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You can touch this! Brain correlates of aesthetic processing of active fingertip exploration of material surfaces

Barbara E. Marschallek [1,*], Andreas Löw [1], Thomas Jacobsen

Experimental Psychology Unit, Helmut Schmidt University/University of the Federal Armed Forces Hamburg, Postbox 700822, 22008, Hamburg, Germany

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ABSTRACT

The haptic exploration and aesthetic processing of all kinds of materials' surfaces are part of everyday life. In the present study, functional near-infrared spectroscopy (fNIRS) was used to investigate the brain correlates of active fingertip exploration of material surfaces and subsequent aesthetic judgments of their pleasantness (feels good or bad?). In absence of other sensory modalities, individuals ($n = 21$) performed lateral movements on a total of 48 textile and wood surfaces varying in terms of their roughness. Behavioral results confirmed the influence of the stimuli's roughness on aesthetic judgments, with smoother textures being rated as feeling better than rough textures. At the neural level, fNIRS activation results revealed an overall increased engagement of the contralateral sensorimotor areas as well as left prefrontal areas. Moreover, the perceived pleasantness modulated specific activations of left prefrontal areas with increasing pleasantness showing greater activations of these regions. Interestingly, this positive relationship between the individual aesthetic judgments and brain activity was most pronounced for smooth woods. These results demonstrate that positively valenced touch by actively exploring material surfaces is linked to left prefrontal activity and extend previous findings of affective touch underlying passive movements on hairy skin. We suggest that fNIRS can be a valuable tool to provide new insights in the field of experimental aesthetics.

1. Introduction

Each and every day, we touch the surfaces of various materials to discover whether or not they feel good. While an increasing amount of research has been conducted to understand the neural underpinnings of aesthetic processing, domains underlying visual representations have by far received the greatest interest, including architectural or landscape spaces (Coburn et al., 2020; Isik and Vessel, 2021; Skov et al., 2022; Vartanian et al., 2015), faces (Aharon et al., 2001; Kampe et al., 2001; O'Doherty et al., 2003), graphic patterns (Jacobsen et al., 2006), paintings (Cattaneo et al., 2014; Cela-Conde et al., 2004; Ishizu and Zeki, 2011; Kawabata and Zeki, 2004; Vartanian and Goel, 2004), and sculptures (Di Dio et al., 2007). In the plastic, performing, and fine arts, in particular, the sensory systems that are usually addressed provide information from stimulus sources in the receiver's distant environment, and it is usually not desired, or even possible, to touch the (aesthetic) entity (Marschallek et al., 2021)–here, the visual system is of primary interest. The psychology of aesthetics, however, does not only deal with primarily artistic domains, but it is also concerned with the beauty and the like of natural settings and everyday objects (e.g., Jacobsen, 2010). Here, sensory systems that provide information from stimulus sources in the receiver's close environment gain importance.

In this context, the sense of touch stands out. This sensory system uses receptors in our largest organ, the skin (e.g., Zimmerman et al., 2014), and therefore, provides information in direct contact with the body (e.g., Etzi and Gallace, 2016). Compared to vision, for example, it is regarded as being physiologically more arousing (Etzi and Gallace, 2016), as more intimate and active (Gallace and Spence, 2011), and as a way to "contact" and "communicate" with the external world, and vice versa (e.g., Gallace and Spence, 2011; Montagu, 1984). In addition, Gibson (1962) differentiates between active (i.e., touching) and passive touch (i.e., being touched), making touch the only "active" human sensory modality (e.g., Carbon and Jakesch, 2013). Touching someone or something, the individual will also be touched oneself (Sonneveld and Schifferstein, 2008), and this interactivity can lead to strong personal experiences using the haptic sense (Carbon and Jakesch, 2013). Surprisingly, despite these unique aspects of touch, there is relatively little literature covering this sense in the (neurocognitive) psychology of

* Corresponding author.
E-mail addresses: marschab@hsu-hh.de (B.E. Marschallek), loew@hsu-hh.de (A. Löw), jacobsen@hsu-hh.de (T. Jacobsen).
[1] Shared first authorship.

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aesthetics (Brown et al., 2011).

Research in haptic or tactile aesthetics often investigated the *(un) pleasant* aspects of touch (Etzi et al., 2014) and focused on differences between the stimulation of the C-tactile (CT) afferent system and of Aβ fibers. CT nerves are a group of unmyelinated low-threshold mechanoreceptive fibers mostly located on hairy skin, for example forearm, and respond specifically well to slow stimulation (1–10 cm/s) and very low indentation forces (0.3–2.5 mM; Löken et al., 2009; McGlone et al., 2014; Taneja et al., 2021). Aβ fibers, on the other hand, are rapidly conducting myelinated nerves, which are present in both the hairy and glabrous skin (e.g., Etzi et al., 2014; McGlone et al., 2007; McGlone et al., 2014). Active touch relies on four different types of Aβ innervated low-threshold mechanoreceptors (LTMRs) that encode different properties of handled stimuli including pressure, vibrations, slip and texture (McGlone et al., 2014). The LTMRs (Pacinian corpuscles, Meissner's corpuscles, Merkel's disks, and Ruffini endings) can be mostly found in the glabrous skin with the highest density in the fingertips (for an overview see Abraira and Ginty, 2013).

Even though the stimulation of glabrous skin can be perceived as emotionally positively valenced as well (Bhatta et al., 2017; Klöcker et al., 2012), it is a common view that the stimulation of the CT nerves of the hairy skin is perceived as more pleasant in general (Bennett et al., 2014; Essick et al., 2010; Etzi et al., 2014; Gordon et al., 2013; Guest et al., 2009; Löken et al., 2009). However, a recent meta-analysis on differences of the perceived pleasantness between skin types found large heterogeneity across studies and revealed no systematic preference for affective touch on hairy or glabrous skin (Cruciani et al., 2021).

Experimental attempts to identify neural correlates of pleasant touch have indicated different activation patterns for both skin types[2]: CT-targeted touch typically showed a network of activation including the orbitofrontal cortex (OFC; Francis et al., 1999; Hua et al., 2008; Kida and Shinohara, 2013; McGlone et al., 2012; Rolls et al., 2003; Voos et al., 2013), the medial prefrontal cortex (mPFC; Gordon et al., 2013; Kida and Shinohara, 2013; Voos et al., 2013), the right dorsolateral prefrontal cortex (dlPFC; Bennett et al., 2014; Voos et al., 2013), the pregenual anterior cingulate cortex (pgACC; Lindgren et al., 2012), the right posterior superior temporal sulcus (right pSTS; Bennett et al., 2014; Voos et al., 2013), the contralateral posterior insular region (Björnsdotter et al., 2009; Gordon et al., 2013; McGlone et al., 2012; Olausson et al., 2002, 2008; Perini et al., 2015; Voos et al., 2013), as well as the amygdala (Gordon et al., 2013; Voos et al., 2013). Pleasant touch to the glabrous skin, on the other hand, showed, above all, increased activations in the sensorimotor cortices (McGlone et al., 2012; Olausson et al., 2002; Perini et al., 2015), but in some studies also in the right cerebellum and left parietal cortex (Gordon et al., 2013), as well as in the anterior and mid insular cortex (McGlone et al., 2012), and the OFC (Francis et al., 1999; Rolls et al., 2003). Overall, these different activations patterns suggest that the stimulation of CT-afferent nerves is processed in emotion- and reward-related areas of the brain (Rolls, 2000, 2004; Vallbo et al., 1999) and represents an innate non-learned process, whereas the latter represents, above all, an analytical process (McGlone et al., 2012). It mainly activates brain areas which play a crucial role in discriminative encoding, that is, the detection, discrimination, and identification of the stimuli (Case et al., 2016; McGlone et al., 2014; Olausson et al., 2008; Perini et al., 2015).

It is of particular interest that these studies have mainly focused on brain correlates underlying passive touch, that is, individuals' skin being touched—often in a social context (for a review see Taneja et al., 2021). This might be due to the aspect that touch applied by another individual leads to increased perceived pleasantness of stimulation compared to self-delivered touch (Guest et al., 2009). These boundary conditions are, however, not exclusively applicable to every domain of aesthetics. One of these are *materials,* which are understood as the physical substances that constitute many kinds of human works—for example, buildings, furniture, or vehicles (e.g., Marschallek and Jacobsen, 2020). Individuals find themselves in constant interaction with all kinds of materials—often through the haptic sense—for instances, with ceramics when drinking coffee in the morning, with plastic, leather or wood when holding the steering wheel of the car, or with metal when turning a doorknob. Therefore, beholders experience all kinds of materials' sensorial characteristics on a regular basis, for example, their roughness or its interrelated concept smoothness (e.g., Bergmann Tiest and Kappers, 2006; Etzi et al., 2014; Faucheu et al., 2019; Hollins et al., 1993; Hollins et al., 2000; Picard et al., 2003). However, empirical attempts to identify neural correlates of aesthetic processing underlying active touch of materials are hardly present. Instead, previous studies have mainly either investigated affective touch of different material surfaces in the context of active exploration with the absence of neural correlates (e.g., Bhatta et al., 2017; Fujisaki et al., 2015; Klöcker et al., 2012) or the neural correlates of passive touch, including self-directed stimulation (Taneja et al., 2021). Yet, in a recent study (Henderson et al., 2022), cortical oscillatory activity underlying active touch exploration of different textures with the index finger was investigated using electroencephalography. Increased activation over sensorimotor cortices that covaried with subjective ratings of smoothness and softness was found, whereas no covariation with the perceived pleasantness of the textures was observed.

The lack of such studies may be related to methodological reasons of feasibility. Functional magnetic resonance imaging (fMRI) determines the blood oxygen level-dependent (BOLD) response resulting from changes in the relative concentration of oxygenated (HbO) and deoxygenated hemoglobin (HbR; Logothetis and Wandell, 2004). Even though the technique has a high spatial resolution, there are restrictions that hamper its usefulness to investigate aesthetic aspects of actively touching materials. These include susceptibility to motion artifacts, low temporal resolution and the general experimental setup (scanner noise, supine position).

An alternative approach is the application of functional near-infrared spectroscopy (fNIRS), which is an imaging technique that measures changes in cortical activity by means of changes in the tissue absorbance of light at near-infrared wavelengths (700–1000 nm; e.g., Scholkmann et al., 2014). The method relies on the different absorbent characteristics of HbO and HbR at different wavelengths. Compared to fMRI, it is more robust to motion artifacts and environmental noise (Meidenbauer et al., 2021; Pinti et al., 2018; Yücel et al., 2021), has a finer temporal resolution and is easier to administer (Cui et al., 2011). Therefore, it has the potential to be a valuable and advantageous tool for research in tactile aesthetics.

The present fNIRS study aimed to identify neural correlates of active fingertip exploration of material surfaces and subsequent aesthetic judgments of their pleasantness. For this purpose, multiple custom-built textile and wood stimuli with either a smooth or a rough surface, and in form of a decontextualized, flat sample were used (for a review see Veelaert et al., 2020). Decision for these materials and the stimulus manipulation was based on the intention to portray a lifelike depiction of aesthetic processing, which includes the usage of actual, physical materials as well as the exploration of these using common hand gestures (Giboreau et al., 2001; Lederman and Klatzky, 1987). Further, roughness–as well as its interrelated concept smoothness (Klatzky et al., 2013)–constitutes a core concept in the aesthetics of materials in general, as well as of textiles and wood in particular (Marschallek et al., 2021). In addition, roughness, or smoothness, is not only an important property for the assessment of surface textures (e.g., Bergmann Tiest and Kappers, 2006; Hollins et al., 1993; Hollins et al., 2000; Picard et al., 2003), but smooth textures have been identified as more pleasant or affectively positive than rough textures (Essick et al., 1999; Etzi et al., 2014; Faucheu et al., 2019). Interestingly, in a recent verbal association study by Marschallek et al. (2021), the adjective "rough," compared to "smooth," was more commonly listed for the aesthetics of textiles,

[2] All results are with respect to neurologically-healthy individuals.

whereas it was the latter for the aesthetics of wood.

This design allowed to analyze whether the aesthetic judgments of the stimuli vary between materials and their roughness and whether and how these aesthetic judgments modulate brain activity during haptic exploration. An increased activation in the contralateral sensorimotor areas was expected during haptic exploration. Furthermore, in line with previous studies investigating affective touch underlying passive movements on hairy skin, it was investigated whether prefrontal regions also play a role in active fingertip exploration of material surfaces and subsequent aesthetic judgments of pleasantness as well.

2. Method

2.1. Participants

Overall, 28 students of the Helmut Schmidt University/University of the Federal Armed Forces Hamburg participated in this study. Seven participants were excluded from further data analysis due to low quality fNIRS data ($n = 5$; see Section 2.6.1 for details on quality check) or to technical issues ($n = 2$). The final sample of 21 participants (7 women and 14 men) had a mean age of 23.67 years ($SD = 2.71$, ranging from 19 to 33 years) and majored either in psychology ($n = 12$) or educational science. All participants were native German speakers, with two reporting an additional mother tongue. All were right-handed, had normal ($n = 12$) or corrected vision capacity, and no reported tactile impairments or history of neurological disorders. All participants were naïve with respect to the purpose of the study and gave written informed consent prior to participation. The study was performed in accordance with the declaration of Helsinki and had research ethics committee approval from the university. The total duration of the study was approximately 1 h. If requested, individuals received course credit for participating.

2.2. fNIRS montage and data acquisition

The montage of the optodes was created using NIRSite 2.0 (NIRx Medical Technologies, LLC) and fOLD (fNIRS Optodes's Location Decider; Zimeo Morais et al., 2018), using positions from the 10–5 electrode system (Oostenveld and Praamstra, 2001). Sixteen LED sources that emitted light at wavelengths of 760 and 850 nm and 16 avalanche photodiode detectors were aligned, each separated by an inter-optode distance of approximately 3 cm, creating 48 channels covering the frontal and anterior part of the parietal cortex (see Fig. 1 and Table S1). The emphasis of optode placement over frontal brain areas was based on neuroimaging studies that investigated CT-targeted, pleasant touch.

The data were collected using a continuous-wave NIRScout device (NIRx Medical Technologies, LLC) at a sampling rate of 3.91 Hz using the NIRStar acquisition software, version 15.3.

2.3. Materials

The materials used in this study, that is, the touch stimuli, an experimental box and a screening wall, were custom-built to meet certain requirements.

The stimuli were textiles or wood, having either a rough or a smooth surface (see Fig. 2A for examples and Table S2 for the description of all stimuli).[3] The wood species used were alder, ash, and maple. Eight touch stimuli were obtained from each species by applying four different surface treatments either along or across its grain (see Table S2, Column 5 and 6). To attain rough and smooth surfaces for the textiles, multiple material compositions were used. Linen, canvas, and wools generated the stimuli for the rough condition and various satin, viscose and cottons for the smooth condition. Similar to the wood stimuli, some textiles were both meant to be touched along and across its grain. This resulted in a total of 48 unique stimuli, constituting a 2 (material: textiles vs. wood) x 2 (surface: rough vs. smooth) factorial design with 12 stimuli per cell each.

To keep the contact pressure while touching the materials comparable, the textiles were attached to particleboards, which were of the same size as the wood stimuli (200 mm length, 120 mm width, 10 mm height). All stimuli were then attached to a Polymethyl methacrylate plate (230 mm length, 140 mm width, 10 mm height). They were stored under normal room temperature (approximately 21 °C). Two additional practice stimuli were prepared using paper to avoid any priming.

An experimental box and a screening wall (between participant and experimenter) were constructed to ensure the absence of visual exploration while presenting the touch stimuli (see Fig. 3). The experimental box, 26 cm long, 16 cm wide, and 12.5 cm high, consisted of grey unplasticised PVC and continuously cold-rolled stainless steel. It was open at the front and one side and its cover was frontal protruding to prevent the view into the box. Its inner was equipped with a slide rail enabling the experimenter to easily change the touch stimuli. The screening wall, made of continuously cold-rolled stainless steel, was coupled with the side opening of the box. During a pilot phase, reflections on the steel were noted. Hence, the screening wall's side was taped using white paper (see Fig. 3B).

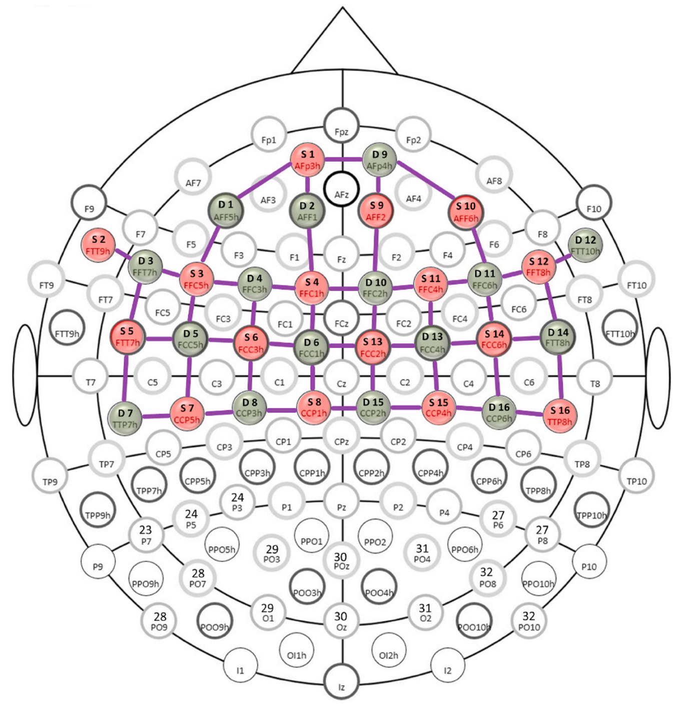

Fig. 1. FNIRS probe layout in international 10–5 coordinate space. Colored circles indicate optical sources (red) and detectors (green). The 48 channels are marked as purple lines.

2.4. Procedure

The experiment was conducted in a climate-controlled room with a constant temperature of approximately 21 °C. Before the experiment, the participants were instructed to clean their hands with disinfectant followed by warm water and soap and were then seated comfortably apart from the experimenter. Using paper and pencil, individuals first gave information on their demographics. Further, as mood priming processes (Forgas, 1995) can affect the overall aesthetic processing (e.g., Belke et al., 2006; Brattico et al., 2013; Chatterjee and Vartanian, 2014;

[3] Pretests with 10 additional participants were performed to validate the test stimuli for their roughness.

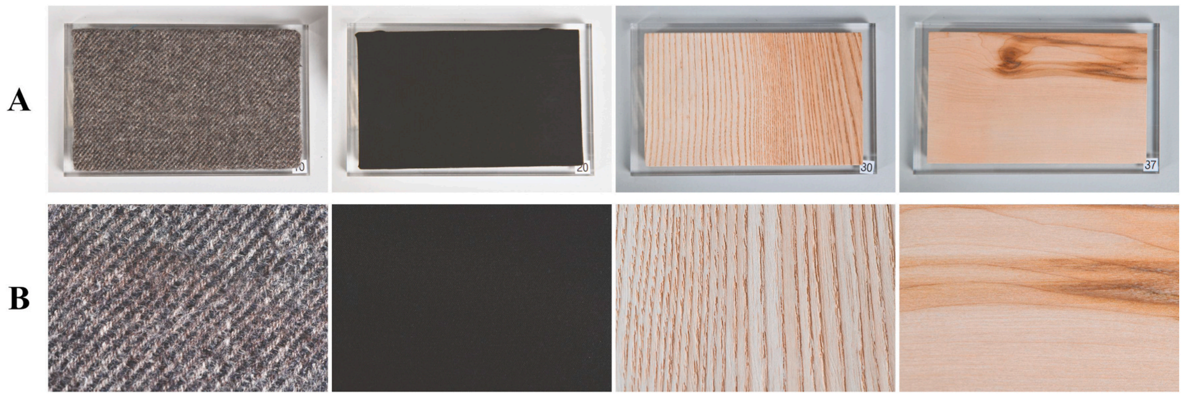

Fig. 2. Photographs of test stimuli of each of the four types of stimuli. Order of the photographs in figures (A, B) from left to right: rough textiles, smooth textiles, rough wood, smooth wood. A: Photographs of the whole stimulus. B: Close-up of test stimuli.

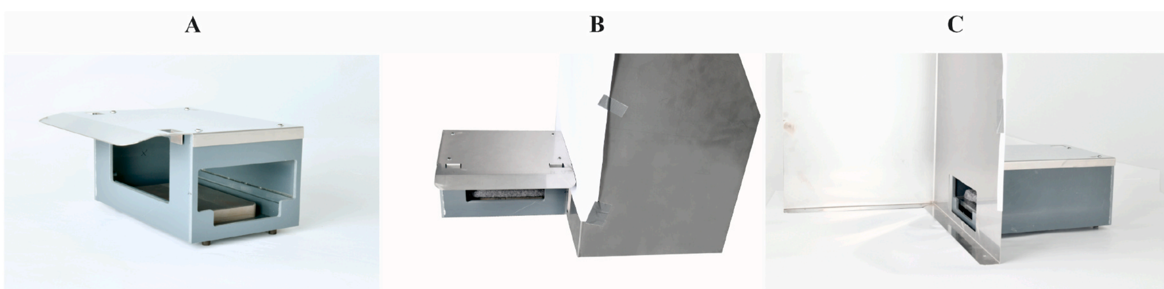

Fig. 3. Experimental box. A: Experimental box without any test stimuli and the screening wall. B: Frontal view on the experimental box including a test stimulus and the screening wall. C: Side/back view on the experimental box including a test stimulus and the screening wall; corresponds approximately to the view of the experimenter.

Leder et al., 2004; Marković, 2012; Wagner et al., 2016), we measured their affective state at the beginning of the study using the Self-Assessment Manikin (SAM; Bradley and Lang, 1994) and the self-report scales Positive and Negative Affect Schedule (PANAS; Krohne et al., 1996; Watson et al., 1988). The SAM measures the participants' felt pleasure, arousal, and dominance, whereas the PANAS offers insights into participants' positive (PA) and negative affect (NA). Subsequently, they were informed about the experiment's procedure and started with the first two practice trials. If there were no further questions, participants were instructed to insert earplugs in order to avoid any auditory disturbances.

Subsequently, the fNIRS cap was placed on the participants' head. A particular measurement of head size was not performed as a range between 56 cm and 58 cm was defined as inclusion criteria. After turning off the room light, the device was calibrated and checked for sufficiently high data quality of each channel before continuing. If needed, placement of the respective sensors was repeated before continuing. The ambilight of the screen in front of them was kept on throughout the whole experiment to make it more pleasant for the eyes. Next, participants completed another two practice trials and, unless any additional questions arose, proceeded to the test stimuli. To avoid inter-participants effects, participants rated all 48 stimuli, which were presented in randomized order with the restriction that each successive group of four stimuli always contained all four types of stimuli. To minimize mere exposure effects (Zajonc, 1968), there was no stimulus repetition. After half of the trials, individuals could take a voluntary break. After completing the experiment, the light was turned back on, the cap was removed, and the participants' state affect was assessed a second time using the SAM and PANAS. This second measurement was done to control for potential changes due to the procedure of the study.[4]

2.5. Haptic exploration and aesthetic judgment

Overall, participants completed 48 test trials and four additional practice trials. Each trial consisted of the haptic exploration, the aesthetic judgment and a following resting period (see Fig. 4). The haptic exploration was performed with the right hand. To do so, they were asked to keep this hand inside the box during the experiment. Their left hand maintained on the keyboard and was to be used to give the aesthetic judgment. Their gaze should remain fixed on the screen throughout the experiment.

Participants were instructed to only lower their right hand with appearance of a dot on the screen, signalizing the start of the haptic exploration. The stimuli had to be touched following the dot's movement, that is, its speed and direction. It travelled at a speed of 3 cm/s (Perini et al., 2015), making six transverse, lateral movements starting from left to right (Giboreau et al., 2001; Lederman and Klatzky, 1987), totaling 36 cm and 12 s haptic exploration. Individuals were instructed

[4] In closing individuals were asked if they experienced any pain triggered by the fNIRS cap, which could have influenced their aesthetic judgment (10-point scale, 0 = *zero pain* to 10 = *greatest possible pain*). This was done to control for possible exclusion. The majority reported zero pain ($n = 13$), six reported slight and two participants medium pain. Based on this result, no participants were excluded due to the pain item.

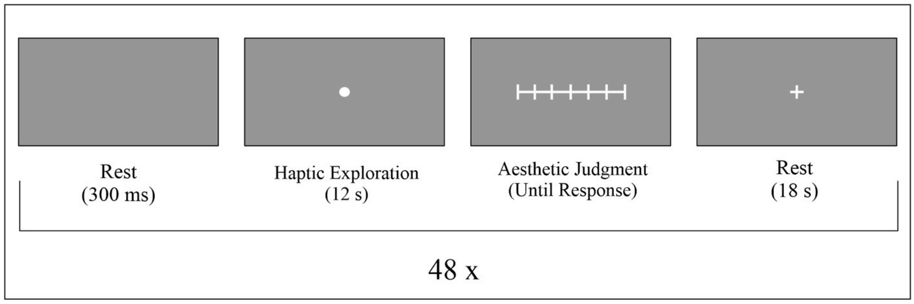

Fig. 4. Schematic diagram of test trials.

to use their four fingertips, excluding the thumb, while touch pressure was not controlled (Bhatta et al., 2017). With disappearance of the dot, participants lifted their right hand and were asked to give their aesthetic judgment with their left hand using the arrow keys and to confirm their judgment with the Enter key. In particular, the instructions on the screen read as follows: "How good did the surface of the … feel?" Depending on the specific category, the instructions included either the word "textiles" or "wood." Participants indicated their judgment on a 7-point bipolar scale with anchors from *very bad* (−3) to *very good* (+3).[5] From a theoretical point of view, it would be arguable to use anchors entitled *ugly*−*beautiful* or *unpleasant*−*pleasant* instead. However, this wording was chosen as it seems rather uncommon to subscribe the concept of beauty to the sense of touch (Etzi et al., 2014) and idiosyncratic to use the literal translation of the term "pleasant" (German *angenehm*). In the following resting period of 18 s, the experimenter exchanged the touch stimuli.

2.6. fNIRS data analysis

2.6.1. Quality check

In a first step, signal quality of each channel was assessed for each participant using the QT-NIRS toolbox (Quality Testing of Near Infrared Scans; https://github.com/lpollonini/qt-nirs/). This MATLAB-based toolbox uses the scalp coupling index (SCI; Pollonini et al., 2014) to quantity the signal-to-noise ratio of a channel. As the SCI can be inflated by movement artifacts, the peak power of the cross-correlated signal between the signals of the two wavelengths was used as an additional metric. Data was filtered between 0.7 and 1.5 Hz and a channel was marked as bad if the SCI was below 0.7 or the peak power was below 0.1 in more than 20% of the analyzed 5 s windows. Participants which had more than 50% bad channels were excluded from any further analysis.

Two different data analytic approaches were employed. An averaging approach was used to illustrate the morphology and the topographical distribution of the signal. This was followed by GLM-based analysis to investigate the association of brain activity with the aesthetic processing. Only HbO values are reported as these offer a higher signal-to-noise ratio compared to HbR values (Strangman et al., 2002).

2.6.2. Waveform analysis

The averaging analysis was performed using MNE-NIRS (vs 0.1.2, Luke et al., 2021). Data were converted to optical density and bad channels that were identified as bad (see Section 2.6.1) were interpolated using nearest neighbors. On average, 9.62 ($SD = 6.40$) channels were interpolated (range: 0–23). Motion artifacts were corrected using Temporal Derivative Distribution Repair (TDDR; Fishburn et al., 2019) and low and high-frequency artifacts were attenuated by a fourth-order zero-phase shift Butterworth bandpass filter (0.02–0.5 Hz). The signal was then converted to changes in hemoglobin concentrations using the modified Beer-Lambert law using a pathlength factor of 6. In order to remove systemic, extracerebral signals (respiration, Mayer waves) a PCA was performed (Franceschini et al., 2006) and the eigenvectors which accounted for at least 70% of the variance were eliminated. On average, 2.0 (range: 1–3) components were removed. For each stimulus, epochs ranging from 4 s before to 20 s after stimulus onset were created. Individual epochs that exceeded a peak-to-peak amplitude of 80 μM in any of the channels (<1% of the epochs) were excluded. Data were averaged per condition for each participant and channel. Then, the average HbO values from 8 to 16 s after the start of the haptic exploration were entered into a repeated measure ANOVA that included the factors material (textiles vs. woods) and surface (smooth vs. rough). False discovery rate control was applied to the data (p-values for all channels, oxy- and deoxyhemoglobin, and condition) and the corresponding q-values were computed according to Benjamini and Hochberg (1995).

2.6.3. GLM analysis

In a second independent analysis, individual fNIRS responses were fit to a GLM model using the MATLAB-based NIRS Brain AnalyzIR Toolbox (Santosa et al., 2018). The canonical SPM HRF function (double gamma function) was used to model the HRF response and convolved with a boxcar function of 12 s, representing the duration of the stimulus and active touch.

Furthermore, individual, trial-specific ratings of the aesthetic judgments were used as parametric modulator to construct a second regressor that varied the amplitudes with the values of the ratings. This allows to identify channels where the hemodynamic brain response linearly covaries with the individual ratings. To account for individual differences in the overall rating patterns, the z-scored ratings were used.

Autoregressive iterative least squares (AR-IRLS; Barker et al., 2013) were used to solve the model. This approach is robust to the statistical properties of noise of the fNIRS signal and therefore no correction of systemic physiological confounds and motion artifacts was applied. In short, an autoregressive filter is used to whiten both sides of the linear regression model. Serially correlated errors are attenuated and the outliers due to motion artifacts are down-weighted by the use of robust statistics.

The estimates of beta coefficients and the full noise covariance matrices of the first level regression were used for a second-level, group analysis to evaluate responses for each stimulus conditions and the parametric modulations thereof for each channel (Santosa et al., 2018). A linear mixed-effects model that accounted for condition with participant as random variable was solved by using weighted least squares. In Roger-Wilkinson description, this could be formulated as 'beta $\sim -1 +$ condition $+ (1|$subject$)$'.

Channel-wise t-contrasts were used to estimate the effects of materials and surfaces as well as of the parametric modulation based on individual ratings. The false discovery rate method (Benjamini and Hochberg, 1995) was used to control for multiple comparison (p_FDR $=$ 0.05).

[5] The original German instructions were: "Wie gut hat sich die Oberfläche des … angefühlt?" Depending on the specific category, the instructions included either the German word *Textils* or *Holzes*. The according original German anchors of the 7-point bipolar scale were *sehr schlecht* and *sehr gut*.

2.7. Research data

The data and code of this study are available from the corresponding author for qualified academic researchers and scientific use upon request. Data and code will be obtained upon a formal request including a project outline stating the purpose for which the data will be used.

3. Results

3.1. Behavioral data

For the aesthetic judgments, means and standard deviations were calculated for each condition by averaging the ratings of the respective stimuli. The surface of smooth wood stimuli had the highest mean ranking ($M = 1.32$, $SD = 1.01$), followed by smooth textiles ($M = 1.24$, $SD = 0.66$). The surface of rough textiles and rough wood had the lowest mean rating ($M = 0.02$, $SD = 1.15$ and $M = 0.01$, $SD = 1.10$, respectively). A two-way repeated-measures analysis of variance revealed a main effect of surface on the ratings ($F(1, 20) = 38.95$, $p < .001$, $\eta^2 = 0.66$), with the rough surfaces ($M = 0.01$, $SD = 0.80$) feeling significantly worse compared to smooth surfaces ($M = 1.28$, $SD = 0.68$). The analysis did, however, neither reveal a significant interaction between the effects of material and surface on the ratings ($F(1, 20) = 0.05$, $p = .83$, $\eta^2 = 0.002$), nor a main effect of material ($F(1, 20) = 0.03$, $p = .87$, $\eta^2 = 0.001$; wood: $M = 0.67$, $SD = 0.74$; textiles: $M = 0.63$, $SD = 0.79$).

The participants' affective state was measured before and after the experiment, labeled hereafter as Time Point 1 (TP1) and Time Point 2 (TP2). A Wilcoxon signed-rank test[6] revealed significant differences for participants' pleasure between TP1 ($Mdn = 3$) and TP2 ($Mdn = 4$), $z = -2.11$, $p = .04$, $r = 0.47$, and a t-test for participants' arousal between TP1 ($M = 6.14$, $SD = 1.59$) and TP2 ($M = 7.71$, $SD = 1.15$), $t(20) = -3.77$, $p = .001$, $d = 0.82$, reflecting a decrease in both pleasure and arousal. There were no significant differences for participants' dominance between TP1 ($Mdn = 8$) and TP2 ($Mdn = 8$), $z = -1.57$, $p = .13$, $r = 0.35$, indicating that individuals felt emotionally under control during the experiment. Additionally, participants' positive affect decreased significantly from TP1 ($M = 3.18$; $SD = 0.41$) to TP2 ($M = 2.86$, $SD = 0.57$), $t(20) = 2.73$, $p = .01$, $d = 0.60$. Likewise, individuals' negative affect decreased significantly from TP1 ($M = 1.21$, $SD = 0.24$) to TP2 ($M = 1.09$, $SD = 0.19$), $t(20) = 4.65$, $p < .001$, $d = 1.01$.

3.2. fNIRS activation results

3.2.1. Waveform analysis

The topographical distribution of the evoked hemodynamic response (HbO) is illustrated in Fig. 5A, and the corresponding waveform for the channel S7-D8, which showed the most pronounced evoked response, in Fig. 5B. Active touch of the materials with the right hand was accompanied by activity over contralateral sensorimotor regions. No significant differences (FDR-corrected) were evident between materials, surface, or the interaction thereof.

3.2.2. GLM analysis

3.2.2.1. Overall analysis. As also evident from the waveform analysis, a strong HbO response–relative to the baseline and irrespective of the materials and the ratings–was displayed across a large number of channels. Forty out of the 48 channels differed from baseline ($q < 0.01$; see Table S3 for the results of all channels). This response, while actively touching the materials with the right hand and evaluating them subsequently, was most pronounced over sensorimotor cortex contralateral to the right hand (see Fig. 6A). The largest activity was revealed at channel S7-D8 ($q < 0.001$; see Table S1 for the channel specificities).

A second cluster of activity was identified over a left prefrontal area located approximately over BA 6, 9, and 10, and the largest activity was at all channels that included the source S1 (all $p < .001$).

3.2.2.2. Material- and surface specific effects. Significant main effects and interactions are listed in Table 1. Actively touching textiles (compared with touching woods) evoked significantly larger HbO values at several channels, which were mostly located over sensorimotor cortex. On the other hand, larger HbO values while touching woods (compared with touching textiles) were found at two channels located bilaterally over the (inferior) frontal gyrus.

Moreover, touching rough surfaces (compared with touching smooth surfaces) evoked larger HbO values over two bilateral clusters (significant for three left, and three right-sided channels), each comprising multiple areas, inter alia, the over right (inferior) frontal gyrus and left sensorimotor cortex. Additionally, one channel located over the primary motor cortex also displayed larger HbO values for rough compared with smooth surfaces.

Interaction effects between material and surface were evident at three channels. One channel over the left somatosensory cortex displayed lower HbO values when touching smooth woods (compared with the other categories). Two channels were located over the right frontal cortex and the beta values for each material category revealed that the interaction was driven by enhanced HbO values for rough woods.

3.2.3. Parametric modulation based on ratings

3.2.3.1. Overall analysis. Relative to baseline, parametric modulation of the HbO signal by individual aesthetic processing was evident at eight channels. Seven of these channels were clustered over the left prefrontal gyrus, approximately including BA 2, 9, and 46, and parametric modulation was most pronounced over channel S1-D9 ($\beta = 15.46$, $p < .001$), located approximately over BA 10 (see Table 2 and Fig. 6B). In addition, activity at channel S7-D8 was linearly modulated by the aesthetic ratings.

3.2.3.2. Material- and surface specific effects. Four channels reached FDR-corrected significance when testing for material specific effects. Three channels over left frontal cortex (highest specificities for approximately BA 6, 8 and 9) showed larger parametric modulation of HbO values for wood compared to textiles. This relationship, that is, larger brain responses associated with larger beta values, was revealed for woods, but not for textiles. One channel located over sensorimotor cortex (S8-D15; located approximately over BA 4), showed the reversed pattern: Lower aesthetic ratings were associated with larger beta values for woods compared to textiles.

Seven channels showed significant differences of the parametric modulation for the two different surfaces. A cluster of three sensors over the left sensorimotor cortex was the most pronounced pattern. Smooth surfaces (relative to rough ones) showed a negative association between aesthetic ratings and brain activity, that is, lower ratings were associated with larger beta values.

These main effects of material and surface were driven by interaction effects were smooth woods evoked category-specific effects. Over the sensorimotor cortex, the relationship between the subjective aesthetic ratings and brain activity was negative (lower beta values for more positive ratings). On the other hand, over left frontal cortex, located approximately over BA 6, 8, and 9, a reversed pattern was observed, that is, in contrast to the other categories, smooth woods showed a positive relationship between aesthetic ratings and brain activity.

4. Discussion

The present fNIRS study identified brain correlates of active fingertip

[6] Analysis was performed using a non-parametric test for data that violated the assumption of normality as indicated by the Shapiro-Wilk test.

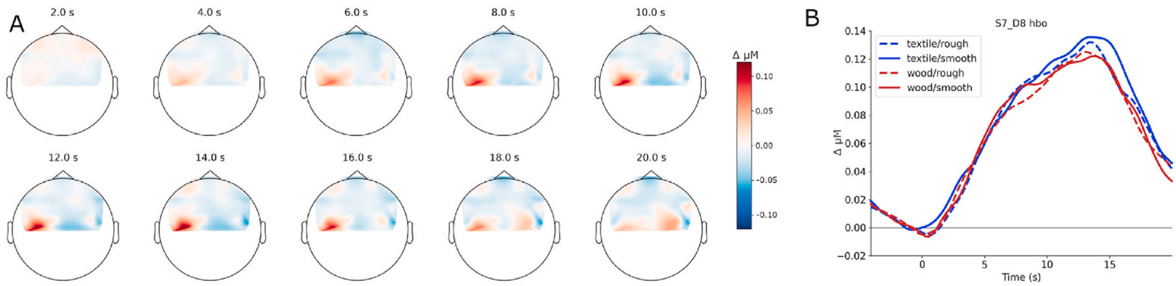

Fig. 5. Results of waveform analysis. A: Time-course of topographic distribution of the fNIRS response averaged across all types of stimuli. Maps are displayed in steps of 2 s. B: Average fNIRS response amplitudes for each stimulus type at the channel with the largest response.

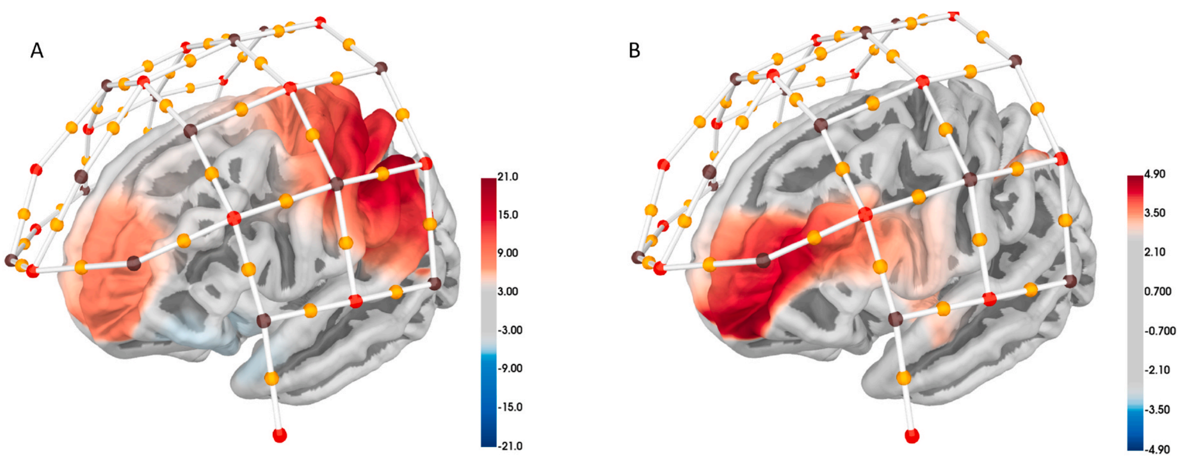

Fig. 6. Group-level hemodynamic activity. A: Canonical BOLD response to all stimuli contrasted against baseline. B: Parametric modulation of the BOLD response by individual ratings. Maps of *t*-values are interpolated from single-channel data and projected to the cortical surface for illustrative purposes. Sources are marked in red, detectors are marked in black and the links between them (channels) are marked in yellow.

Table 1
GLM Analysis Material and Surface Specific Effects.

Source	Detector	Beta	*SE*	*t*	*p*	*q*	*power*
Material (textiles > wood)							
3	1	−2.37	0.85	−2.78	.006	.048	.61
7	5	3.00	0.94	3.20	.002	.027	.76
8	8	4.79	0.95	5.07	<.001	<.001	.99
8	15	3.33	0.81	4.11	<.001	.003	.95
10	11	−2.79	0.89	−3.13	.002	.029	.74
12	11	2.47	0.73	3.40	.001	.016	.82
13	15	2.53	0.88	2.87	.005	.045	.64
14	14	3.08	1.04	2.95	.004	.039	.67
15	13	3.79	1.27	2.99	.003	.039	.69
15	15	4.67	1.34	3.49	.001	.015	.84
Surface (rough > smooth)							
5	3	3.97	0.95	4.20	<.001	.004	.95
5	5	2.92	0.79	3.67	<.001	.009	.88
7	5	3.09	0.94	3.30	.001	.019	.79
8	15	3.23	0.81	4.01	<.001	.005	.93
10	11	2.57	0.89	2.89	.004	.047	.65
12	11	2.39	0.72	3.31	<.001	.019	.79
14	14	3.80	1.04	3.64	<.001	.009	.87
Interaction							
7	5	3.44	0.94	3.67	<.001	.012	.88
10	11	3.55	0.89	3.99	<.001	.005	.93
12	11	3.83	0.72	5.28	<.001	<.001	1.00

Note. Channels with an FDR-corrected $q < 0.05$ are listed. The *p*-values are before FDR-correction. Power was calculated as minimum detectable change (Harcum and Dressing, 2015) and represents an estimate of a type-II power for the entry.

exploration of material surfaces and subsequent aesthetic judgments of their pleasantness (feels good or bad?). Multiple custom-built textile and wood stimuli with varying smooth or rough surface textures were used for the purposes of this study. As we assumed the aesthetic judgments to modulate the brain activation during stimulation, ratings were included in further analysis. In line with previous studies investigating affective CT-targeted touch (i.e., hairy skin sites), it was particularly investigated whether prefrontal regions are significantly relevant in the stimulation of individuals' Aβ fibers which innervate the glabrous skin sites as well.

The behavior results are consistent with previous findings in that participants rated smoother textures as more positive than rough textures (Essick et al., 1999; Etzi et al., 2014; Faucheu et al., 2019). This accounted for both materials, with smooth woods being rated slightly better than smooth textiles. In a previous study by Marschallek et al. (2021), the term "smooth" compared to "rough" had a higher relative listing frequency for wood; for textiles, on the other hand, the "term" rough had a higher listing frequency. These frequencies indicate differences in the preeminence of the terms "rough" and "smooth" in the conceptual structures of the aesthetics of both materials.

At the neural level, the waveform analysis revealed enhanced cortical activity during active fingertip exploration of material surfaces for all conditions, which was most pronounced over sensorimotor areas contralateral to the moving hand. The waveforms reflect a canonical hemodynamic response, with the peak response around 12–16 s after stimulus onset, consistent with the duration of the haptic exploration.

The results of the GLM analysis (overall analysis) revealed increased activation (compared to baseline) in two clusters: again, in the contralateral sensorimotor areas and additionally in left prefrontal areas located approximately over BA 6, 9, and 10. This activation pattern is likely to reflect the discriminative encoding of the stimuli, that is, not

Table 2
Parametric Modulation Based on Ratings.

Source	Detector	Beta	*SE*	*t*	*p*	*q*	*power*
Overall							
1	1	11.79	2.41	4.90	<.001	<.001	.99
1	9	15.46	3.38	4.58	<.001	<.001	.98
3	1	10.94	2.48	4.41	<.001	.001	.97
3	3	7.78	2.15	3.61	<.001	.007	.87
3	4	5.99	1.94	3.09	.002	.025	.72
3	5	10.92	2.32	4.70	<.001	<.001	.99
5	3	9.04	2.78	3.25	.001	.019	.77
7	8	11.89	2.84	4.19	<.001	.001	.95
Material (textiles > wood)							
4	4	−3.66	0.97	−3.78	<.001	.006	.90
4	10	−3.32	0.88	−3.77	<.001	.006	.90
6	4	−5.70	1.55	−3.67	<.001	.006	.88
8	15	9.46	1.96	4.82	<.001	<.001	.99
Surface (rough > smooth)							
4	4	−3.38	0.97	−3.49	.001	.012	.84
4	10	−2.65	0.88	−3.01	.003	.042	.70
8	6	11.89	2.59	4.59	<.001	<.001	.98
8	8	12.04	2.30	5.24	<.001	<.001	1.00
8	15	15.80	1.95	8.09	<.001	<.001	1.00
10	9	6.31	1.88	3.35	.001	<.016	.80
12	11	6.39	1.80	3.54	.001	<.012	.85
Interaction							
4	4	−3.34	0.97	−3.45	.001	.018	.83
4	10	−3.41	0.88	−3.87	<.001	.015	.91
8	15	6.62	1.96	3.38	.001	.018	.81
13	6	−7.36	2.11	−3.48	.001	.018	.84
14	16	9.33	2.72	3.42	.001	.018	.82

Note. Channels with an FDR-corrected $q < 0.05$ are listed. The *p*-values are before FDR-correction. Power was calculated as minimum detectable change (Harcum and Dressing, 2015) and represents an estimate of a type-II power for the entry.

only the detection, but also discrimination, and identification of the stimuli's materials and surfaces (Case et al., 2016; McGlone et al., 2014; Olausson et al., 2008; Perini et al., 2015). Tactile perception begins with the initial sensory and motor processing of the stimuli's characteristics, for example their texture (Gomez-Ramirez et al., 2016), and is followed by higher-order processing of the stimuli, such as the comparison with previous tactile experiences (McGlone et al., 2012). The stimulation of the present participants' Aβ fibers, which innervate receptors in their glabrous skin sites, were likely to activate brain areas depicting the initial interaction of the active hand movement as well as the sensory feedback induced by the exploration of the materials surfaces (e.g., Ackerley et al., 2012), which is usually represented in the contralateral primary somatosensory cortex (SI; Penfield and Rasmussen, 1950). The activation of the prefrontal regions, on the other hand, may be associated with fine detailed discrimination and identification of the stimuli's characteristics to gather information for the following aesthetic judgment, as they are usually suggested to play a special role in top-down control, namely to direct attention to relevant environmental features in order to achieve a specific goal or task (e.g., Miller and Cohen, 2001).

Furthermore, the results of the parametric modulation (overall analysis) support the assumption that the activation of the left prefrontal gyrus (with significant activation of areas located approximately including BA 9, 10 and 46) is not only relevant for the fine detailed discrimination and identification of the stimuli's characteristics, but that it also directly reflects the perceived pleasantness of touching the stimuli and is also in line with findings on CT-targeted touch. In particular, when participants judged the surface of the stimuli to feel good (as compared to feel bad), the left prefrontal areas showed enhanced concentration changes in oxygenated hemoglobin. Likewise, the activation of the sensorimotor cortices cannot be suggested to be only related to the physical aspects of the stimulation (Case et al., 2016; Francis et al., 1999). This finding is consistent with the idea that the various aspects of touch are represented in multiple brain regions (Francis et al., 1999). The role of the prefrontal regions was already shown to play a crucial role in the aesthetic appreciation of other stimuli underlying the visual modality. Specific regions comprised the dlPFC (mainly in the left hemisphere), the mPFC and orbital prefrontal cortices (e.g., Cattaneo et al., 2014; Cela-Conde et al., 2004; Cupchik et al., 2009; Ishizu and Zeki, 2011; Jacobsen et al., 2006; Jacobsen and Höfel, 2003; Kirk, 2008; Vessel et al., 2012; Zhang et al., 2016). In the context of these studies, the activations of these regions are interpreted as being related to the process of evaluative judgment, either based on internally and/or externally generated information, as well as to the distribution of attentional resources (Nadal, 2013). The results by Jacobsen et al. (2006), for example, showed a greater activation in the frontomedian cortex (BA 9/10) when individuals were instructed to judge the beauty of abstract graphic geometric patterns compared to when instructed to judge their symmetry. The results by Cela-Conde et al. (2004), on the other hand, showed a greater activity in the dorsolateral prefrontal cortex while participants viewed photographs and painting they judged as beautiful. In line with Christoff and Gabrieli (2000), these different patterns were explained by the different information used to form the aesthetic judgments: Whereas the frontomedial prefrontal cortex is related with the evaluation of internally generated information, activity in the dorsolateral prefrontal cortex seems to be primarily involved with information elaborated externally, for example, degree of artistry, explicit content and style (Cela-Conde et al., 2004). With the present study, we are only able to provide approximate areas included in the aesthetic processing underlying haptic exploration of different materials in form of decontextualized, flat samples. Therefore, participants were likely to base their decisions on the perceived tactile characteristics of the materials and internally generated information, rather than on any richer, externally generated information such as degree of artistry or style. Overall, in line with the studies by Jacobsen et al. (2006) and Cela-Conde et al. (2004), we do find support for the assumption, however, that the prefrontal areas subserve the process of aesthetic judgments and we extend these findings by showing that this also applies to aesthetic judgments of pleasantness underlying haptic exploration.

The activations observed in the prefrontal areas were lateralized to the left hemisphere. This may be explicable in terms of the above-mentioned allocation of attentional resources (Nadal, 2013). Cela-Conde et al. (2004) also showed an increased left prefrontal activity while participants viewed beautiful stimuli and the authors interpreted this activation to reflect the process of aesthetic perception. Similarly, Cupchik et al. (2009) argued the activation of the left lateral PFC (BA 10), in particular, to be associated with a top-down control of directing perception towards an aesthetic orientation. In line with these findings, our results suggest that the lateralization, that is, the activation of the left prefrontal areas, to be associated with the fine detailed discrimination and identification of stimulus objects as well as the perceived aesthetic quality (whether the surface felt good or bad to touch). Thus, it might be speculated that rather than focusing on the stimuli's surfaces only, the participants' cognitive control may have been guided to approach the materials from an aesthetic orientation depending on their perceived aesthetic quality.

Interestingly, we found a significant interaction with smooth woods showing category-specific effects. Behavioral analyses revealed smooth wood to have the highest mean rating, presumably leading to the most pronounced effect of activation. Wood is omnipresent in everyday life, especially in construction and interior design. It has already received much attention in previous research, for instance, regarding the preference for certain visual properties (Høibø and Nyrud, 2010; Nyrud et al., 2008), differences in perception of its properties based on the sensorial modality (Fujisaki et al., 2015; Overvliet and Soto-Faraco, 2011) or on the varying naturalness of surfaces (Bhatta et al., 2017). Due to its natural and traditional character, it is often associated with craftsmanship (Ashby and Johnson, 2014), and has ecological value and potential for individuality due to visual imperfections (Ashby and Johnson, 2003). Moreover, research indicates that its use in living areas has a positive impact on emotional states and psychological health (e.g., Demattè et al., 2018; Jiménez et al., 2016; Nyrud et al., 2014; Rice et al., 2007; Zhang et al., 2016; Zhang et al., 2017). Overall, all these factors may have led to the positive relationship between the subjective ratings and left frontal activity, located again approximately over BA 9, and the negative relationship between the ratings and the sensorimotor cortex.

The current study has a few limitations, which provide potential for future research. First, fNIRS has a spatial resolution of only approximately 1 cm (e.g., Boas et al., 2004), and thus has an inferior resolution than fMRI (Glover, 2011). For this reason, we can only provide approximations of activated areas or clusters of brain regions. Furthermore, are we not able to draw conclusions on deeper brain regions, for example, regions of the emotion and reward circuitry including the OFC, ACC, insula, amygdala and striatum (Bartra et al., 2013; Brown et al., 2011; Kühn and Gallinat, 2012; Sescousse et al., 2013), nor on brain areas outside the optode placement, for instance, the posterior parietal cortex, which has been linked to sensorimotor integration (Andersen and Buneo, 2002).

Furthermore, we did not investigate the time course of brain activity underlying the present aesthetic processing. Some authors suggested multiple stages of processing during aesthetic experiences, some of which may only occur after prolonged exposure to or removal of the stimulus and each with distinct active networks (Cela-Conde et al., 2013; Jacobsen and Höfel, 2003). Future research on the question whether this accounts for the processing of haptic input as well would be beneficial.

Aesthetic processing in general is known to be influenced by a variety of factors, that is, on the part of the beholder, the processed entity as well as the situation (e.g., Jacobsen, 2006). Individuals' characteristics, such as materials' expertise or cultural background may be worthwhile to consider in future studies. For example, the individuals' Need for Touch (NFT), that is, the "preference for the extraction and utilization of information obtained through the haptic system" (Peck and Childers, 2003, p. 431) could be considered. Of particular interest may be the underlying autotelic factor, which is, seeking sensory stimulation from a hedonistic motivation. Additionally, regarding the situation, results by Brieber et al. (2014), for example, suggest that the specific context in which individuals encounter visual artworks modulates both experience and the viewing time. Compared to the laboratory context, the museum context increased the liking of and interest in artwork, as well as the viewing time. Whether this applies to haptic stimuli as well remains an open question. This may also be interesting considering the results of the SAM (Bradley and Lang, 1994) and the PANAS (Krohne et al., 1996; Watson et al., 1988). Based on these two measures, it can be concluded that participants were in a neutral affective state. This is explicable to the usage of more or less (un)pleasant stimuli. It seems worthwhile, however, to investigate whether different framings of the judgment task would generate different results, for example, a positivity bias in an art-framed situation (e.g., Wagner et al., 2016). Whether this would also affect the neural basis remains a desideratum for future research.

In addition, the haptic sense encompasses a variety of potential influencing factors we did not control for (Taneja et al., 2021). Klöcker et al. (2012), for example, showed that during active exploration participants with high fingertip moisture levels perceived rough materials as more pleasant compared to subjects with low levels. Participants in the present study were only instructed to clean their hands with a disinfectant followed by warm water and soap. However, future investigations could test the influence of further factors.

As this study aimed to investigate neural underpinnings of the aesthetic processing of materials underlying haptic experiences only, we cannot draw conclusions about the relationship between a multisensory stimulation, which is, however, of great interest to be investigated in future studies.

All conclusions refer to textiles and wood varying in their roughness. However, the large number of used textile and wood stimuli as well as surface textures allows to assume that the present results apply to similar stimuli as well. Furthermore, mean ratings of pleasantness did not reveal strong negative or positive values. It would be interesting to investigate whether neural correlates would be more pronounced using stimuli which surfaces are rated as feeling less good or better. Based on our results, it may be suggested that this is the case. In addition, as mentioned before, from a theoretical point of view, it would be arguable to use anchors entitled *ugly–beautiful* or *unpleasant–pleasant* instead of *very bad–very good*. Any conclusions drawn from this study must bear in mind these language boundaries.

In conclusion, the use of functional near-infrared spectroscopy and a custom-built setup enabled the measurement of aesthetic judgments in a situation close to everyday life and provided initial evidence for neural underpinnings of active touch of different materials and surfaces. With this, previous findings investigating affective touch underlying passive movements on hairy skin that showed prefrontal regions to play a major role were extended and a direct link between perceived pleasantness of materials' surfaces and left frontal activity was found. Our results show that positively valenced touch can be mediated through Aβ fibers in the glabrous skin sites as well. We suggest that fNIRS can make valuable contributions to the (neurocognitive) psychology of aesthetics in general and on tactile aesthetics in particular. Furthermore, these insights deepen our understanding of the aesthetic processing of materials and the importance of the sense of touch.

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Author contribution

Barbara E. Marschallek: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing, **Andreas Löw:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Validation, Visualization, Writing - Original Draft, Writing - Review & Editing, **Thomas Jacobsen:** Conceptualization, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing - Review & Editing.

Ethics approval

The study received ethics approval from the Ethics Committee of Psychology of the Faculty of Humanities and Social Sciences of the Helmut Schmidt University/University of the Federal Armed Forces Hamburg, and it was performed in accordance with the declaration of Helsinki.

Declaration of competing interest

The authors declare that there is no conflict of interests.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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