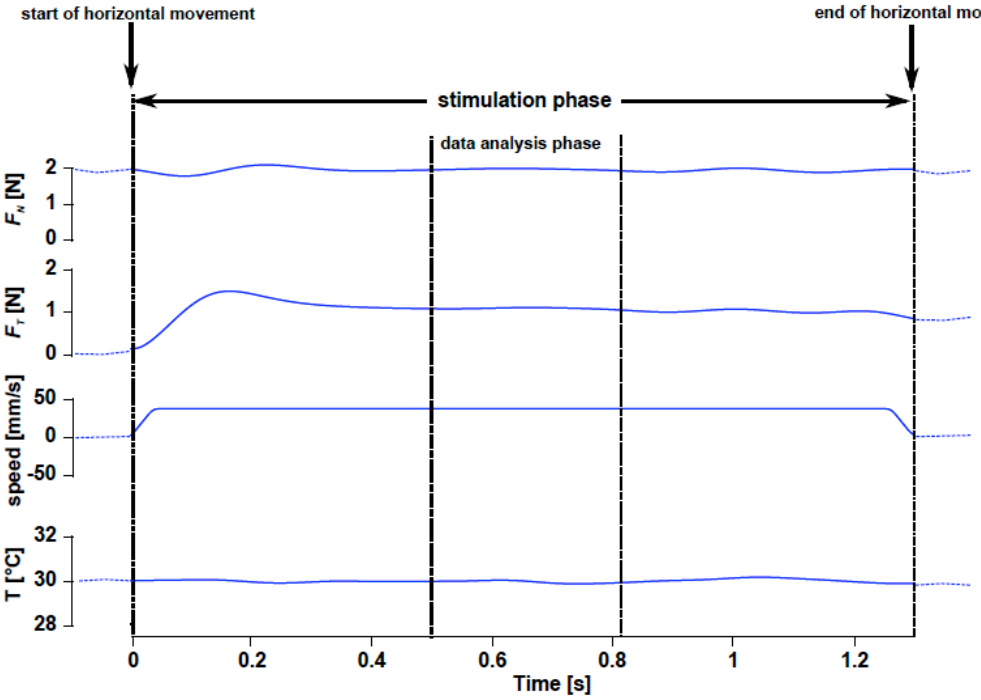

Figure 7: Typical trial of one stimulation

If the aluminum plates were applied at 15°C, mean fingertip moisture level, M, and mean fingertip temperature, T_F, were respectively 39±2.7 arbitrary units (a.u.) and 33±0.2°C. If the aluminum plates were applied at 30°C, M was 40±3.2 a.u. and T_F was 32±1°C. If the aluminum plates were applied at 40°C, M was 39±3.4 a.u. and T_F was 33±0.2°C. Room temperatures ranged from 23.1°C to 30.9°C and room humidity from 44.5 % to 58.1 %.

4.1.4. Data processing

One ordinal pleasantness total score could be calculated per stimulus. These scores could range from 0 (all participants rated it very pleasant) to 44 (all participants rated it unpleasant). The Rasch model was used to logarithmically transform these scores into linear and unidimensional pleasantness measures. DIF was investigated for M, T_F, age, gender, T_R and H.

All data analyses of the stimulation variables (*i.e.* f_N, f_T, T_S) focused on 600 ms of the steady-state fingertip stimulation phase (third phase) (Figure 7). The software package Matlab® (version 7.10) was used to (i) numerically low-pass filtered (Butterworth 4th order filter; 5 Hz) all data and (ii) compute mean f_T, f_N, μ as well as T_S per stimulation and per participant. Table 4 summarizes the mean f_T and μ values per aluminum plate and normal force level.

Table 4: Mean tangential force values and mean dynamic coefficient of friction

Normal force [N]	**Smooth plate** **(MEAN±SD)**	**Medium plate** **(MEAN±SD)**	**Rough plate** **(MEAN±SD)**
0.5	F_T = 0.27±0.12 [N] μ = 0.54±0.24 [-]	F_T = 0.22±0.03 [N] μ = 0.44±0.06 [-]	F_T = 0.25±0.01 [N] μ = 0.5±0.02 [-]
1.0	FT = 0.52±0.22 [N] μ = 0.52±0.22 [-]	FT = 0.46±0.03 [N] μ = 0.46±0.03 [-]	FT = 0.56±0.02 [N] μ = 0.56±0.02 [-]
2.0	FT = 1.01±0.42 [N] μ = 0.63±0.22 [-]	FT = 0.92±0.16 [N] μ = 0.45±0.08 [-]	FT = 1.14±0.01 [N] μ = 0.57±0.007 [-]

4.1.5. Statistical analyses

Stepwise forward multiple linear regression has been used to investigate whether pleasantness perception of the stimulations could be predicted by (i) the surfaces' topographies, (ii) the friction forces occurring during stimulation, (iii) the normal force with which the stimuli were applied and (iv) the stimulus temperature. The linear and unidimensional pleasantness measures were defined as dependent variables, whereas Ra, f_T, f_N, T_S, T_F, M were defined as independent variables. This analysis was performed with JMP® 10.0 (SAS Institute Inc., Cary, NC 27513, USA) where effects were considered significant for $p < 0.05$.

4.2. Results

One stimulus was rated as unpleasant by every participant (rough plate, 2 N, 15°C) and had thus an extreme score. This indicates that the stimulus was too unpleasant for the subject sample. As it is not possible to determine a definite pleasantness level for such stimuli, it was no longer taken into account for further investigations[2]. The final *Passive Pleasant Touch Scale* was thus formed of the 26 remaining stimuli. In Table 5, all stimuli are presented according to their pleasantness measures (expressed in logits) along with their associated standard errors. The rough plate, 2 N, 40°C, was the most unpleasant stimulus of the scale, whereas the smooth plate, 0.5 N, 30°C, the most pleasant one. The invariance analysis did not highlight any DIF.

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[2] To illustrate this phenomenon, imagine students would take mathematical test where only 20% were able to say that 5^2 equal 25. This allows locating the difficulty level of this exercise respective to the ability level of the sample. Indeed, the result indicates that the difficulty to solve this problem should be lower than the mean ability of the 20% of students who were able to solve it but higher than the mean ability of the 80% of students who were not able to solve it. However, if no student would have been able to answer the problem correctly, it would be impossible to fix a difficulty level based on the students' abilities. The only information would be that this exercise was too difficult for the sample.

Table 5: Items of the *Passive Pleasant Touch Scale*

Stimulus	Pleasantness [logit]	SE [logit]
R F2 T40	-4.359	1.332
R F2 T30	-3.004	0.731
R F1 T40	-1.449	0.431
R F1 T15	-1.396	0.425
R F1 T30	-1.395	0.425
M F2 T15	-1.145	0.401
R F0.5 T15	-0.523	0.359
S F2 T15	-0.414	0.355
R F0.5 T30	-0.382	0.353
R F0.5 T40	-0.325	0.351
M F2 T40	-0.002	0.342
M F2 T30	0.123	0.339
S F1 T15	0.218	0.338
S F2 T40	0.231	0.338
S F0.5 T15	0.232	0.338
M F0.5 T15	0.35	0.337
M F1 T15	0.393	0.337
M F1 T40	0.572	0.337
M F1 T30	0.915	0.341
M F0.5 T40	1.012	0.343
S F1 T40	1.023	0.343
M F0.5 T30	1.4	0.356
S F2 T30	1.594	0.366
S F0.5 T40	1.962	0.390
S F1 T30	2.035	0.396

S F0.5 T30	2.336	0.424

The multiple linear regression analysis showed that only *Ra* and f_T significantly predicted the pleasantness measures as defined through the *Passive Pleasant Touch Scale*. Together, *Ra* and f_T explained 88% of the variance of the pleasantness measures. *Ra* seemed to predict a higher part (54%) of these measures than f_T (34%). Figure 8 shows actual pleasantness measures vs. those predicted by the model as well as the model's equation. The latter highlights that stimuli are perceived as less pleasant if (i) their *Ra* increases and (ii) the f_T, brought about by the movement of the plate under the fingertip increases.

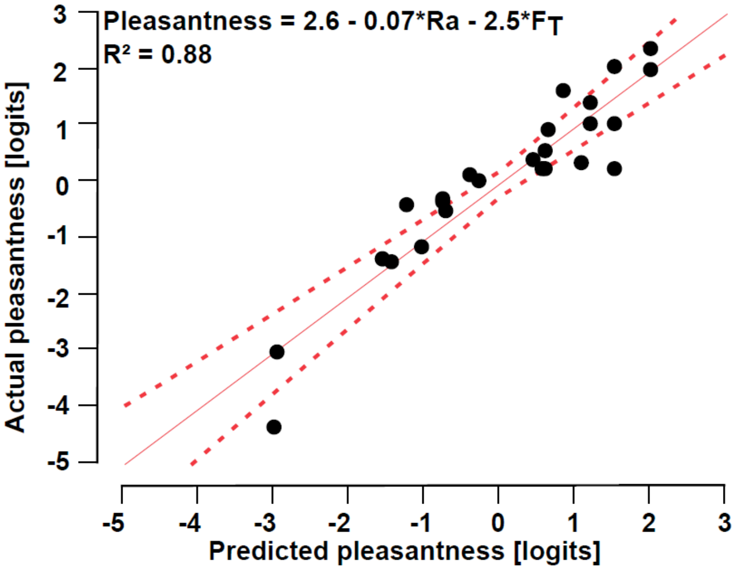

Figure 8: Typical trial of one stimulation

5. GENERAL DISCUSSION

Touching and exploring surfaces with the fingertips induces skin deformations which will be transformed into nerve impulses, leading to a perception or a conscious experience (Kandel, 2000). At fingertip level four different afferent units respond to such mechanical skin deformations. However, no afferent fiber type at fingertip level responds specifically to the pleasantness level of stimuli applied to the skin. We hypothesized therefore that pleasantness sensation at fingertip level arises through the (combined) activity of specific mechanoreceptive afferent systems and is thus dependent on specific physical characteristics of surfaces.

For more than 1 century, scientists are interested in the study of pleasant touch. Major (1985) asked subjects to explore fifty-one different textures and found that “stiffness”, “roughness” and “coarseness” perceptions were found unpleasant. The contrary was shown for “softness” or “smoothness” perceptions. Further studies strengthened these indications (Ripin & Lazarsfeld, 1937; Ekman et al., 1965; Guest et al., 2009; Essick et al., 2010). The studies suggested thus that the subjective perception of surface texture played a role in subjective pleasantness perception occurring through stimulations at fingertip level. However, none of them investigated whether the subjective ratings of pleasantness and of texture qualities met fundamental scaling properties, questioning the psychometric validity of these ratings. Some studies went even a step further and applied parametric statistics to these data.

Reliable measures of latent variables should result from objective measurement scales. Fundamental scaling properties of such measurement scales should also be tested, by using for example the Rasch Model. Consequently, we used this model to elaborate a unidimensional and linear *Pleasant Touch Scale* (Klöcker et al., 2012). This scale pointed to material physical properties being perceived as more or less pleasant to touch, namely (i) the materials’ surfaces topographies and (ii) the friction occurring at interface finger-surface during exploration. The second study strengthened our initial findings (Klöcker et al., 2013). Indeed, the pleasantness level of twelve materials of the *Pleasant Touch Scale* could significantly be correlated with the average friction force arising at finger-surface interface through tactile surface sensing. Furthermore, their pleasantness levels could significantly be correlated to variables reflecting the frequency content of the exploration induced vibrations. The third study (Klöcker et al., 2014) dealt with passive touch. The latter indicated that, similar to the active touch condition, friction occurring at interface finger-surface during fingertip stimulation as well as the average surface roughness level of a stimulus (or its surface topography) predict both pleasantness levels of stimuli during passive touch. Furthermore, results of this study indicated that neither the stimulus temperature nor the normal force with which stimuli were applied to the fingertip had the potential to influence the pleasantness perception.

The results of the studies presented in this manuscript are of relevance for the “tactile branding” field. The aim of “tactile branding” is to generate a connection between the consumer’s emotional feeling and the brand through the stimulation of the tactile sense. Indeed, what a product feels like can influence people’s decision on buying this product or not (Spence and Gallace 2011). For example, the textile industry typically aims to create comfortable and pleasant products. Indeed, consumers are more likely to pick up and touch products with pleasant material properties (McCabe et al. 2003) which may induce them to buy these products. The electronic industry tries also to use more and more “tactile branding” to promote their products. For example, the Apple iPod can easily be recognized by only touching it (Spence and Gallace 2011). Another industry dealing with tactile sensation is the cosmetic industry (Horiuchi et al. 2009). Indeed, users like to achieve a smooth tactile sensation after the application of a hand lotion. Finally, it is interesting to note that marketing campaigns use nowadays even other sensory modalities, such as the visual or auditory modalities, to evoke specific tactile perceptions. This is of importance for the online shopping marked.

In order to avoid any intermodal interference between vision and touch, participants of the studies presented in this thesis manuscript were systematically blindfolded. A future study could explore whether the visual presentation of textures does influence the tactile perception of pleasantness.

The assessment of pleasantness perception induced through tactile surface sensing used in this work was based on a measurement scale which had been elaborated using the Rasch model. The material classification is therefore unidimensional and linear. On the basis of this material classification, physical surface properties could reliably be related to the materials pleasantness levels induced through active and passive surface exploration.

ACKNOWLEDGMENTS

We are grateful for the kind participation of all participants, the technical support provided by Julien Lambert, Domenico Camboni and Dr. Calogero Oddo. This work was supported by a grant from the Commission of the European Union under Contract No. EU-FP7-NMP4-SL-2009-228844, NanoBioTouch. This work was supported by the European Research Council, Advanced Grant PATCH, agreement No.247300.

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