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Tactile perception of natural and simulated textures
A psychophysical approach

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List of published articles

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Foreword by the author

My thesis was conducted within PROTOTOUCH, a European Commission Seventh Framework Project. The project aims to develop a new generation of tactile displays that will recreate the perception of touching shapes and textures. In order to achieve that goal, knowledge of how texture information is transmitted and coded by the mechanoreceptors and the nervous system is essential. The goal of my PhD thesis was to define and investigate psychophysically the most relevant features influencing the sensation of touch (peripheral and central tactile processing, friction modulation, texture's perception…). In the second phase of the PhD, the textures were generated by tactile devices providing haptic feedback.

1 CHAPTER I: GENERAL INTRODUCTION

1.1 Natural touch and Haptics

The sense of touch is less understood than the visual and auditory senses even though we are continuously using it in our everyday life to interact with the world around us at several levels: texture perception, vibration detection, assessment of the position of our body and limbs (proprioception). We also use it extensively for sharing affection with our loved ones and a kiss or a hug are considered more intimate than waving and saying hello. The tactile sense is so embedded in us that we barely notice its existence unless an injury or pathology deprives us from it. Its crucial contribution to our health is highlighted by several studies reporting that impairment of the sense of touch has severe consequences on the life of patients, who become unable to perform tasks that usually go almost unnoticed (Augurelle et al., 2003; Cole and Paillard, 1995; Robles-De-La-Torre, 2006). There are many studies demonstrating that nerve block hence disruption of the bottom-up tactile feedback impairs our capacity to perform the easiest manipulation tasks. For example, it was observed that carpal tunnel syndrome increases the tactile thresholds especially after prolonged flexion of the wrist (Sesek et al., 2007) and a longitudinal observations of patients with sectioned median nerve showed that these patients lose their capacity to judge the roughness of materials right after their injury. In this second study, most patients took up to 20 months to recover depending on the speed of the regeneration of the median nerve and related tendons (Libouton et al., 2012). It is also well established that tactile feedback is a crucial component of artificial limbs and hands, which aim at restoring the capacity for haptic manipulation in amputees and paraplegic patients (Tabot et al., 2013). Thus, the question is no longer if tactile feedback is needed for prosthetics and dexterous robotics but which are the most efficient ways of implementing it (Anikeeva and Koppes, 2015).

The recent advances in our knowledge of the sense of touch have also opened new developments and perspectives for the field of Haptics. Historically, touch has been considered as more perceptually stable and robust and was referred as the sense providing the truth to the other while we are keener to accept visual or auditory illusions (Hayward, 2015). Nevertheless, there is growing evidence that touch is as prone as the other sense to be deceived and can be similarly challenged by ambiguous stimuli as the other senses (Botvinick and Cohen, 1998; Pei et al., 2008). A major contribution to this new perception of the sense of touch has been made by De La Torre and Hayward who demonstrated that our perception of shape depends on the contact forces rather than on the geometry (Robles-De-La-Torre and Hayward, 2001). This finding opened a new perspective on the possibility to create virtual textures through manipulation of the contact forces during fingertip-surface interaction (Amberg et al., 2011; Biet et al., 2008; Chubb et al., 2010) or through vibrational patterns that reproduce those who are induced by the exploration of the texture (Wiertlewski et al., 2011; Wiertlewski et al., 2010). Despite these promising advances, many mechanisms of tactile perception remain to be better understood as for example, the respective contributions of the peripheral coding mechanisms and the central integration, in order to foster the comprehension of tactile perception and the rise of a new generation of haptic technologies.

1.2 The tactile modalities

The usual modalities of touch are considered to be: proprioception, nociception, thermal perception, vibrotaction and discriminative touch. In addition, several recent studies have emphasized the relevance of pleasant and affective touch (Ackerley et al., 2014; Klöcker et al., 2012). Each of these modalities relies on specific afferents and sensory channels that encode stimuli depending on the preferential signals that they capture.

1.2.1 Proprioception

Most of our touch experiences being dynamic, an accurate spatial representation of the finger and arm movement is essential when we need to achieve a stable tactile perception of an object across all the possible exploratory and grasping conditions (different speed of exploration, different position of the limb, different environment). Proprioception refers to the inner knowledge of the spatial and mechanical status of our limbs during movements and object manipulation (Stillman, 2002) which derives mainly from the various types of proprioceptors that encode the spatial evolution of muscles and joints (Hogervorst and Brand, 1998). This claim is supported by the observation that electrical stimulation of the finger joint proprioceptive afferents produces the illusion of finger movement (Burke et al., 1988; Macefield et al., 1990). The muskuloskeletal receptors and vestibular apparatus are usually considered full members of the proprioceptive system. There is also growing evidence that all the skin mechanoreceptors are acting as part-time proprioceptors in addition to their primary role of encoding external stimuli (Edin and Johansson, 1995; Moscatelli et al., 2016). At a psychophysical level, Lederman (Lederman, 1983, 1974) showed that large changes in the scanning velocity and contact force have only minor influence on the perceived roughness. This means that proprioceptive inputs are processed by the central nervous system and contribute to keep a stable perception of the same textures and objects across different exploratory strategies. The stable perception of roughness across various speeds of exploration seems to be sometimes altered by removing proprioceptive cues (Yoshioka et al., 2011) although the input from part-time proprioceptors seems sufficient to ensure perceptual stability for most tasks (Lederman, 1981; Vega-Bermudez et al., 1991). The role of part-time proprioceptors was further demonstrated by inducing illusory displacement of the finger through vibratory cues mimicking a granular material on a stationary hand (Terekhov and Hayward, 2015) or by a subtle variation of the contact area of the fingertip through change of compliance (Moscatelli et al., 2016). It was therefore hypothesized that if movements are small, displacement of joints can hardly be used to determine the finger's movement and proprioception is mainly achieved using the fingertip deformation as a cue based on prior knowledge of the objects, textures and materials. In conclusion, proprioception is relevant for large exploratory movements eliciting signals in the proprioceptors at joint level but also for cues at the level of the fingertip where the skin-object interaction is a main contributor to local proprioception.

1.2.2 Thermal perception

Our perception of the thermal properties of our immediate environment are mediated by Aδ and C-fibers that are activated at different temperatures and hence categorized as cold and warm receptors (Spray, 1986). Perceptual difference of cold and warm also suggest that the related stimuli are processed separately (Greenspan et al., 2003). Heating and cooling of the skin are often signaled by separated fibers but can also be signaled by multimodal receptors like low-threshold C fibers (Hahn, 1971). Humans perform poorly at judging absolute temperature because our sensation of temperature is prone to thermal adaptation and it is mainly the difference between this adaptation temperature and the absolute one that mediates the sensation (Tritsch, 1988). The thresholds for perception of thermal cues are also observed to increase with age (Stevens and Choo, 1998). Discrimination is possible between objects of the same temperature but with different thermal properties especially heat extraction and heat capacity.

As often, one of the first study was conducted by David Katz who asked participants to classify materials, all at the same temperature, from “colder” to “warmer”. Discrimination was found more difficult when the t° of the surface was close to the temperature of the skin. For stimuli, which are above skin temperature, the perceived order of “warmer” and “colder” was reversed (Katz, 1925).

Several investigations have targeted the perception threshold for the differences in thermal properties. An essential phenomenon is thermal conductivity, which is the amount of heat needed to increase the t° of a material by a given amount when the fingers touches it. For a long time, studies were difficult to conduct due to the difficulty to find materials with appropriate spacing of their thermal properties. A first estimation was made in 1974 using Minnesota disks, which were designed for application on the skin of materials with different thermal properties without thermal contamination due to the experimenter’s hand. The threshold was found to be one order of magnitude difference in the heat transfer rate (Dyck et al., 1974). A later series of studies on natural textures by Lynette Jones showed that three times larger thermal conductivity could be reliably discriminated (Jones and Berris, 2003) but suggested that the contact coefficient, which merges thermal conductivity, heat capacity and density of the material, is a more meaningful cue. However, these studies on natural materials were limited by the properties of the available materials in their attempt to quantify the thermal thresholds. Therefore, Pelletier heat pumps have been introduced in order to adjust the thermal properties to any desired level and were shown to provide a faithful rendering of the thermal properties of materials (Caldwell and Gosney, 1993; Ho and Jones, 2004; Ino et al., 1993). By implementing this technique to vary the thermal conductivity at the threshold level, it was found that for 10° difference between the finger and the material, the Weber fraction was at 43% difference in the thermal diffusivity (Tiest and Kappers, 2009). This study also pointed that for brief touch with one finger, the heat capacity does not contribute to the tactile sensation since the material does not have time to warm-up. In conclusion, if thermal cues are certainly used in active touch, their threshold is rather large and sensing the heat flow requires a large time window of static touch (approximately 10 seconds) that is not often available in spontaneous exploration or manipulation of objects (Hensel, 1952).

1.2.3 Discriminative touch

1.2.3.1 The limits of tactile perception

The sense of touch also displays an unsuspected precision in sensing and coding the micro-topography of the surfaces that we touch. It is known for a long time that touch discriminate readily materials whose spatial topography differ by a few micrometers (Libouton et al., 2010; Miyaoka et al., 1999). Tactile perception is also especially accurate for perceiving vibrotactile cues. Applied vibrations with the absence of movement can be sensed down to an amplitude of 200 µm (Bensmaïa, 2003; Hollins and Risner, 2000). In addition, the threshold amplitude depends on the frequency of the vibration since different frequencies are mediated by specific channels relying on mechanoreceptors with specific sensitivity although the receptive bandwidths of the four channels overlap to some extent (Bolanowski, 1988). However, when it comes to active exploration of surfaces, touch is so sensitive that the design of surfaces requires controlled sub-micrometers spatial features and represents a complex challenge. This challenge was recently addressed by Skedung et al. who could produce surfaces displaying sinusoidal wrinkles ranging in surface wavelength from 270 nm to 90 µm. They implemented a similarity scaling procedure, which did not require a specific attribute to be quantified, and found that the minimal surface that could be distinguished from the perfectly flat control surface had a wavelength of 760 nm with an amplitude of only

13 nm (Skedung et al., 2013). Although it is not clear which dimension of touch was predominantly used for the detection, it is interesting to notice that the resolution of touch is of the order of magnitude of the molecular components of some materials. Therefore, touch could potentially distinguish molecular properties of materials that share similar topographies.

1.2.3.2 The four distinct types of mechanosensitive afferents involved in discriminative touch

When we touch a surface, the interfacial signal is captured by the *stratum corneum*, which covers the skin. Vibrotactile signals are additionally magnified by a specific resonance of the fingerprints, especially in the specific range of the Pacinian receptors (Scheibert et al., 2009). Then, detection of the features of a surface is done by thousands of mechanoreceptors embedded at specific locations in the skin depending on their type. Each type of mechanoreceptors is specifically sensitive to certain types of deformations and activates when the threshold is reached in its specific bandwidth. The different types of mechanoreceptors have been predicted by psychophysical investigation of the vibrotactile sensitivity in humans, which found out the existence of four sensory channels (Bolanowski, 1988; Verrillo and Bolanowski, 2008; Verrillo, 1962). The specific properties of the related mechanoreceptors have been also investigated in humans and primates through respectively single-unit electrophysiological recordings in human primates termed “microneurography” (Johansson and Vallbo, 1979; Knibestöl and Vallbo, 1970) and single-unit recordings in non-human primates (Talbot and Mountcastle, 1968). On the other hand, single-unit electrophysiological recordings of cortical neurons are solely performed in non-human primates (Mountcastle, 1957; Mountcastle et al., 1969). Microneurography consists in recording the single mechanosensitive afferent fiber directly in the nerve with a microscale blunt needle, in which an electrode is embedded. This technique has the advantage of being minimally invasive, hence, it can be used in humans, which enables a more straightforward coupling with psychophysical tasks. However, the implementation of microneurography is really complex and only a limited amount of units are usually collected. On the other hand, single-unit electrophysiology in non-primate humans is more reliable due to more invasive procedures like anaesthesia during the recordings and is also performed on cortical neurons. However, the mapping with psychophysics is less straightforward since it often requires combining recordings from primates and psychophysical data from humans (Weber et al., 2013).

Four types of mechanosensitive afferents have been observed. The classification is based on the afferent's response to mechanical stimuli and its receptive field (Johansson and Vallbo, 1979). Two types of afferents are called *slowly adapting (SA)* as they respond to ongoing stimuli with sustained discharges and the remaining two are called *fast adapting (FA)* as they respond to the onset of a mechanical stimulation with an outburst of activity which decreases very quickly if the stimulus remains static. Afferents types are further classified on the basis of their receptive fields and appended accordingly with the Latin numbers I (small receptive field) and II (large receptive field). Therefore, the four types of afferent are FA-I, SA-I, FA-II and SA-II.

FA-I and SA-I afferents innervate the superficial layer of the skin and have a particularly high density in the fingertips. FA-I respond preferentially to relatively high frequencies of skin deformation, from 8 and 70 Hz (Johansson et al., 1982), which are typical of contact forming and breaking with surfaces, initial phases of object lifting or changes in the pattern of exploration of a texture (Birznieks et al., 2001; Johansson and Westling, 1984; Khamis et al., 2014). SA-I respond with sustained activity to lower frequency skin deformations, up to 8 Hz (Johansson, Landström, and Lundström 1982). The larger number of FA-I afferents compared to the number of SA-I afferents in the fingertip is considered to reflect the ecological importance of coding transient dynamical events, such as fast contact forming or breaking, slip of the fingerpad or scanning across a texture (Johansson and Flanagan, 2009).

On the other hand, FA-II and SA-II have a lower and roughly uniform density. In glabrous skin sites, they also terminate deeper in the dermal and sub-dermal fibrous tissues (Abraira and Ginty, 2013). FA-II afferents end in pacinian corpuscule (Vallbo and Johansson, 1984) and are often referred to as "Pacinians". Being sensitive to a larger range of vibrations from 70 to 300 Hz, they are optimized for detecting transient mechanical events, fine vibrations (Bolanowski, 1984; Gescheider et al., 2009) or fine surface features (Weber et al., 2013). Hundreds of FA-II are distributed throughout the hand and the forearm and easily excited by fine vibrations occurring anywhere on the hand due to their particularly large receptive fields (Delhaye et al., 2012; Manfredi et al., 2012; Vallbo and Johansson, 1984). SA-II afferents are found in muscle fascias, joint capsules and ligaments of the finger and the hand and can respond to remotely applied lateral stretching of the skin.

1.2.3.3 Functional neural integration mediating texture perception

The early psychophysical results led to the hypothesis of four tactile channels (Bolanowski, 1988; Verrillo, 1962), which was confirmed by subsequent recordings of afferents whose sensitivity matched the one of the predicted tactile channels. Early studies investigating the cortical coding within the tactile sense provided evidence that neurons of the primary somatosensory cortex (S1) are clustered according to their adaptation properties: Slowly Adapting or Rapidly Adapting (Sur et al., 1984, 1981). Different types of neurons were moreover shown to have a columnar organization in S1 (Mountcastle, 1997, 1957). At a psychophysical level, it was also found that these channels could be independently adapted by prolonged over-threshold vibrotactile stimulation in their preferred vibrational range. In consequence of this adaptation, the threshold of the afferent for detecting vibrotactile signals is increased for several minutes before recovering its baseline sensitivity (Berglund and Berglund, 1970; Gescheider and Wright, 1969; Hahn, 1968).

This compelling evidence of segregation of the afferent types lifted the hypothesis that afferent types assume different functional roles. In consequence, it was hypothesized that each channel has a specific role and mediates the tactile perception of specific haptic interactions with textures or objects. In this framework, SA-I were thought to code shape and texture, RA motion and transient mechanical deformations while Pacinians would code fine vibrations. This view was strongly developed and best advocated for a long period by Ken Johnson in several compelling studies and review papers (Johnson and Hsiao, 1992; Johnson, 2001; Johnson et al., 2000). This conception was quickly challenged by Mark Hollins. He reinvigorated the duplex theory of touch first proposed by Katz in 1925 by showing that different types of afferents seemed to code coarse (with spatial period larger than 200 µm) and fine surfaces (with spatial period smaller than 200 µm) (Hollins and Risner, 2000). He also shown that vibrotactile adaptation can enhance rather than impair performance in discrimination of tactile signals, which suggested an interaction between processing from the different afferent types (Goble and Hollins, 1994, 1993). In fact, although the experimental methods were flawless, the studies advocating afferent type segregation only considered very specific stimuli like dot patterns, which cover only a small portion of the range of stimuli that touch is capable to process. Many studies have since then brought additional evidence that challenges the view that textures and shapes are only spatially coded (Bensmaïa, 2003; Gamzu and Ahissar, 2001; Libouton et al., 2012) and provided evidence that temporal coding of textures' topography also mediates tactile perception (Harvey et al., 2013; Weber et al., 2013). In addition, segregation of the signals from the different afferent type in the somatosensory cortex was shown to be less pronounced for more naturalistic stimuli, for which S1 neurons rather exhibit functional selectivity (ex: stimulus orientation) in their response to the stimulus (Bensmaia et al., 2008; Dépeault et al., 2013).

These novel temporal coding mechanisms for texture perception do not imply that touch is mediated by temporal coding but rather that all afferents are recruited by cortical neurons, which have higher level functional roles and integrate the input from many afferents of different types to fulfil their role (Saal and Bensmaia, 2014).

1.2.4 Peripheral and central pathways mediating touch

The signal resulting from tactile interaction is primarily processed and filtered by the different layers of the skin: the fingerprints (Scheibert et al., 2009; Wandersman et al., 2011), the area in contact (Andre et al., 2011; Delhaye et al., 2014) and the (epi)dermis (Sripati and Bensmaia, 2006) before being selectively transduced by the mechanosensitive afferent endings. The single unit tactile signals are conveyed by single afferent nerve fibers through the nerves innervating the hand and the forearm. They enter the spinal cord through the dorsal root ganglia, follow the ipsilateral posterior column, which connect to the cuneate neurons through synapses (Saal and Bensmaia, 2014). In the cuneate, a first stage of integration of peripheral tactile input is performed (Hayward et al., 2014). Cuneate neurons receive signals from several mechanosensitive afferents and exhibit selective sensitivity to spatial and temporal aspects of mechanical stimuli. Axons rooting from the cuneate reach the contralateral hemisphere and the ventroposterior nucleus of the thalamus from where they are projected to the primary sensorimotor cortex.

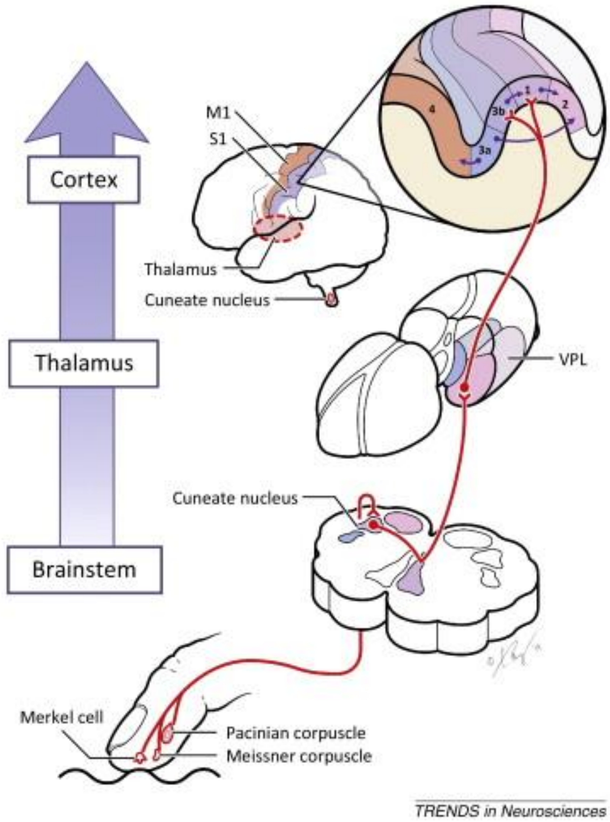

Figure 1. Illustrated summary of the tactile pathway from the explored texture to the primary somatosensory cortex. Adapted from Saal et al. 2014 (original work by Christofer Raney).

Tactile representation in the cuneate, thalamus as well as in the areas 1 and 3b primary somatosensory cortex has been shown to follow the afferent type segregation observed at peripheral level (Harvey et al., 2013; Mountcastle et al., 1990; Sur et al., 1981) although there is growing evidence that areas 1 and 3b are more dedicated to the processing of higher-level features like motion (Pei et al., 2011), speed (Dépeault et al., 2013) and precision grip (Salimi et al., 1999). Neurons from higher areas have been demonstrated to integrate different tactile signals relevant for complex tactile interactions (Iwamura et al., 1980; Sakata et al., 1973; Salimi et al., 1999).

1.3 The human perception of frictional cues

1.3.1 The role of forces at the skin-surface interface

The tactile signal proceeds out of the complex mechanics occurring at the skin-fingertip interface during haptic contact. The tangential and normal loading forces at the contact play a crucial role by inducing surface strains and stretches, which propagate on the skin and are further transmitted to the mechanosensitive afferents (Delhaye et al., 2016). With the growing evidence for a hierarchical functional organization of the somatosensory cortex, frictional patterns have become more central to the study of touch since they provide an integrated information about the performed haptic or exploratory task (van Kuilenburg et al., 2013). An elegant proof of the crucial role of interfacial forces to mediate high-level perception is that forces can give the illusion of geometry even when they are incongruent with the topography of the surface (Flanagan and Lederman, 2001; Robles-De-La-Torre and Hayward, 2001). In addition, experimentally impaired tactile interaction with gloves, cooling or local nerve-blocks have also been shown to dramatically affect our capacity to feel and manipulate objects (Augurelle et al., 2003; Kinoshita, 1999; Nowak and Hermsdörfer, 2003). Still, surprisingly little is known about the tactile processing of frictional patterns when we consider how predominant they are in our tactile experience. Probably, this is mainly due to the complexity of introducing controlled friction compared to controlled indentation of the skin or vibrotactile cues and also to the lack of psychophysical evaluation in a large amount of the research done on tactile friction.

1.3.2 Relationship between friction and vibrotaction

The role of tactile friction in the subjective perception of objects and surfaces is still debated because it is a largely multi-level phenomenon (Adams et al., 2013) that has an especially high perceptual dimensionality (Hayward, 2011) and cannot be easily reduced to a 'frictional dimension'. Some studies suggest that the friction of the fingertip might not play a primary role in assessing the surface roughness. For example, it has been shown that rough/smooth and soft/hard are more prominent than sticky/slippery (Hollins et al., 2000). However, the perceptual role of friction cannot be limited to the sticky/slippery dimension since roughness and friction have been demonstrated to correlate (Smith et al., 2002a) and lubrication has been shown to reduce the perceived magnitude of roughness (Verrillo et al., 1999). Friction has also been linked to a *wet/dry* subjective scaling (Chen et al., 2009), which is consistent with humidity of the fingertip playing a major role in the finger-surface friction (Andre et al., 2011). A recent study also showed a close relationship between exploratory kinetics and the frictional properties of a surface (Callier et al., 2015). Moreover, it is known that participants optimally adjust the lateral and normal forces during the exploration of a surface with typically smaller normal loads than those that would be used for grip (Smith et al., 2002b).

All these findings argue for a meaningful role of friction in texture exploration. Nevertheless, it is still difficult to assess the precise contribution of friction in our tactile experience due to the difficulty to disentangle its contribution from vibrotaction and skin deformation. A promising method for bridging the gap is to refer to the Fourier spectrum of the tangential force rather than to average values (Wiertlewski and Hayward, 2012; Michael Wiertlewski et al., 2011; Wiertlewski et al., 2010) with low-frequencies being more representative of net friction and high-frequencies of vibrotaction. For example, it was shown that although participants retain their capacity to perceive textures when the low-frequency components are filtered, they find the textures significantly less natural (Michael Wiertlewski et al., 2011). Thus, there is increasing evidence that friction and vibrotaction are not distinct modalities and the resulting perceptual dimension for a given texture rather depends on the overall shape of the interfacial forces' frequency spectrum. This framework was validated in a recent study that compared 12 naturalistic textures for their pleasantness, including textures strongly related to vibrotaction like sandpapers (Klöcker et al., 2013). The tactile pleasantness of the material was shown to be higher when higher frequencies were underrepresented and when the intensity of the frictional noise was lower. Thus, the current findings suggest that net friction and vibrotaction do not oppose but are encompassed in the more general spectrum of the interfacial forces.

1.3.3 Parameters affecting friction

Frictional cues used in touch are complicated to study since they depend on the inner chemistry of materials. Thus, many study investigating tactile perception of different frictional levels used water, talc or oil on the finger to modulate the stickiness of the material (Adams et al., 2007; Bobjer et al., 1993; Khamis et al., 2014). However, this additions result in introducing an additional layer between the fingertip and the material, which might change other parameters of the tactile interaction like the real contact area or mask the material's fine topographical features. Nevertheless, the role of friction in touch has been subject to much research and the combination of a large amount of experiments has enabled to gain some understanding of the frictional contact. Dinç and Ettles performed a thorough investigation of the parameters affecting friction during touch in the early 90's (Dinç et al., 1991). They confirmed and extended earlier findings showing that the dynamic coefficient of friction (defined as the ratio between the tangential and normal component of the force) increased in function of the humidity of the skin and the normal load while it decreased as a function of the speed of exploration and the roughness of the surface.

These results have been refined by numerous studies, which have also shown that the dependence between the hydration of the fingertip rather follows a bell-shaped curve with maximal values of the coefficient of friction occurring at intermediate levels of humidity (Andre et al., 2011; Pasumarty et al., 2011; Skedung et al., 2010; Tomlinson et al., 2011). Moreover, there is evidence that moisture values during a grip task evolve to reach this maximal value of the coefficient of friction, which is optimal to prevent slippage (André et al., 2010). It is not clear though if this optimization mechanism extend to tactile exploration of textures. Similarly, the coefficient of dynamic friction between the finger and smooth surfaces exhibits a maximum in the range of tactile exploration (Pasumarty et al., 2011), which spans typically from 10 to 200 mm s^{-1} (Callier et al., 2015; Libouton et al., 2010). The influence of load force on the coefficient of friction is less clear. A larger normal force (NF) will increase the gross area of contact and hence the potential shear stress up to 1N but seems to have only a small influence on the coefficient of dynamic friction (Andre et al., 2011; Derler et al., 2009). It was also shown that the apparent area of contact does not change significantly during fingertip's sliding on a glass surface (See Figure 2). Thus, the coefficient of friction is apparently more impacted by the real area of contact resulting from the topographical roughness of the skin (Adams et al., 2007). The influence of the real area of contact also explains why the coefficient of friction decreases with the increased roughness of the surface (Skedung et al., 2010) and increases with the moisture level. Increased humidity is known to soften the asperities of fingerpad and consequently reduce Young's modulus, which defines the elasticity of the skin. (Papir et al., 1975).

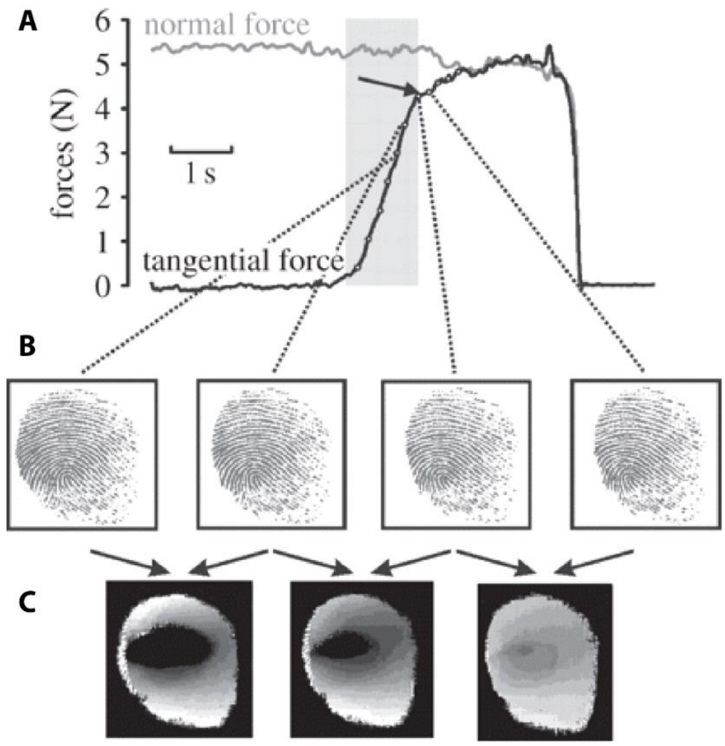

Figure 2. A) time-course of the evolution of the underlying normal and tangential forces during a fingertip's slide on a glass surface. B) Several frames were selected during the tangential preload period and display no change in the apparent contact area. C) The stick area decreases toward zero with the increase of the tangential force. Adapted from André et al. 2011

1.3.4 Temporal dynamics of friction

Although stationary physiological and environmental parameters certainly influence the frictional properties of the finger-surface contact, new findings point out that they are of second order in comparison of the mechanisms underlying the temporal evolution of touch (Adams et al., 2013). During tactile contact with an impermeable surface, continuous sweat secretion strongly influences the evolution of the coefficient of friction. This is especially true for smooth surfaces since moisture is trapped and accumulates within the contact area. As mentioned above, this induces a softening of the asperities at the surface of the *stratum corneum* termed occlusion and a reduction of Young's modulus. These specific dynamics result is an increase of the coefficient of friction within a characteristic time of tens of seconds. It was first observed that the coefficient of friction increases with the number of consecutive strokes on smooth surfaces during a subjective scaling task (Smith and Scott, 1996). Subsequently, Pasumarty et al. measured the interfacial friction as function of the contact time for several surfaces: optically flat glass, smooth polypropylene, cellulosic filter paper, roughened glass slide and stainless steel mirror (Pasumarty et al., 2011). The characteristic time for the increase of friction was relatively independent from the sliding velocity with mean values around 20 seconds. It was also found consistent with the characteristic time of the increase in skin humidity. They concluded that the very large range of values of the coefficients of friction reported in the literature (Derler and Gerhardt, 2012) mainly result from differences in occlusion time. Only the filter paper did not exhibit occlusion but rather a slight decrease of friction. Another study confirmed this phenomenon during tactile exploration of several types of printing papers (Skedung et al., 2010). This specific dynamics probably stem out from a continuous absorption of the excess of water by the paper, which counterbalance sweating. In conclusion, occlusion and a subsequent increase of friction seems to be a widespread phenomenon that is especially strong on smooth surfaces but also extends to roughened surfaces as long as they are impermeable to water. Thus, when one investigates the frictional properties of natural surfaces, a possible effect of characteristic time should be taken into account. An open question about this mechanism is the perceptual value of occlusion for which, to our knowledge, there is no direct proof. The non-stationarity of friction also represents a major challenge for tactile perception, which needs to extract invariants in order to achieve a stable long-term representation of objects and textures in order to deal with everyday tactile and haptic tasks.

1.4 Psychophysical estimates of the sensory thresholds

1.4.1 Psychophysics for haptics

Psychophysical principles and methods for haptics were recently reviewed by L.A. Jones and H.Z. Tan (Jones and Tan, 2013). Any sensation can vary along four dimensions: intensity (how strong is the sensation), quality (subjective perceptual dimension), extension (perceived area of stimulation) and duration. The aim of psychophysical experiments is to determine the relation between the physical stimuli and their perception by focusing on linking the physical magnitude of the stimulus to the sensory magnitude of perception. Thus, several methods have been developed to quantify the sensory perception. Essentially, these methods implement a large amount of stimulations in order to disentangle the perception of the stimuli from the influence of the experimental and behavioural noise.

From this perspective, the case of haptic is specific because while in audition and vision, stimuli are usually short (a few hundreds of milliseconds), haptic research requires participants to interact manually with the surfaces. During a single trial, participants might explore two or three surfaces sequentially for 10 to 20 seconds and are additionally slower at making a judgment (Lederman and Klatzky, 1997; Plaisier et al., 2010). Thus, the number of stimuli that can be presented is often small. Haptic research is also made complex by the multi-dimensionality of the typical haptic stimuli, which induces many cues due to continuous contact, the thermal properties of materials, the specific indentation of the skin, uncontrolled vibrations, etc. We also discussed above that the properties of the skin can change significantly within 10-20 seconds and additionally bias tactile perception of the task. In consequence, it is not rare that participants base their judgment on an experimental artefact rather than on the investigated parameter. Thus, experiment in haptics require either an extremely careful calibration of the delivered stimuli (Hayward et al., 2014) or integrate the complexity of the stimulus into the psychophysical protocol and the data analysis (Skedung et al., 2013).

1.4.2 Relative and absolute thresholds of perception

Psychophysical methods that aim at investigating the sensory threshold focus on determining the smallest variation of energy needed to produce a difference in the experienced sensation. The absolute threshold is a limit case where the reference is the background null stimulus and the sensory noise of the system. The absolute threshold is also known to strongly depend on the experimental conditions. For this reason, comparisons between different studies are to be done cautiously (Gescheider et al., 2009). This variation of energy is classically expressed by Weber's fraction determined by E.H Weber in 1834 who determined that the change in stimulus intensity ($\Delta\Phi$) that can be discriminated is a constant fraction (c) of the intensity of the stimulus (Φ):

$$\frac{\Delta\Phi}{\Phi} = c$$

Weber's law has been found to work for a wide range of stimulus intensities even if c was found to increase for low intensities of stimulation. However, some haptic modalities do not follow Weber's law. For example, the physical threshold does not systematically increase with increasing finger-span (Durlach et al., 1989). Weber's fraction is also referred to as the just noticeable difference (JND) or sometimes as Differenz Limen (DL). In 1860, Fechner built up on the work of Weber to elaborate three method for the estimation of the sensory thresholds, which have become classical and are still widely used (Jones and Tan, 2013): the constant stimuli method, the method of limits and the method of adjustment.

1.4.3 The classical psychophysical methods

1.4.3.1 Constant stimuli method

The method of constant stimuli is based on a set of stimulations defined prior to the experiment with such a span as to encompass the sensory threshold (Simpson, 1988). All stimuli are delivered the same number of times in a random order. Performance is expected to vary from near zero for the lower intensities to perfect for the higher ones. The proportion of detected stimuli or correct answers are fitted to a psychometric function from which the psychophysical threshold and the perceptual equivalence are extracted (Wichmann and Hill, 2001). This method has the advantage of completely randomizing the different levels of stimulation and therefore counterbalancing possible biases like habituation, increasing lenience or unforeseen changes in the experimental conditions. A disadvantage of the method is that many trials are implemented at stimulation levels for which perception is obvious. In the case of a large range of thresholds among the participants, the threshold could also be missed. To prevent this, a common approach is to estimate quickly the thresholds with a fast method before implementing the constant stimuli protocol.

1.4.3.2 Method of limits

The method of limits is based on ascending and descending series of stimuli with respectively increasing or decreasing intensities. A series is stopped when the stimulus either starts to be perceived (ascending series) or stops to be perceived (descending series). The sensory threshold is estimated as the mean over the thresholds of each series (Gescheider, 1997). Usually, descending and ascending thresholds are different and estimated separately. This method is faster for estimating the psychophysical threshold than the method of constant stimuli. Nevertheless, it is prone to biases, which are habituation, expectation and possibly the time course of the experimental conditions. This is especially true in touch where friction might change by several orders of magnitude within several strokes (Smith and Scott, 1996) and where prolonged vibrotactile stimuli are known to affect the sensitivity of the mechanoreceptors with a characteristic time of a few minutes (Berglund and Berglund, 1970). The method of the limits can also be biased by reaction time if the intensity of stimuli is increased or decreased continuously during the experimental protocol.

1.4.3.3 Method of adjustment

In this method, the participant adjusts the intensity of the stimulus to what he perceives as a difference (or perceptual equivalence) between stimuli. It is also possible to use this protocol to estimate the absolute threshold. Even if this method was implemented successfully in psychophysical experiments (Shevell et al., 1992), it is considered the least precise because it does not attempt to evaluate and control the perceptual biases of participants. In haptics, this method has been used for perceptual comparison of viscosity (Jones and Hunter, 1993).

1.4.4 Statistical measurement of the psychophysical thresholds

Participant's perception during experiments is mingled with noise. Each participant has its personality. Some will keep constant attention while awareness might fluctuate for others and other factors like self-confidence might also influence participant's responses. A major challenge in psychophysics is to deal with the uncertainty related to deciding if the input comes from the presence of the stimulus or from external or internal noise related to the background. The participant is assumed to set a criterion for detecting the signal from the background, which is individual and might change during the time-course of the experiment. To distinguish between sensitivity and criterion bias, forced-choice methodologies were developed, which are more objective to study psychophysical perception.

Forced-choice method provide data that can be analysed by computational methods from signal detection theory to derive the sensitivity index of the stimulus *d′* together with an independent estimate of the participant's response bias *β* (Tanner and Swets, 1954) (See Figure 3). The sensitivity index *d′* is the normalized distance between the means of the perceptual distributions of the compared stimuli S_1 and S_2 (the same stimulus is not always identically perceived). Thus, *d′* provides an objective measure of the participant's sensitivity to the difference between the two stimuli regardless to its response bias. The response bias depends on the response criterion and on the middle point between the means of the two perceptual probability functions mentioned above. If $\beta = 0$, the participant's criterion is ideally placed to discriminate between the stimuli. A positive *β* shows a bias toward responding S_1 while a negative *β* shows a bias toward responding S_2.

Several designs of forced-choice procedure are available. Common designs are: i) one-interval, two-alternatives, forced-choice (1I-2AFC), ii) two-interval, two-alternatives, forced-choice (2I-2AFC) and iii) three-intervals, two/three-alternatives, forced-choice (3I-2/3AFC).

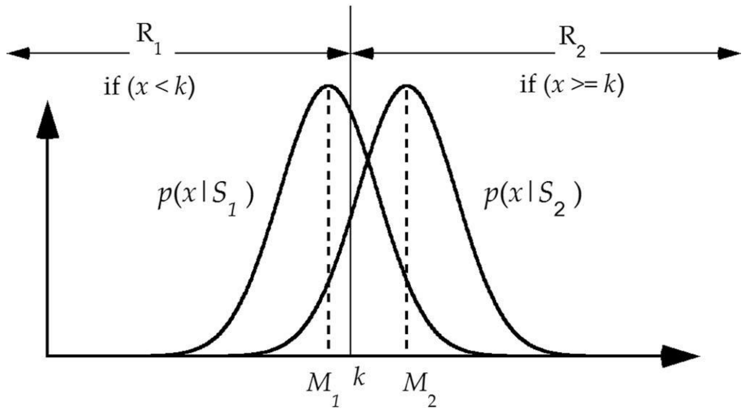

Figure 3. The perception elicited by a stimulus $p(x \mid S)$ is not always identical but rather falls within the range of a normal distribution. Thus, the challenge of distinguishing between two stimuli S_1 and S_2 is the challenge of setting a criterion k between the two probabilistic distributions in order to give the correct answer R_1 or R_2. Ideally, this criterion optimizes the classification but could also be biased toward a preferred response. Adapted from Jones et al. 2013

In the 1I-2AFC, the participant is presented with one out of two possible stimuli in each trial and has to pick the correct one without the possibility of saying "I don't know". 1I-2AFC are trial efficient but could reach working memory limitations if stimuli are complex (Spence and Gallace, 2007).

In the 2I-2AFC, two stimuli are presented in each trial and the participant has to pick one of them depending on a previously set question (ex: *which stimulus is rougher? Which stimulus is more intense?).* 2I-2AFC are very widely used to study roughness (Hollins and Risner, 2000). However, they previously constrain the target dimensionality, which might be unwanted in some experiments

In the 3I-2/3AFC, participants are either asked to decide which one out of two stimuli is most similar to a reference stimulus "similarity task" (3I-2AFC) or to pick the stimulus that they perceive as different from the other two "odd-man-out task" (3I-3AFC) (Cholewiak et al., 2010). The advantage of this design is that it does not force the experimenter to establish a dimensionality of interest prior to the experiment. Theoretically, one can imagine even higher numbers of intervals and alternatives. However, since this increases the total experimental time and strain on working memory, very few studies go beyond three intervals.

1.4.5 Adaptive methods

In touch, trials are time-consuming due to the necessity to rub the surfaces or interact with an object for some time. In addition, tactile thresholds can be evolving or transient by definition (e.g. vibrotactile adaptation). To deal with these challenges, researchers developed adaptive procedures to estimate psychophysical thresholds. These procedures build on the answers of the participant in previous trials to set the intensity level of the following stimuli. These methods estimate the threshold while using less trials. Most adaptive methods are derived from the method of limits, which is considered an adaptive method since its time-course depends on participant's answers. Currently used adaptive methods are based on various types of up and down staircases.

The classical up and down staircase is a limit case of the method of limits. The difficulty of the task is increased by a constant step when the response is incorrect and decreased by the same step when the response is correct. A larger step can be used for the first few reversals to quickly bring the stimulus level in the neighbourhood of the threshold being estimated. A fair criticism of this method is that the oversimplified procedure might be learned by the participant who could adapt its responses to the method rather than the stimulus. However, this flaw is easily addressed by interlacing the staircases for different conditions in such a way that trials from a single staircase are not consecutive (Konkle et al., 2009). It is important to note that this method is unsuitable for forced-choice procedures where the correct response probability is 0.5. In this case, even if the participant is clueless, the procedure will stabilize at a random value, which will be erroneously recorded as the 50% correct threshold.

More refined “up and down staircases” were designed on the basis of various sequences of up and downs, typically one-up three-down. Since three correct answers are required to decrease the stimulation level while one error is sufficient to increase it, they stabilize at higher thresholds than 50%. Brisben et al. developed and implemented a method based on consecutive correct answers, which tracks the 79.4 percent point on the psychometric function (Brisben et al., 1999) while Zwislocki and Relkin proposed a modified version of the method where correct answers do not need to be consecutive and therefore stabilizes at the 75 percent just noticeable difference (Zwislocki and Relkin, 2001). The advantage of these staircases compared to the simple “up and down” staircase is that they are compatible with commonly used 2 alternatives forced-choice procedures (2-AFC) and are less prone to learning bias when not interlaced.

1.5 Overview of friction modulating tactile devices

The scope of this thesis is to build on recent studies highlighting the important role played by frictional forces in our tactile interactions to investigate how the properties of the human tactile sensing could suggest efficient designs for tactile displays with Haptic feedback.

Several technologies have been developed to embed friction modulation in tactile displays. In the early 2000’s, an ingenuous displacement of pin-arrays stretch the skin was shown to induce an illusory sensation of displacement of the fingertip (Pasquero and Hayward, 2003). This phenomenon is very robust and can also be induced by lateral vibration of a plate. It is currently used by Apple in track pads technology for Macbook Pro laptops. These track pads and displays do not displace downwards, but nevertheless give a usual reassuring button press sensation to the user. However, this technology is constrained by the necessity to place an opaque pin array on the touch screen or under it (Iwata et al., 2001), which prevents a potential adaptation to the global market of portable interactive screens.

To be commercially promising, a haptic feedback technology should be compatible with simultaneous visual feedback. Thus, the haptic feedback has to be delivered either by non-transparent piezoelectric actuators situated around the screen (Giraud et al., 2012) (See Figure 4) or transparent actuators embedded in it (Bernard et al., 2016). The current leading technologies for friction mediated haptic feedback are ultrasonic lubrication (Biet et al., 2007), which reduces friction by creating a squeeze film effect at the finger-surface interface, and electrovibration (Bau et al., 2010; Chubb et al., 2010), which increases friction through electrostatic attraction between the polarized finger and the surface. In addition, Vezzoli et al. (Vezzoli et al., 2015) showed that both techniques could be implemented simultaneously on a unique device since the total friction modulation resulting from application of both techniques is the sum of the respective changes in friction. Therefore, psychophysical results related to friction modulation are probably valid for all current friction modulating devices.

Figure 4. Interaction with a transparent touch screen with haptic feedback. Friction is modulated through piezoelectric actuators located on the frame of the device. Adapted from Giraud et al. 2012.

1.5.1 Psychophysics of friction modulating tactile devices

Very little is known about the psychophysical thresholds related to friction modulation considering how crucial a realistic user interaction is for a future breakthrough on the market. Building on preliminary studies showing correlations between the tactile perception of real and simulated roughness (Nara et al., 2001), spatial perception of virtual square gratings created by a tactile device modulating friction (STIMTAC) was evaluated on eight participants who actively explored the surfaces (Biet et al., 2008). The results showed that the Weber fractions were not dependent on the spatial period used a as a standard reference in the forced-choice task and had a value of 8.96% on average. This value was in line with the range of Weber fractions found for real textures, which span from 5% to 11% depending on the experimental conditions (Morley et al., 1983; Nefs et al., 2001). Another study attempted to quantify the tactile perception of friction by asking participant to discriminate surfaces with different levels of uniform friction reduction (through electrovibration of the plate) hence different dynamic coefficients of friction (Samur et al., 2009). They found a Weber fraction of 18% but the experiment was performed on only one participant. There are also several suggestions of novel methods for using previous frictional interaction with real texture to build a library of spectra that could be delivered by friction modulation devices (Meyer et al., 2016; Michael Wiertlewski et al., 2011). However, to our knowledge, only limited psychophysical results are available to support these novel methods and the current knowledge on the temporal and inter-individual properties of human friction suggests that such frictional library will need to take into account the evolution of the fingertip's physiological state. In conclusion, much remains to be done to psychophysically assess the reproduction of shapes and textures through friction modulation.

1.6 Organisation of the chapters and annexes of this thesis

1.6.1 Organization of the chapters

As briefly stated in the foreword, the scope of this thesis is to define and investigate psychophysically the most relevant features influencing the sensation of touch in order to guide the development of new haptic technologies.

In chapter I, we investigate the peripheral and central components of tactile perception of vibrotactile cues by using electric and vibrotactile adaptation. The conditions for the occurrence of adaptation to vibrotactile signals and its time-course are well-known. However, it is not known if habituation to specific modes of vibrations occurs at central level. Thus, the goal of the study presented in chapter I was to evaluate if the central nervous system would adapt to specific frequency delivered by electric stimulation, which bypasses the receptors' mechano-transduction.

Chapter II focuses on the perception of subtle frictional cues available during the exploration of smooth surfaces made of different materials. In this chapter, we compare the tactile perception and contact mechanics of two perfectly flat materials, which additionally have similar coefficient of dynamic friction. We also develop a new method for the investigation of the time-course of tactile exploration that uses quantitative cues to distinguish between the loading of the finger on the surface, the onset of the motion (where the contact area is partly moving and partly stuck) and the stabilized exploration (where the whole contact area is uniformly in motion).

In chapter III, we evaluated the possibility to improve the energetic efficiency of a tactile display producing virtual gratings by using the findings of chapter II about the perceptual importance of transient frictional cues. For virtual gratings, we reduce the duration of the stimulus provided at each period up to 80% compared to the reference while keeping the same sharpness of the frictional transitions and use a psychophysical task to estimate when participants start to feel the stimulus to be perceptually different than the reference.

1.6.2 Organisation of the annexes

The results presented in the main body of the thesis triggered ideas for follow-up studies, which are still in a work-in-progress phase.

Annex I presents complementary analysis of the investigation presented in chapter III. Indeed, we noticed a different perceptual pattern when we allowed participants to explore freely the surfaces compared to when exploration was limited to single strokes. We analyse the coefficients of dynamic friction for two exploratory strategies and discuss a possible perceptual role of a different characteristic time of occlusion for the two smooth materials studied in chapter III.

In annex II, we use a novel technology to modulate the tangential force with high temporal resolution and precise amplitude and combine it with a robot capable of producing passive slides with perfectly controlled normal force, position and speed. This setup enabled us to estimate the human detection threshold for 100 ms transient reductions of the tangential force on three different interfacial materials.

2 CHAPTER II: Central vs Peripheral Determinants of Vibrotactile Adaptation

(Adapted from the paper *Klöcker, A., *Gueorguiev, D., Thonnard, J. L., & Mouraux, A. (2015). Peripheral vs. central determinants of vibrotactile adaptation. *Journal of Neurophysiology*, jn-00519. *equally contributing authors)

2.1 Summary

Long lasting mechanical vibrations applied to the skin induce a reversible decrease in the perception of vibration at the stimulated skin site. This phenomenon of vibrotactile adaptation has been studied extensively. Yet, there is still no clear consensus on the mechanisms leading to vibrotactile adaptation. In particular, the respective contribution of (i) changes affecting mechanical skin impedance, (ii) peripheral processes, and (iii) central processes is largely unknown. Here, we used direct electrical stimulation of nerve fibers to bypass mechanical transduction processes and, thereby, explore the possible contribution of central vs. peripheral processes to vibrotactile adaptation. Three experiments were conducted. In the first, adaptation was induced using mechanical vibration of the fingertip (51 or 251 Hz vibration delivered for 8 minutes, at 40x the detection threshold). In the second, we attempted to induce adaptation using transcutaneous electrical stimulation of the median nerve (51 or 251 Hz constant-current pulses delivered for 8 minutes, at 1.5x the detection threshold). Vibrotactile detection thresholds were measured before and after adaptation. Mechanical stimulation induced a clear increase of vibrotactile detection thresholds. In contrast, thresholds were unaffected by electrical stimulation. In the third experiment, we assessed the effect of mechanical adaptation on the detection thresholds to transcutaneous electrical nerve stimuli, measured before and after adaptation. Electrical detection

thresholds were unaffected by the mechanical adaptation. Taken together, our results suggest that vibrotactile adaptation is predominantly the consequence of peripheral mechanoreceptor processes and/or changes in biomechanical properties of the skin.

2.2 Introduction

In 1930, Kampik showed that one hour of constant mechanical vibration applied to the skin induces hypoesthesia, specifically, a reversible decrease in the perception of vibration at the stimulated site (Kampik.A, 1930). This phenomenon has been defined as *vibrotactile adaptation* and is generally characterized by an increase of vibrotactile detection threshold or a reduction of vibrotactile sensibility (Francisco et al., 2011; Gescheider and Wright, 1969; Hahn, 1966).

The phenomenon of vibrotactile adaptation has been used extensively to study the mechanoreceptor systems responsible for the detection and transmission of vibrations applied on the skin, and the obtained results have provided support for the two-channel theory (Hahn, 1968; Hollins et al., 1990) according to which the transduction of low frequency vibrations (10-60 Hz) is preferentially achieved by rapidly adapting type I (RA) and slowly adapting type I (SAI) mechanoreceptors, whereas the transduction of high frequency vibrations (200-300 Hz) is preferentially achieved by rapidly adapting type II Pacinian mechanoreceptors (RAII/PC). Indeed, studies have shown that vibrotactile adaptation induced using low or high frequency vibrations may preferentially affect the detection threshold of low and high frequency test stimuli, respectively; thus suggesting the existence of two distinct sensory channels, with distinct frequency bandwidths.

Several non-mutually exclusive hypotheses have been put forward to explain the mechanisms of vibrotactile adaptation. Hahn suggested that changes affecting mechanical skin impedance (e.g. change in skin elasticity) could contribute to vibrotactile adaptation by impacting the transmission of vibrations through the skin and, thereby, reduce the mechanical stimulation of mechanoreceptors (Hahn, 1966). Several authors have proposed that vibrotactile adaptation probably involves transient changes in ionic conductance at the level of the mechanoreceptors, leading to axonal hyperpolarization and, thereby, a reduced ability of the mechanoreceptors to generate action potentials following mechanical vibrations (Ribot-Ciscar et al., 1996). Gescheider and Wright advanced a two-factor hypothesis where both changes in mechanical skin impedance and changes in the peripheral nervous system would account for vibrotactile adaptation (Gescheider and Wright, 1969). Finally, neurophysiological investigations in animals have suggested that both changes at peripheral level (e.g. increased spiking threshold of mechanoreceptors), and/or changes at central level (e.g. reduced synaptic transmission) contribute to the phenomenon of vibrotactile adaptation (Bensmaia, 2005; Burke and Applegate, 1989; Leung, 2005; O'Mara et al., 1988; Whitsel et al., 2003).

In the present study, we used direct electrical stimulation of afferent nerve fibers to bypass mechanical transduction processes and, thereby, explore the possible contribution of peripheral and central processes to vibrotactile adaptation. In a first series of two experiments, we compared directly the effects of mechanical vibrotactile adaptation vs. repeated and sustained transcutaneous electrical nerve stimulation on mechanical vibrotactile detection thresholds. We hypothesized that changes in threshold due to mechanically-induced variations in skin impedance or mechanoreceptor transduction processes would be induced only by mechanical adaptation, whereas changes in vibration threshold due to processes occurring at the level of the central nervous system would be induced by both mechanical and electrical adaptation. Furthermore, we hypothesized that if the detection of low and high-frequency vibrations involves distinct sensory receptors or pathways, adaptation induced by low or high-frequency vibrations could exert a differential effect on low and high frequency detection thresholds.

Finally, central changes induced by sustained vibrotactile adaptation could be dependent on subtle characteristics of the afferent input generated by mechanical vibrations which would not be reproduced by repeated electrical stimulation. For this reason, we conducted a third experiment in which we assessed the effect of low- and high-frequency mechanical adaptation of the fingertip on the detection of transcutaneous electrical nerve stimuli delivered to the same fingertip. In this experiment, we hypothesized that if mechanical adaptation induces changes at central level, these changes should affect not only the detection threshold of mechanical stimuli, but also the detection threshold of electrical stimuli bypassing mechanoreceptor transduction.

2.3 Material and Methods

All experiments were approved by the local Ethical Committee (*Comité d'Ethique hospital-facultaire des Cliniques universitaires Saint Luc*, Brussels) and subjects gave their written informed consent.

2.3.1 Experiment 1. Effect of low-frequency mechanical and electrical adaptation on the detection of low- and high-frequency vibrations

Thirteen subjects took part in Experiment 1 (7 male, 29 ±3 years, all right handed). Each subject participated in two successive sessions: a low frequency (51 Hz) mechanical adaptation session, and a low frequency (51 Hz) electrical adaptation session. The order of the two sessions was counterbalanced across participants. Furthermore, in half of the participants, mechanical adaptation was applied to the left hand and electrical adaptation was applied to the right hand. In the other half, mechanical adaptation was applied to the right hand and electrical adaptation was applied to the left hand. Each session was divided in three successive parts: (i) estimation of *baseline* vibrotactile detection threshold to short-lasting low-frequency (51 Hz) and high-frequency (251 Hz) sinusoidal mechanical vibrations applied to the index fingertip, (ii) eight minutes of low frequency (51 Hz) mechanical or electrical adaptation and (iii) estimation of *adapted vibrotactile* detection thresholds to the same short-lasting low- and high-frequency mechanical vibrations (Figure 5A). Before the start of the experiment, subjects were seated, blindfolded and their arm was comfortably installed on a support. During the entire experiment, participants listened to white noise delivered through earphones at a comfortable level. This ensured that auditory input did not contribute to the detection of the vibrotactile stimuli.

Baseline and *adapted* detection thresholds to low- and high-frequency mechanical vibrations were estimated using an interlaced adaptive staircase procedure (Figure 5B), performed immediately before and immediately after adaptation, respectively. The tested fingertip was placed against an 8 mm diameter probe of a mechanical vibrator (Measurement Exciter Type 4810, Brüel & Kjaer), palm facing downwards. The test stimuli lasted 500 ms and consisted in 51 Hz or 251 Hz sinusoidal vibrations of varying amplitude, applied normally against the index fingertip. The inter-stimulus interval varied randomly between 2 and 3 s. This, combined with the fact that the stimulus was not cued by a warning signal, and the fact that a large number of stimuli were not detected, ensured that the participants could not predict when to expect the occurrence of the test stimulus. Participants were instructed to press a button with the other hand as soon as they perceived a vibration.

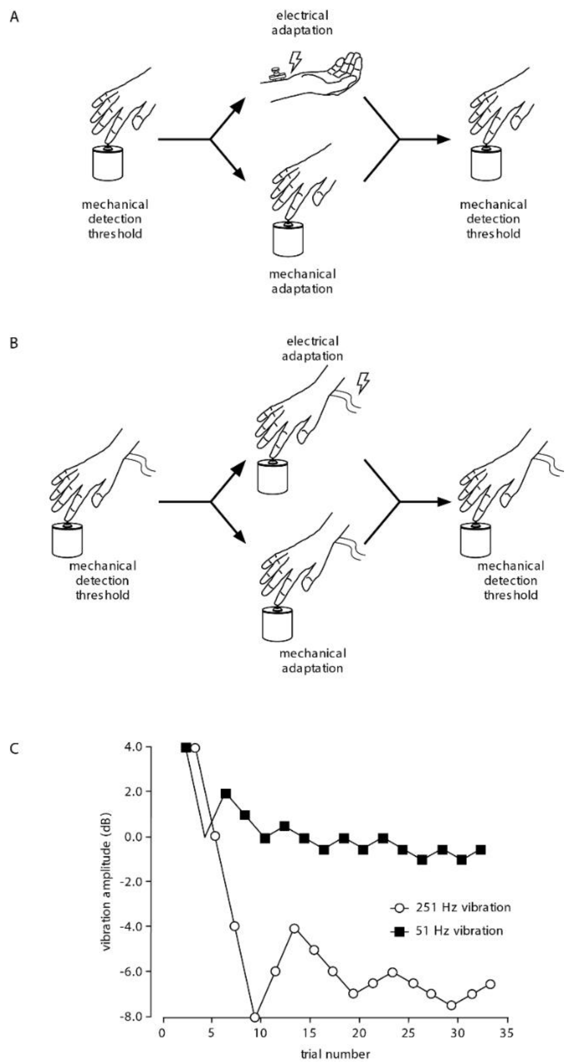

Figure 5. A) In Experiments 1 and 2, the detection threshold to short lasting low frequency (51 Hz) and high frequency (251 Hz) sinusoidal mechanical vibrations applied to the index fingertip was assessed before and after applying eight minutes of low-frequency (51 Hz) or high-frequency (251 Hz) mechanical or electrical adaptation. B) In Experiments 1 and 2, differences in the effects of mechanical and electrical adaptation could have been due to the fact that participants maintained their fingertip on the mechanical stimulator during mechanical adaptation, whereas they were requested to change the position of the hand during electrical adaptation. To address this question, a control experiment was conducted in which electrical adaptation was delivered while participants maintained their fingertip on the mechanical stimulator. C) In all experiments, an interlaced staircase procedure was used to estimate the detection threshold to low and high frequency mechanical vibrations delivered to the index fingertip.

If a detection was reported during the inter-stimulus interval, the stimulus was considered as detected, and the amplitude of the following stimulus of the same category was decreased by 4 dB. If not, the stimulus was considered as undetected, and the amplitude was increased by 4 dB. Following the first three staircase reversals of each category, the amplitude of the staircase step was divided by two, thereby reaching a final step size of 0.5 dB. A total of 33 trials were obtained for each of the two interleaved staircases. The threshold was defined as the mean of the vibration amplitude of the two last turnover points. The entire threshold estimation procedure lasted approximately 2 minutes.

Low frequency *mechanical vibrotactile adaptation* was achieved by applying a pure 51 Hz sinusoidal vibration to the index fingertip during 8 minutes, delivered using the mechanical stimulator also used to the deliver the test vibrotactile stimuli. The fingertip thus remained against the probe of the mechanical stimulator during the entire experiment. The amplitude of the vibration was set to 40 times the amplitude of the baseline low-frequency vibrotactile detection threshold. The chosen duration and vibration amplitude were based on previous studies showing that vibrotactile adaptation is successfully induced using such parameters (Hahn, 1968; Hollins et al., 1990).

Low frequency *electrical adaptation* consisted in transcutaneous electrical stimulation (TES) of the median nerve at the level of the wrist for 8 minutes, using a constant-current electrical stimulator (Digitimer Constant current Stimulator, DS7) and bipolar feltpad electrodes positioned at the level of the wrist such as to stimulate the median nerve (8 mm diameter). During the stimulation, the hand rested on the table, palm facing upwards. This position was chosen to ensure optimal and stable electrical stimulation of the median nerve. The intensity of stimulation was set to 1.5 times the detection threshold to a single 500 µs constant-current square-wave pulse. The position of the electrodes was adjusted until the stimulus elicited a clear sensation which included the index fingertip, i.e. until the stimulus activated nerve fascicles innervating the index fingertip. The stimulation consisted in trains of 500 µs pulses separated by a 1.5 ms inter-pulse interval. These trains of stimuli were modulated by a repeating boxcar function, such that within each train, periods of stimulation alternated with periods without stimulation of equal duration, with a periodicity of 51 Hz. The intensity of the adapting stimulus was chosen in order to induce a clear sensory response without eliciting any motor response. When participants received electrical adaptation, they were requested to delineate, at the end of the experiment, the area within which the electrical stimulation had been felt by drawing this area on a picture representation of the hand. In all participants, this area included the index fingertip.

2.3.2 Experiment 2. Effect of high-frequency mechanical and electrical adaptation on the detection of low- and high-frequency vibrations

Twelve subjects participated in Experiment 2, nine of which had also participated in Experiment 1 (4 male, 30 ±3 years, all right handed). This experiment was identical to Experiment 1 with the exception that the frequency of the mechanical and electrical stimulation used to induce adaptation was 251 Hz instead of 51 Hz.

2.3.3 Experiment 3. Effects of low- and high-frequency mechanical adaptation on the detection of electrical stimuli

Ten subjects participated in Experiment 3 (3 male, 32 ±4 years, all right handed). Such as for Experiments 1 and 2, Experiment 3 consisted in two successive sessions: a low-frequency (51 Hz) mechanical adaptation session, and a high-frequency (251 Hz) mechanical adaptation session. Again, the order of the two sessions was counterbalanced across participants and, in half of the participants, mechanical adaptation was applied to the left hand and electrical adaptation was applied to the right hand. Each session was also divided in three parts: (i) estimation of *baseline* electrical detection threshold, (ii) eight minutes of low- or high-frequency mechanical adaptation and (iii) estimation of *adapted* electrical detection thresholds (Figure 6A).

Baseline and adapted electrical detection thresholds were estimated using a staircase procedure, as illustrated in Figure 6B. Constant-current electrical stimuli were delivered as a single 500 µs square-wave pulse using two adhesive electrodes pasted on the index fingertip (6x11 mm *Ambu Blue Sensor NF ECG Electrodes, NF-50-K/12/EU;* 5 mm inter-electrode distance). The intensity of the first stimulus was set to 2.00 mA. This stimulus was detected by all participants. The inter-stimulus interval varied randomly between 1 and 3 s. Participants were instructed to report when they perceived the stimulus. Such as in Experiments 1 and 2, detecting or not detecting the stimulus determined the intensity of the following stimulus. The initial step size was set to 0.20 mA. After the first staircase reversals, the step was reduced to 0.10 mA, 0.05 mA, and 0.02 mA. The staircase was interrupted after the occurrence of three staircase reversals at this final step size. The threshold was defined as the mean intensity of the two last turnover points. The entire threshold estimation procedure lasted approximately 2 minutes.

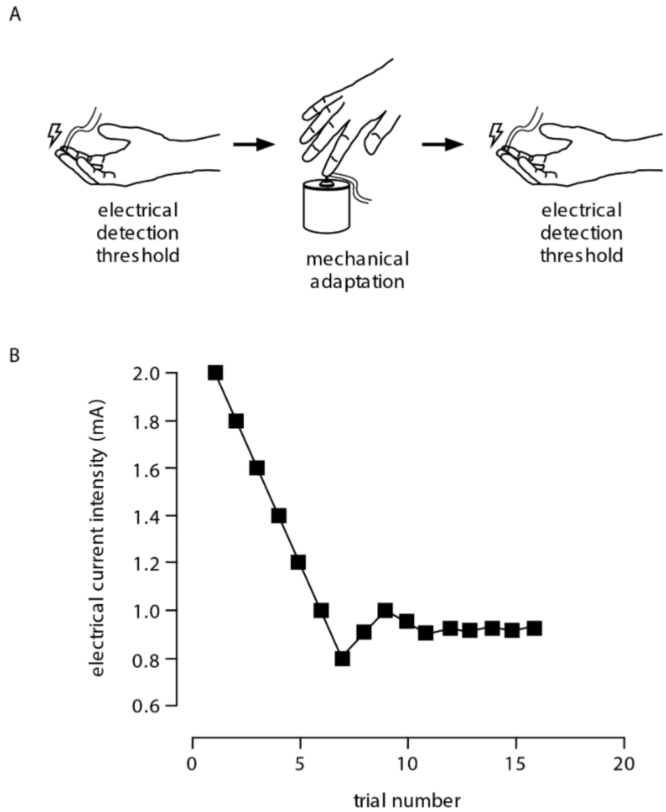

Figure 6. A) In Experiment 3, the detection threshold to single short-lasting electrical square-wave pulses delivered to the index fingertip was assessed before and after eight minutes of mechanical adaptation. B) A single staircase procedure was used to estimate the detection thresholds.

Such as in Experiments 1 and 2, *mechanical vibrotactile adaptation* was achieved by applying a pure 51 Hz or 251 Hz sinusoidal vibration to the index fingertip during 8 minutes, at 40 times the amplitude of the vibrotactile detection threshold (defined prior to the baseline electrical detection threshold).

2.3.4 Control experiments

In Experiments 1 and 2, mechanical adaptation was delivered while participants maintained their index fingertip against the mechanical stimulator used to assess mechanical vibrotactile detection thresholds, whereas electrical adaptation was delivered with the hand resting on a table, palm facing upwards, in order to reliably position the feltpad stimulation electrodes. To examine whether differences between the effects of mechanical adaptation and the effects of electrical adaptation could have been due to moving the hand after electrical adaptation but not after mechanical adaptation, we performed a first control experiment in which electrical adaptation was delivered without moving the hand, i.e. with the index maintained against the probe of the mechanical stimulator. To make this possible, electrical stimulation was delivered using 30x22 mm self-adhesive electrodes (30x22 mm *Ambu Blue Sensor NF ECG Electrodes, NF-50-K/12/EU*; inter-electrode distance: 15 mm) pasted over the median nerve, at the level of the wrist. The electrodes were positioned before the beginning of the experiment. The effects of low-frequency and high-frequency electrical adaptation on low- and high-frequency mechanical detection thresholds were assessed in 10 (7 male, 25±4 years, 9 right handed) and 8 participants of 18 participants (11 male, 24±3 years, 7 right handed), respectively.

A second control experiment was conducted to assess whether the intensity of the percept generated by the mechanical adapting stimulus differed from the intensity of the percept generated by the electrical adapting stimulus. Seven participants took part in this experiment (3 male, 30±6 years, 6 right handed). After estimating the electrical detection thresholds using the same adaptive procedure as in Experiments 1 and 2, ten trains of low-frequency and high-frequency electrical stimulation lasting 10 seconds were applied to the median nerve in separate sessions separated by at least 4 hours. The intensity was set 1.5 times the detection threshold, i.e. the intensity used to deliver the electrical adaptation stimulus in Experiments 1 and 2. In two other sessions, 10 low-frequency and high-frequency mechanical vibrations lasting 10 seconds were applied to the index fingertip, at an intensity corresponding to 40 times the low-frequency and high-frequency vibrotactile detection threshold, i.e. the intensity used to deliver the mechanical adaptation stimulus in Experiments 1 and 2. In each session, participants were requested to rate the intensity of each stimulus using a 0-10 numerical rating scale.

2.3.5 Statistical analyses

In Experiments 1 and 2, the effects of mechanical and electrical adaptation on mechanical vibration detection thresholds were assessed using a repeated-measures ANOVA with the factors ‘time’ (before vs. after adaptation), ‘adaptation modality’ (mechanical vs. electrical adaptation) and ‘detection frequency’ (detection of low vs. high frequency vibrations). To assess the specific effects of mechanical and electrical adaptation, a repeated-measures ANOVA with the factors ‘time’ and ‘detection frequency’ was then used for each modality of adaptation.

In Experiment 3, the effects of low- and high-frequency mechanical adaptation on the detection of electrical stimuli were assessed using a repeated-measures ANOVA with the factors ‘time’ (before vs. after adaptation) and ‘adaptation frequency’ (low- vs. high-frequency mechanical adaptation).

All statistical analyses were conducted using IBM® SPSS® (version 21). Significance levels was set at $p<0.05$.

2.4 Results

2.4.1 Intensity of the sensation elicited by mechanical and electrical adaptation

The average intensity of the sensation elicited by the low-frequency mechanical adaptation stimulus was not significantly different from the intensity of the sensation elicited by the low-frequency electrical adaptation stimulus (z=-1.18, p=0.24; Wilcoxon signed-rank test). The sensation elicited by high-frequency mechanical adaptation was perceived as significantly less intense as the sensation elicited by high-frequency electrical adaptation (z=-2.20, p=0.028).

2.4.2 Effect of low-frequency mechanical and electrical adaptation on the detection of low- and high-frequency vibrations

After *mechanical* adaptation at 51 Hz, the mechanical detection threshold increased similarly for 51 Hz vibrations and 251 Hz vibrations, indicating that adaptation had a similar effect on the ability to perceive low and high frequency vibrations (Figure 7). In contrast, both mechanical detection thresholds appeared to be unaffected by *electrical* adaptation (Figure 7). This was confirmed by the three-way repeated-measures ANOVA (Table 1), which showed a significant interaction between the factors 'time' (before vs. after adaptation) and 'adaptation modality' (mechanical vs. electrical adaptation) (F=22.10, p=.001).

For mechanical adaptation, the follow-up two-way ANOVA showed a main effect of 'time' (before vs. after adaptation: F=52.26, p<.001), and no interaction between the factors 'time' and 'detection frequency' (F=0.18, p=.205) (Table 2). In contrast, for electrical adaptation delivered using feltpad electrodes (Experiment 1) as well as self-adhesive electrodes (Control experiment), the two-way ANOVA showed no effect of 'time' (Experiment 1: F=0.00, p=.987; Control experiment: F=1.09, p=.324) and no interaction between 'time' and 'detection frequency' (Experiment 1: F=0.83, p=.381; Control experiment: F=0.05, p=.836).

Taken together, the results of Experiment 1 show that low-frequency mechanical adaptation induces a similar increase in the detection threshold for low- and high-frequency mechanical vibrations, whereas low-frequency electrical adaptation has no significant effect on the detection of both low- and high-frequency mechanical vibrations. Furthermore, the results of the Control experiment show that the lack of effect of low-frequency electrical adaptation observed in Experiment 1 was not due to an unaccounted effect of moving the hand to deliver the electrical stimulus.

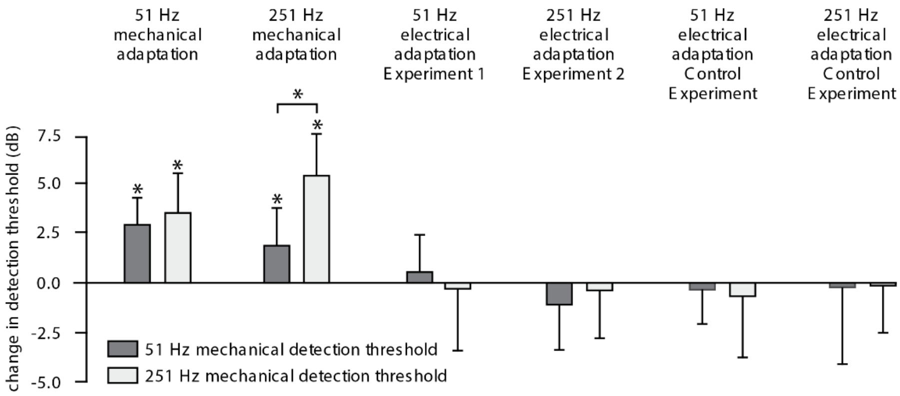

Figure 7. Group-level average (± standard deviation) change in mechanical detection thresholds induced by eight minutes of mechanical or electrical adaptation (Experiment 1, Experiment 2 and Control experiment). Low-frequency (51 Hz) mechanical adaptation induced a significant increase of vibrotactile detection threshold to both low (51 Hz) and high (251 Hz) frequency mechanical vibrations. High-frequency (251 Hz) mechanical adaptation also increased low- and high- frequency detection thresholds, but this effect was significantly greater for high frequency vibrations (251 Hz) as compared to low frequency vibrations (51 Hz). Contrasting with the effects of mechanical adaptation, electrical adaptation at 51 Hz and 251 Hz did not exert any effect on mechanical detection thresholds. Significant changes in detection thresholds relative to baseline are marked by an asterisk. Significant differences in the change in detection threshold across conditions are marked by a horizontal line (p<0.05).

2.4.3 Effect of high-frequency mechanical and electrical adaptation on the detection of low- and high-frequency vibrations

After *mechanical* adaptation at 251 Hz, the mechanical detection threshold was increased for both 51 Hz vibrations and 251 Hz vibrations. However, the increase in threshold was greater for 251 Hz vibrations, indicating that high-frequency mechanical adaptation has a stronger effect on the ability to perceive high frequency vibrations as compared to low frequency vibrations (Figure 7). In contrast, and similarly to Experiment 1, both low- and high-frequency mechanical detection thresholds appeared to be unaffected by *electrical* adaptation (Figure 7). This was confirmed by the three-way repeated-measures ANOVA (Table 1), which showed a significant interaction between the factors 'time' (before vs. after adaptation) and 'adaptation modality' (mechanical vs. electrical adaptation) ($F=35.89$, $p<.001$), but also a significant interaction between the factors 'adaptation modality' and 'detection frequency' ($F=9.72$, $p=.010$), and between the factors 'time' and 'detection frequency' ($F=13.83$, $p=.003$). There was, however, no significant interaction between the three factors ($F=3.13$, $p=.105$).

For mechanical adaptation, the two-way ANOVA showed a significant main effect of 'time' ($F=95.19$, $p<.001$), and a significant interaction between the factors 'time' and 'detection frequency' ($F=14.18$, $p=.003$) (Table 2). Post-hoc pairwise comparisons showed that both the 51 Hz and the 251 Hz detection thresholds were increased, but that this increase was significantly greater for the detection of 251 Hz vibrations as compared to 51 Hz vibrations (Figure 7). In contrast, for electrical adaptation delivered using feltpad electrodes (Experiment 2) as well as self-adhesive electrodes (Control experiment), the two-way ANOVA showed no effect of 'time' (Experiment 2: $F=1.57$, $p=.236$; Control experiment: $F= 0.03$, $p=.880$) and no interaction between the factors ‘time’ and ‘detection frequency’ (Experiment 2: F=0.59, p=.460; Control experiment: F=.143, p=716).

Table1. Three-factor repeated measures ANOVA results of Experiments 1 and 2.

INDEPENDENT VARIABLES	EXPERIMENT 1	EXPERIMENT 2
Adaptation modality	$F_{(1,11)}$=24.85 p<0.001*	$F_{(1,11)}$=54.29 p<0.001*
Time	$F_{(1,11)}$=10.86 p=0.007*	$F_{(1,11)}$=41.05 p<0.001*
Detection Frequency	$F_{(1,11)}$=5.30 p=0.042*	$F_{(1,11)}$=9.78 p=0.010*
Adaptation modality x Time	$F_{(1,11)}$=22.10 p=0.001*	$F_{(1,11)}$=35.89 p<0.001*
Adaptation modality x Detection frequency	$F_{(1,11)}$=2.43 p=0.147	$F_{(1,11)}$=9.72 p=0.010*
Time x Detection frequency	$F_{(1,11)}$=0.024 p=0.881	$F_{(1,11)}$=13.83 p=0.003
Adaptation modality x Time x Detection frequency	$F_{(1,11)}$=1.766 p=0.211	$F_{(1,11)}$=3.130 p=0.105

Table 2. Two-factor Repeated-measures ANOVA results of Experiments 1 and 2.

INDEPENDENT VARIABLES	EXPERIMENT 1		EXPERIMENT 2	
	ELECTRICAL ADAPTATION	MECHANICAL ADAPTATION	ELECTRICAL ADAPTATION	MECHANICAL ADAPTATION
Time	$F_{(1,11)}$=0.00 p=0.987	$F_{(1,12)}$=52.25 p<0.001*	$F_{(1,11)}$=1.57 p=0.236	$F_{(1,11)}$=95.18 p<0.001*
Detection frequency	$F_{(1,11)}$=7.953 p=0.017*	$F_{(1,12)}$=2.953 p=0.111	$F_{(1,11)}$=17.5 p=0.002*	$F_{(1,11)}$=2.081 p=0.177
Time x Detection frequency	$F_{(1,11)}$=0.83 p=0.381	$F_{(1,12)}$=0.17 p=0.2047	$F_{(1,11)}$=0.58 p=0.460	$F_{(1,11)}$=14.18 p=0.003*

Taken together, the results of Experiment 2 show that high-frequency mechanical adaptation induces a significant increase in the detection threshold for both low- and high-frequency vibrations, but that this increase in threshold is greater for high-frequency vibrations. In contrast, high-frequency electrical adaptation has no significant effect on the detection of both low- and high-frequency mechanical vibrations. Furthermore, the results of the Control experiment show that the lack of effect of high-frequency electrical adaptation observed in Experiment 2 was not due to an unaccounted effect of moving the hand to deliver the electrical stimulus.

2.4.4 Effects of low- and high-frequency mechanical adaptation on the detection of electrical stimuli.

As shown in Figure 8, mechanical adaptation at 51 Hz and 251 Hz had no effect on the detection threshold to transcutaneous electrical stimuli delivered to the index fingertip. The two-way repeated-measures ANOVA showed no main effect of 'time' (F=2.30, p=.164), no main effect of 'adaptation frequency' (F=0.06, p=.831) and no interaction between the two factors (F=1.82, p=.210).

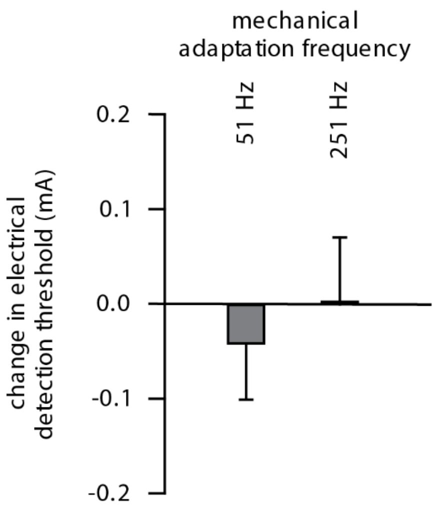

Figure 8. Group-level average change in electrical detection threshold induced by eight minutes of mechanical adaptation. Low frequency (51 Hz) and high frequency (251 Hz) mechanical adaptation had no significant impact on the detection threshold of single short-lasting square-wave electrical pulses delivered to the index fingertip.

2.5 Discussion

The results of our study can be summarized as follows. First, we confirm that mechanical vibration of the index fingertip induces vibrotactile adaptation, as evidenced by the increased detection thresholds to both low-frequency (51 Hz) and high-frequency (251 Hz) vibrations. Second, we show that low-frequency mechanical adaptation induces a similar increase in the detection thresholds to low- and high-frequency vibrations, whereas high-frequency mechanical adaptation has a stronger effect on the detection of high-frequency vibrations. Third, we show that direct, repeated and sustained electrical stimulation of the nerve trunk conveying sensory information from the index fingertip does not induce adaptation and, conversely, that mechanical adaptation of the index fingertip does not affect the ability to detect the sensation elicited by direct electrical stimulation of that fingertip.

2.5.1 Differential effect of low- and high-frequency mechanical adaptation on the ability to detect low- and high-frequency vibrations

Low-frequency (51 Hz) mechanical adaptation was equally effective in raising the threshold for low-frequency (51 Hz) and high-frequency (251 Hz) vibrations. In contrast, high-frequency (251 Hz) mechanical adaptation induced a much stronger increase in the detection threshold for high-frequency vibrations than for low-frequency vibrations. The observed differential effect of low- and high-frequency mechanical adaptation provides further support to the notion that vibrotactile adaptation at different frequencies may involve changes in distinct sensory channels, in particular, PC and non-PC mechanoreceptors.

Vibrations at 251 Hz may be expected to elicit strong responses within PC receptors, as this corresponds to their peak of optimal sensitivity (Fleming and Luo 2013). In contrast, non-PC receptors may be expected to elicit little or no responses at 251 Hz, as this is clearly above the range of frequencies to which they respond predominantly. Therefore, 251 Hz mechanical adaptation may be hypothesized to preferentially affect the sensitivity of PC receptors and, thereby, preferentially affect the ability to detect high-frequency vibrations. In contrast, considering the large bandwidth of PC receptors, vibrations at 51 Hz may be hypothesized to elicit strong responses in both PC and non-PC receptors. Therefore, 51 Hz adaptation would affect the sensitivity of both PC and non-PC receptors and, thereby, affect equally the ability to detect low- and high-frequency vibrations. Hollins et al. reported similar findings using 10 Hz and 50 Hz adapting and test vibrotactile stimuli (Hollins et al., 1990). The 50 Hz adapting frequency was equally effective in raising the thresholds to 10 Hz and 50 Hz vibrations. In contrast, the 10 Hz adapting stimulus was more effective in raising the threshold to 10 Hz stimuli as compared to the 50 Hz vibration thresholds. Hollins et al. also explained their results within the context of PC and non-PC mechanoreceptors. Specifically, they interpreted that 50 Hz adaptation affected similarly both classes of receptors, whereas 10 Hz adaptation had a stronger effect on non-PC receptors as compared to PC receptors (Hollins et al., 1990).

Our results, showing a similar effect of low and high frequency adaptation contrasts with findings obtained using single unit recordings from the ulnar and median nerves of Macaque monkeys (Bensmaia, 2005), highlighting that the amount of adaptation increases as the adapting frequency is increased, independently of the type of mechanoreceptor (SAI, RA, PC).

Finally, Leung et al. assessed the time course of adaptation and recovery from adaptation in SAI, RA and PC mechanoreceptors (Leung, 2005). They found that the time required to induce adaptation and the time required to recover from adaptation was reduced as compared to the results of studies using psychophysical methods to assess changes in detection threshold (Gescheider and Wright, 1969; Hollins et al., 1991, 1990). This led the authors to conclude that changes at the level of the central nervous system could contribute to the change in detection threshold. However, as they could also be explained by the use of different methods to induce adaptation (e.g. differences in the diameter of the vibrating probe, differences in vibration amplitude), these differences in recovery times should be interpreted with caution.

2.5.2 Lack of adaptation induced by direct electrical stimulation of sensory afferents

Contrasting with the marked effect of both low-frequency and high-frequency mechanical adaptation, sustained electrical stimulation of the median nerve during 8 minutes did not induce any measurable change in the ability to detect vibrotactile stimuli delivered to the fingertip. These findings are in line with the results of Burke and Applegate (1989), showing that 10 minutes of electrical stimulation of a digital nerve at 200 Hz does not alter the responses to natural stimuli applied to the pulp of the stimulated phalanx.

Importantly, the intensity of the sensation elicited by low-frequency sustained electrical stimulation of the median nerve was similar to the intensity of the sensation elicited by low frequency mechanical adaptation, and the intensity of the sensation elicited by high-frequency electrical adaptation was, on average, greater than the intensity of the sensation elicited by high-frequency mechanical adaptation. This indicates that the sustained afferent input generated by mechanical adaptation was not more intense than the sustained afferent input generated by electrical adaptation.

Past studies have compared the compound sensory nerve action potential (CSNAP) and somatosensory-evoked potentials (SEP) elicited by electrical and mechanical fingertip stimulation (Hashimoto et al., 1990; Krarup and Trojaborg, 1994). Even though these studies suggest that the CSNAP recorded at the level of the wrist in response to electrical stimulation of the fingertip is triphasic while the CSNAP elicited by mechanical stimulation is polyphasic, the morphology and scalp topography of the SEPs elicited by electrical and mechanical stimulation were similar (Hashimoto et al., 1990; Krarup and Trojaborg, 1994). It can therefore be hypothesized that the sustained afferent input generated by an electrical and a mechanical stimulation generate grossly similar responses at the level of the central nervous system.

For these reasons, the differential effect of mechanical vs. electrical adaptation observed in our study suggests that vibrotactile adaptation predominantly results from changes occurring at peripheral level, such as changes in the biomechanical properties of the skin or changes in mechanoreceptor transduction processes (Gescheider and Wright, 1969; Hahn, 1966; Ribot-Ciscar et al., 1996).

2.5.3 Lack of effect of mechanical adaptation on the ability to detect electrical stimuli delivered to the adapted fingertip

Sustained electrical stimulation of the median nerve and sustained vibrotactile stimulation of the index fingertip could exert different effects at the level of the central nervous system. Indeed, adaptation mechanisms occurring at the level of the central nervous system could be dependent on a number of aspects differentiating the input generated by the mechanical stimulation of mechanoreceptors from the input generated by the direct and unspecific electrical activation of afferent nerve fibers. For example, unlike the input generated by vibrotactile stimulation of the fingertip, the input generated by the electrical stimulus was not restricted to a specific category of sensory afferents (RA and PC afferents), nor was it restricted to a specific location on the index fingertip.

Therefore, a possible explanation to the finding that sustained electrical stimulation does not induce vibrotactile adaptation (Experiments 1 and 2) could be that, unlike sustained vibrotactile stimulation, sustained electrical stimulation does not induce adaptation at the level of the central nervous system.

To address this alternative interpretation, we conducted a third experiment in which we show that mechanical adaptation affecting the ability to detect vibrotactile stimuli does not affect the ability to detect electrical stimuli applied directly to the index fingertip. This finding provides further support to the notion that changes at the level of the central nervous system do not contribute to the phenomenon of vibrotactile adaptation.

At peripheral level, mechanical vibrotactile stimuli can be expected to activate preferentially specific classes of mechanoreceptors (i.e. RA and/or PC). In contrast, electrical stimuli probably activate all large-diameter afferents indistinguishably. A microneurography study has shown that the different classes of mechanoreceptors have similar conduction velocities (Kakuda, 1992). Consequently, there is no reason to assume that small differences in diameter within any sub-class of mechanoreceptor afferents would separate them with regard to transcutaneous electrical thresholds. However, at cortical level, it is likely that mechanical vibrotactile stimuli and electrical stimuli activate largely overlapping neuronal populations (Saal and Bensmaia, 2014). Consequently, if mechanical adaptation would exert an effect on the responsiveness of cortical neurons processing mechanical vibrotactile stimuli, this change in cortical responsiveness would be expected to affect *both* the ability to detect mechanical vibrotactile stimuli delivered to the adapted fingertip *and* the ability to detect sensations generated by the direct electrical activation of mechanoreceptor afferents innervating the adapted fingertip.

2.6 Conclusion

Taken together, our psychophysical results, assessing directly the effect of bypassing peripheral transduction processes, using direct electrical stimulation of sensory afferents, indicate that vibrotactile adaptation relies predominantly on changes occurring at peripheral level, and question the possible contribution of changes occurring at the level of the central nervous system.

2.7 Acknowledgements

We are grateful for the kind participation of all participants. We thank Julien Lambert and Dr. Gan Huang for their technical support.

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3 CHAPTER III: Touch Uses Frictional Cues to Discriminate Flat Surfaces

(Adapted from Gueorguiev, D. Bochereau, S., Mouraux, A., Hayward, V. & Thonnard, J.L. 2016. Touch uses frictional cues to discriminate flat materials. *Sci. Rep.***6**, 25553; doi: 10.1038/srep25553)

3.1 Summary

In a forced-choice task, we asked human participants to discriminate by touch alone glass plates from transparent polymethyl methacrylate (PMMA) plastic plates. While the surfaces were flat and did not exhibit geometric features beyond a few tens of nanometres, the materials differed by their molecular structures. They produced similar coefficients of friction and thermal effects were controlled. Most participants performed well above chance and participants with dry fingers discriminated the materials especially well. Current models of tactile surface perception appeal to surface topography and cannot explain our results. A correlation analysis between detailed measurements of the interfacial forces and discrimination performance suggested that the perceptual task depended on the transitory contact phase leading to full slip. This result demonstrates that differences in interfacial mechanics between the finger and a material can be sensed by touch and that the evanescent mechanics that take place before the onset of steady slip have perceptual value.

3.2 Introduction

Tactile sensing plays a key role in our interaction with the world around us. We constantly need to assess the nature of the objects we are in contact with in order to go about our daily lives. Thus far, it has been shown that many manipulative and perceptual tasks are performed on the basis of gross shape (Jenmalm and Johansson, 1997; Kappers, 2011) of frictional properties (Westling and Johansson, 1984) and of surface topography (Bensmaïa, 2003; Manfredi et al., 2014). Tactile mechanics provide cues about the physical properties of touched objects, including their shape (Goodwin et al., 1991), their softness (Srinivasan and Lamotte, 1995) or their friction (Smith and Scott, 1996). Therefore, objects made of different materials but having similar shapes, frictional properties, and surface topography represent a challenge for the sense of touch. Under these conditions, objects are generally assumed to be discriminated on the basis of their mass properties or thermal properties (Ho and Jones, 2006; Tiest and Kappers, 2009). To our knowledge, however, it was never suggested that differences in the materials we touch could be detected on the basis of molecular-level properties.

Water is almost universally present in our environment. With rare exceptions, all surrounding objects are naturally coated with water and water represents approximately 60% of the mass of our bodies. Water has specific molecular-level bonding properties, which manifest themselves by the hydrophobic or hydrophilic character of materials. For example, the dew on grass leaves owe its existence to the hydrophobicity of the leaves. The skin's *stratum corneum,* which covers our fingers, is mainly hydrophobic but also exhibits permeation properties (Moser et al., 2001) and moisture endows it with peculiar frictional properties that influence its contact mechanics with surfaces (Pasumarty et al., 2011).

Most previously studied surface-related tactile perceptual tasks rely on sliding fingers on surfaces because discrimination performance is dramatically improved during dynamic exploration (Hollins and Risner, 2000). The primary reason for this enhanced performance is that the mechanical fluctuations induced by sliding bring rich information about the underlying topography of a surface compared to the minute skin deformations induced by static contacts. As shown later, in the limit case of perfectly flat surfaces, complex mechanical fluctuations still take place for a large range of loads and sliding velocities. These fluctuations take place during sliding as well as during the transitory phases between sticking and slipping.

Recent studies have shown that the transition from static to dynamic finger-glass contacts can lead to surprisingly complicated dynamics where contacts can fail progressively or catastrophically under load (Andre et al., 2011; Delhaye et al., 2014; Terekhov and Hayward, 2011) owing to the nonlinear nature of friction and skin biomechanics. Here, we hypothesized that this dynamics could enable humans to discriminate between surfaces that are identical in all their physical aspects, except their molecular structure.

We tested this hypothesis in two experiments where we asked human participants to discriminate between flat surfaces made of glass or made of polymethyl methacrylate (PMMA) (see Supplementary Figure 1). The samples were thermally equalised through bonding to aluminium blocks acting as heat sinks. We established in experiment 1 that discrimination between the two materials was possible. In experiment 2, we reproduced the task and recorded the contact forces with exacting accuracy together with the psychophysical performance of the participants. The two experiment differed also in the thermal conditions. In experiment 1, the temperature of the samples was kept constant at a value near the natural fingertip temperature. In experiment 2, the samples were at room temperature.

3.3 Results

3.3.1 Experiment 1

Three samples were placed in a single row in front of the participants. Of the three samples, one was always different from the other two. Participants could explore the samples freely as many times as they wanted before reporting which was different from the other two. The samples were kept at a constant temperature similar to the average temperature of the skin (33.4 ± 0.9 °C; mean ± s.d.). Performance at the task was significantly better than chance level (one sample t-test: $t(11) = 5.41$, $p = 0.0002$, 95% CI [13.66, 32.38]). (Figure 9a). The results also suggested that participants were better at identifying the PMMA plate among two glass plates as compared to identifying the glass plate among two PMMA plates. We could rule out this bias to be the result of unseen imperfections in their surface because the answers were consistent across the plates and showed no bias towards a specific plate (Supplementary Figure 2). A comparative analysis of the force data was also performed. It suggests that this perceptual bias is due to a different time-course of the frictional properties at the fingertip-material interface of the two materials. This result is further analysed and discussed in Annex I.

3.3.2 Experiment 2

The samples were placed in one single column in front of the participant. They were kept at room temperature (23.5 ± 1.5°C; mean ± s.d.). The participant's hand was guided by the experimenter to the starting point of each exploration to ensure that the samples were explored from the most distal to the most proximal. The participants' movements were constrained in order to allow the collection of mechanical data. Each individual sample was explored from left to right in a single swipe. Participants could repeat the exploration up to five times per trial before reporting a judgment. Despite these constraints, performance was also highly significant (one sample t-test: t(11) = 4.16, p = 0.0016, 95% CI [6.836, 22.17]). (Figure 9b) and there was no significant drop of performance difference between Experiment 1 and 2 (unpaired t-test: t(22) = 1.549, p = 0.136, 95% CI [-19.92, 2.883]). The possibility that detection was mediated by an imperfection of plate surface was also assessed (Supplementary Figure 3) but the answers showed no bias towards a specific plate.

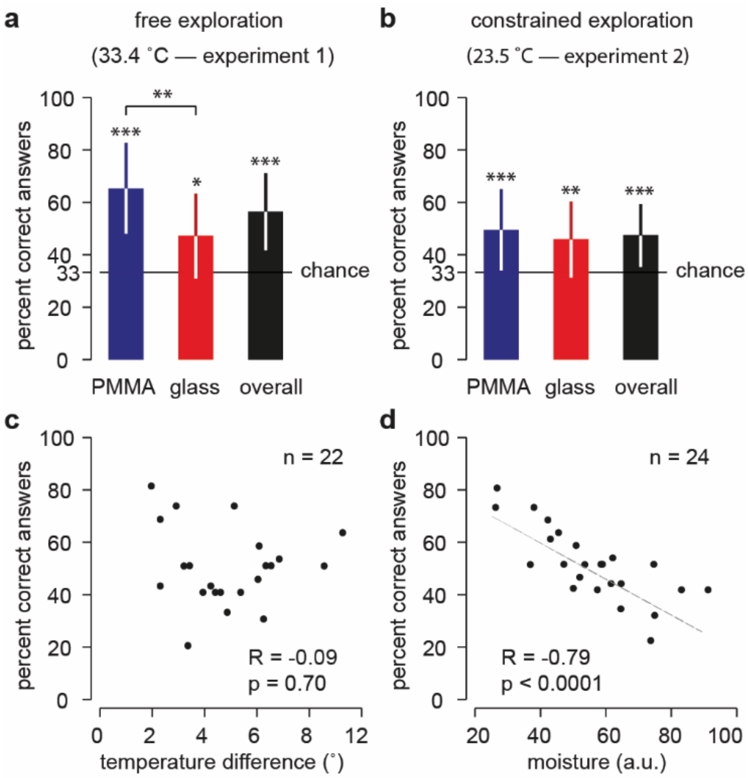


Figure 9. Psychophysical measurements. (a) Performance at the task presented as Mean ± s.d. for experiment 1. (b) Performance at the task presented as Mean ± s.d. in experiment 2. (c) The mean difference of temperature between the fingertip and the samples plotted against performance for all participants of both experiments. (d) Mean moisture level of the fingertip plotted against individual performance for all participants of both experiments.

3.3.3 Overall results

We specifically tested for the possibility that discrimination relied on thermal cues. To this end, in the two experiments and for each participant we recorded the mean temperature difference between the fingertip and the sample. If there was a substantial possibility for thermal cueing, discrimination performance could be expected to be dependent on the amount of thermal difference between the fingertip and the plates. The Pearson's correlation coefficient between the temperature differences and the individual performances showed non-significant trends corresponding to a slight anti-correlation in experiment 1 ($n=12$, $R = -0.30$, $p = 0.33$) in which the samples were warmer and a slight correlation in experiment 2 ($n=10$, $R = 0.62$, $p = 0.06$) in which the samples were colder. Since the distribution of temperature differences was similar in the two experiments (unpaired t-test: $t(20)=1.386$, $p = 0.18$, 95% CI[-0.6722, 3.336]), we computed the overall Pearson's correlation coefficient between the temperature differences and the individual performances, and no correlation was found ($n=22$, $R = - 0.09$ and $p = 0.70$) (Figure 9c). These opposite trends for the two experiments rather suggested an effect of the absolute temperature of the fingertip and indeed, higher finger temperature significantly correlated with a better capacity to discriminate the materials (Pearson' correlation for $n=22$, $R = 0.47$ and $p = 0.026$). This result was in accordance with previous studies indicating lower mechanical detection thresholds when the fingers are warm (Bolanowski and Verrillo, 1982; Gescheider et al., 1997). These results are therefore consistent with a discrimination strategy based on mechanical cues, rather than with a strategy based on thermal cues.

The moisture level of the fingertips was also monitored. We found the moisture level to be strongly anti-correlated with individual performance in experiment 1 (Pearson's correlation for $n=12$, $R = -0.90$, $p < 0.0001$) as well as in experiment 2 (Pearson's correlation for n=12, $R = -0.63$, $p = 0.028$). Since the distributions were similar (unpaired t-test: $t(22)=0.1875$, $p = 0.85$, 95% CI[-12.75, 15.29]), we tested the correlation between moisture level and performance across the two experiments. The correlation was robust (Pearson's correlation for n=24, $R = -0.79$, $p < 0.0001$) (Figure 9d). The strong influence of fingertip moisture on performance discrimination motivated us to investigate further the connection between the perceptual performance and the underlying contact mechanics.

We first verified that, during non-constrained exploration, the behavioural parameters (speed or exploration, normal force applied) did not correlate with individual performance (see Supplementary Figure 4). We then segmented each swipe into three epochs: a loading phase during which the finger contact is stuck, a partial slip phase during which the outer part of the contact area starts slipping (Andre et al., 2011) and a full slip phase during which the contact area is fully sliding (Figure 10a and materials and methods). The aim of this segmentation was to determine which epoch provided the greatest differentiation between the materials being touched.

We computed the dynamic coefficient of friction for the two materials defined as the ratio of the magnitude of tangential and normal forces generated by the interaction during full slip for all trials (Figure 10b). The values of the coefficient of friction varied across participants with a mean value of 1.13 ± 0.13 (mean ± s.d.) but a Mann-Whitney test with a Bonferroni correction did not show significant intra-individual differences related to the materials: nine participants had p-values > 0.05 and one participant, whose performance was average (42,9% of correct answers) had a p-value = 0.042. The coefficients of friction between the two materials were significantly anti-correlated with individual performance (Pearson's correlation for n=10, $R = -0.67$, $p = 0.036$): discrimination performance was, on average, better when the difference in coefficient of friction was small. This indicates that discrimination did not rely on differences in the average dynamic coefficient of friction during full slip, but does suggest a possible role of frictional dynamics during other phases of the exploration. We thus analysed the spectral characteristics of the forces during the different phases of the sliding. For this purpose, the signals were analysed in the spatial domain such as to characterize the fine fluctuations of force independently of the net slip velocity (Klöcker et al., 2013; Michael Wiertlewski et al., 2011). As typically is the case, the spatial frequency amplitude spectrum followed a power law relationship (Michaël Wiertlewski et al., 2011), $T = \beta\eta^{\alpha}$, where β is a magnitude factor and α quantifies the decay of amplitude with frequency (Figure 11a).

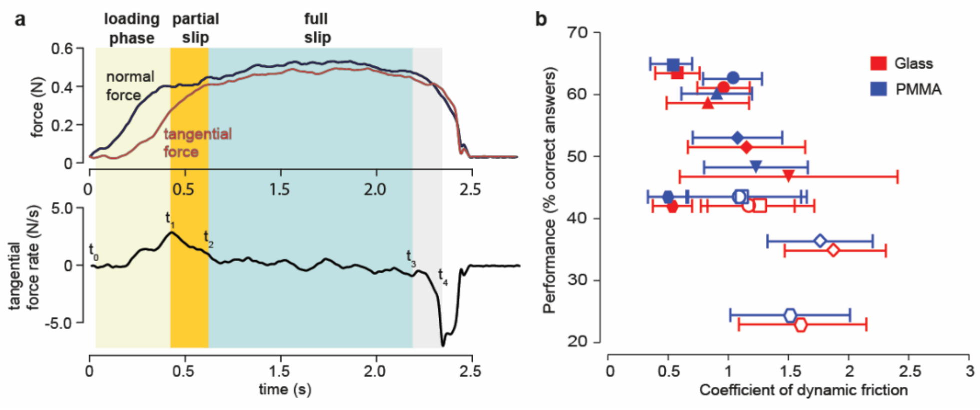


Figure 10. Trial segmentation and coefficient of dynamic friction. (a) The rate of change of the tangential force component enabled the extraction of the objective markers t_1, t_2, t_3 and t_4 (see Materials and Methods), which were used to define the different phases within a swipe: loading phase (t_0-t_1), partial slip (t_1-t_2) and full slip (t_2-t_3). (b) The coefficient of dynamic friction, Mean ± s.d., was not distinguishable between materials. The 10 pairs of symbols represent the glass (red) and PMMA (blue) values for each participant. Although the overall individual performance for both materials is identical for the two datasets, the data for glass are slightly shifted downwards for better visibility.

The spectra were averaged within participants for all trials and the magnitudes and decays were estimated. For each of the three epochs, the spectrum in the range 10^{-1}-10 mm^{-1} was compared between glass and PMMA. There was no significant difference in spectral decay between the materials but the magnitudes differed (Δlogβ, Figure 11b,c,d). Discrimination performance was strongly correlated with |Δlogβ| during partial slip (Pearson's correlation for n=10, $R = 0.83$, $p = 0.003$) and moderately during the loading phase (Pearson's correlation for n=10, $R = 0.70$, $p = 0.023$). On the other hand, correlation was very weak during fully developed slip (Pearson's correlation for n=10, $R = 0.007$, $p = 0.99$). These correlations between the transient frictional dynamics observed during the early stages of a swipe and individual performance suggest that, during these stages, frictional dynamics of the interactions between the fingertip and the two materials differed, and that this difference enabled the participants to discriminate the two materials.

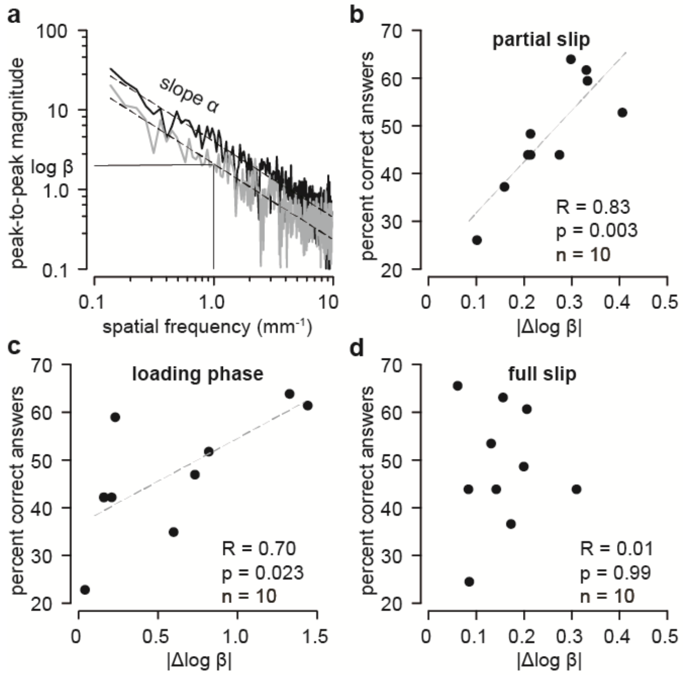


Figure 11. Analysis of the frictional fluctuations. (a) Comparison of the amplitude spectra of the tangential force component in the spatial domain. Linear regression gave parameters α and logβ. The differences Δα and Δlogβ between the mean spectra of the two materials were computed for all participants. (b-d) The differences in the frictional noise │Δlogβ│ between glass and PMMA plotted for each phase against performance: (b) Partial slip. (c) Loading phase. (d) Full slip.

3.4 Discussion

Performance within our sample of participants was significantly above the chance level in the two experiments, showing that tactile discrimination between two flat materials is possible even in the absence of thermal and surface topography differences. If flat surfaces could be distinguished on the sole basis of frictional cues, then differences must have arisen from molecular-scale properties influencing the interfacial contact of the skin-material pair, in turn influencing its frictional dynamics. The moisture content of the fingers strongly correlated with performance across the study, suggesting that the interaction of water either with the skin tissue or with the skin-material interface played an important role in the tactile discrimination of these two flat surfaces.

During steady sliding, there was no measurable difference in contact mechanics (coefficient of friction, spectral properties of force fluctuations) between the two materials. In contrast, there were significant differences in the magnitude of the interfacial force variations during the partial slip phase corresponding to a progressively failing contact. The partial slip phase comprises a mix of adhesion and slip where, typically, an annulus of failure grows from the periphery of the contact region to eventually invade the whole contact (Andre et al., 2011) (see also Supplementary Movie 1). The present measurements corroborated the earlier observation that partial slip tends to last from 100 ms to 300 ms in finger-glass contacts (Terekhov and Hayward, 2011). During this period, the contact evolution can sometimes take the form of a catastrophic failure once a critical load is reached. This finding suggests that the evolution of the contact state, owing to the nonlinearity of friction, can be critically sensitive to small changes in the frictional behaviour of the skin-surface interface.

The observed macroscopic effects must take their roots in smaller-scale physics. The moisture level of the fingertip was already shown to dramatically affect the time course of contact failure under load and thus could explain the performance dependency that we observed between fingertip moisture and discrimination performance (Andre et al., 2011). The surfaces that we employed in the present study differed by their hydrophobicity. Ordinary uncoated glass has a hydrophilic, amorphous solid atomic structure and PMMA is a hydrophobic transparent polymer. The other material of the contact pair, the skin *stratum corneum*, is mostly made of keratin, a natural glassy polymer with strong affinity with water. As reviewed recently (Adams et al., 2013; Derler et al., 2014), water plasticizes the *stratum corneum* and reduces its elasticity leading to combined adhesion mechanisms. A first mechanism is associated with capillary forces at small normal loads and short time scales (Dinç et al., 1991), a second is due to plasticization for longer time scales (Adams et al., 2007), and others to molecular interactions. The difference in material hydrophobicity is likely to affect these phenomena differentially and their relative contributions could impact the evolution of the stick-to-slip dynamics. At onset, the finger would tend to stick more on glass than on plastic owing to a stronger influence of capillary forces in the early stages of a tangentially loaded contact. Subsequently, during the partial slip phase, higher magnitude of frictional dynamics for PMMA could arise from the rate of breaking of the molecular bonds during the progressive failure of adhesion, which is akin to crack formation. Plasticization occurs over a longer time course and it is unlikely to play a direct role during the early transient phase of tactile exploration but the free exploration allowed in experiment 1 also took place on a longer time course than single swipes. Therefore, different plasticization dynamics might be responsible for the difference in discrimination performance between the two materials, which we observed in experiment 1. The strong effect of hydration of the fingertip could also influence the transmission of subtle frictional fluctuations through variations in skin damping.

The onset of slip received no attention until now since it was hitherto assumed that the tactile perception of materials relied predominantly on interactions taking place over extended periods of full slip. Classical studies of touch focus almost exclusively on rigid surface features without consideration of chemistry of the materials (Jones and Lederman, 2006). Our results suggest that other properties affecting frictional dynamics must be taken into consideration, and justifies the current shift toward studies involving naturalistic surfaces (Bergmann Tiest and

Kappers, 2006; Weber et al., 2013). Moreover, recent reports of astonishing tactile discrimination performance with textured surfaces at the nanometre scale (Skedung et al., 2013) could be explained, not by direct differences in topography among these surfaces, but rather by the impact that small scale features have on interfacial frictional dynamics.

3.5 Material and Methods

The ethics committee on human research of Université catholique de Louvain approved the study (Virtual Prototyping of Tactile Displays, PROTOTOUCH-317100). All participants gave written informed consent. The investigation conformed to the principles of the Declaration of Helsinki and experiments were performed in accordance with relevant guidelines and regulations.

3.5.1 Participants

Data were collected from 24 healthy volunteers (12 in experiment 1 and 12 in experiment 2) aged between 22 and 61. Participants were blindfolded and white noise was played at a comfortable listening level through headsets in order to mask auditory cues.

3.5.2 Materials

The samples were made of ordinary glass (clear glass, Leroy Merlin, France) or of polymethyl methacrylate (PMMA) plates (Plexiglas®, ABP Beaumont plastique, France). Surfaces were perfectly flat. They were chosen for their differences in atomic structure and hydrophobicity. The topographical profiles were assessed with a digital holographic microscope (Lyncée Tec, Switzerland) to check the flatness and absence of topographic features (see Supplementary Figure 1). The samples dimensions were 60 x 30 x 2 mm. According to findings from previous studies, the differences in the thermal properties of PMMA (heat capacity: 1460 j/kg, thermal conductivity: 0.2 j/m, Contact Coefficient: 0.6 10^3 $J/m^2s^{1/2}K$) and glass (heat capacity: 837 j/kg, thermal conductivity: 0.78 j/m, Contact Coefficient: 1.3 10^3 $J/m^2s^{1/2}K$) were insufficient to provide thermal cues for the discrimination of the samples or noticeable thermal changes to the fingertip (Ho and Jones, 2004, 2006; Jones and Berris, 2003). Furthermore, the temperatures of the samples were kept equalised by bonding all triplets of samples to 10 mm thick aluminium blocks acting as heat sinks. The edges were protected with adhesive tape to prevent the participants from using them as a source of information. In experiment 1, the samples were warmed using an infrared heat lamp and thermocouples. The thermocouples were located under the plates (OS36, OMEGA engineering Inc.) and controlled by a thermo-controller (MICROMEGA CN77000, OMEGA engineering Inc.) in order to keep the temperature of the samples constant throughout the whole experiment and match the average temperature of the human fingertip. This procedure could not be implemented in experiment 2, because the setup for temperature control could not be combined with the force sensing plates used for the fine measurements of force dynamics.

3.5.3 General procedure

The procedure was a forced choice task with three alternatives (3-AFC) where one sample differed from the other two (“odd-man-out”). This procedure was chosen because we did not have prior assumption of the relevant tactile information that could be used to discriminate the surfaces, and it encouraged the participants to search for any subtle differences. The participants washed their hands with commercial liquid soap and waited five minutes before starting the task in order to stabilize the frictional properties of the skin. Three randomly placed samples were presented to the participant (either two samples of PMMA and one sample of glass, or one sample of PMMA and two samples of glass). The participants explored the samples with the index finger of their dominant hand and reported which of the three samples differed from the others two. At the beginning of the experiment, the samples were cleaned with commercial cleaner for glasses (Si Clair, SI International, France) and checked for imperfections. They were additionally quickly cleaned with microfiber cloth every three trials. The performance of each participant was given by the percentage of correct answers and participants were asked about possible imperfections on the samples. An experiment comprised three blocks of fourteen trials. Before and after each block, the temperature of the samples and of the fingertip was assessed with an infrared thermometer (Raytek MI3-M, Raytek, USA). In experiment 2, the temperature values could not be collected for two participants because of a temporary unavailability of the recording device. The moisture level of the fingertip was also measured by averaging three repeated measures using a corneometer (CM 825, Courage + Khazaka electronic GmbH, Germany).

3.5.4 Force measurements

In experiment 2, the contact forces between the finger and the samples were recorded by a sensitive force sensing plate designed in-house on which the samples were clamped. The force plate measured the normal force components using two load cells (9313AA1, Kistler AG, Switzerland) and the tangential force component using one load cell (9217A, Kistler AG, Switzerland). The offset of the force plate was 1.0 mN for the tangential component of the force and 40 mN for the normal component. The signals were digitized at 10 kHz. The location of the fingertip contact on the plate was estimated by computing the position of the centre of pressure. The force transducer temporarily lost calibration during the study. As a result, the force data of two participants could not be analysed.

3.5.5 Analysis of the contact mechanics

Detailed force analyses were performed on swipes for which the continuous motion on the surface was longer than one second and the exploration length was at least four centimetres. The continuous force measurements were segmented into single epochs corresponding to distinct phases within single swipes (Figure 10a). To express the variations in tangential force during each swipe, the tangential force component was smoothed using a moving average filter with a 0.25 s time constant, and then differentiated. The onset of exploration (t_0) was defined as the instant when the normal force reached a value greater than the maximum noise level of the force plate (40 mN). This time point corresponds to the moment when the force sensor measures a significant increase of normal force due to the finger pressing against the surface. The end of the exploration (t_4) was defined as the instant when the first derivative of the tangential force reaches its minimum. This corresponds to the moment when the participant begins unloading the finger from the surface. Three successive segments were then defined (loading phase, partial slip and full slip). The loading phase segment started at the onset of exploration (t_0). During this phase, the fingerpad remained in static contact with the surface, and an accelerating increase in tangential force was observed. The transition between the loading phase segment and the partial slip segment was defined as the instant when the rate of the tangential force reached a maximum (t_1), as this sudden change in tangential force dynamics was thought to result from the occurrence of partial slip between the fingerpad and surface. The transition from partial slip to full slip was defined as the instant (t_2) when the derivative of the tangential force became smaller than its standard deviation (estimated in the interval $[t_1,t_4]$). This was justified by the fact that once the finger starts sliding steadily against the surface, the tangential force remains relatively constant, provided that both the normal force and the dynamic coefficient of friction stay constant. Finally, the end of the full slip segment was defined as the time point (t_3) when the derivative of the tangential force became more negative than its standard deviation estimated in the interval [t_1,t_4]. This last time point marked the end of the phase during which the finger was steadily sliding against the surface. Since the speed of exploration varied between trials, the force data measurements were converted to the spatial domain (Michael Wiertlewski et al., 2011). After this transformation, the length of the full slip segments were further restricted to two centimetres of sliding in order to match their duration with that of the transient phases. Since averaging the Spatial Fast Fourier Transform (SFFT) over all swipes for each participant required using identical epoch for each swipe, we computed the t_0, t_1 and t_2 values for each participant over all its swipes, turned them into spatial coordinates and used their median values to implement the participant's average SFFT of glass and PMMA.

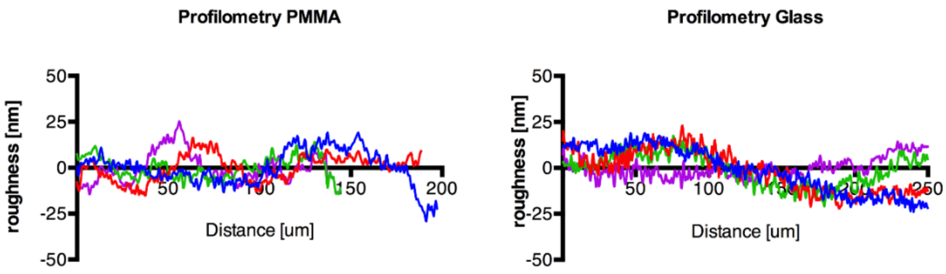
3.5.6 Statistics:

The decision to use parametric or non-parametric statistical methods on given data sample was motivated by the D'Agostino and Pearson omnibus normality test, which we performed on all analysed samples using GraphPad Prism software.

3.6 Supplementary materials

3.6.1 Profilometry of the materials' surface

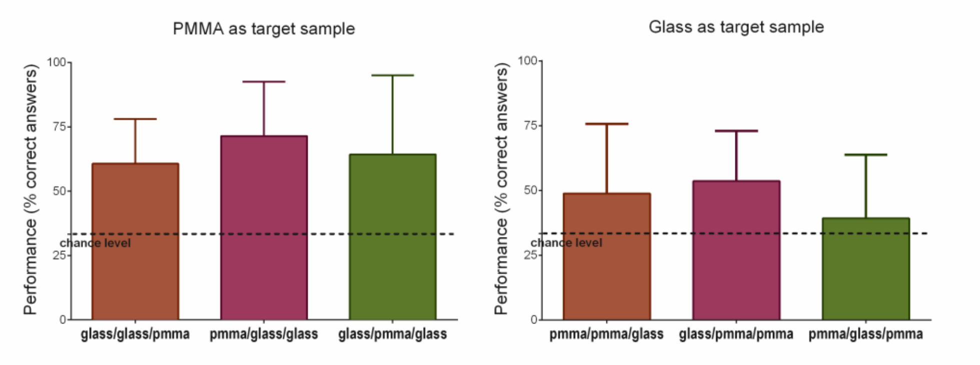
Profilometric measurements were performed with a digital holographic microscope (Lyncée Tec, Switzerland) on four samples of each material to verify their flatness. The surfaces were extremely smooth (R_a glass = 8.1 10^{-6} mm; R_a PMMA = 6.2 10^{-6} mm) and did not exhibit salient topographic features beyond the nanometre scale.



Supplementary Figure 1. Surface topography of the samples, related to materials and methods (subsection "Materials"). Height samples used during experiment 2 were randomly picked and assessed prior to the experiment: four samples of PMMA and four samples of glass.

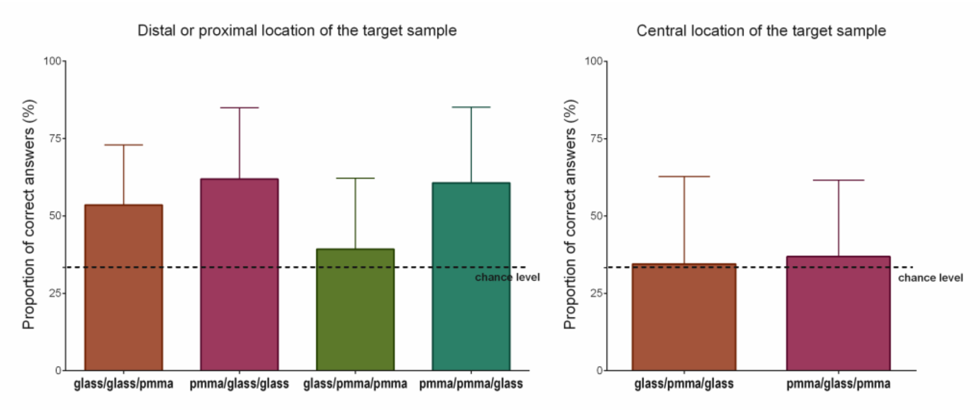
3.6.2 Homogeneity of performance across the experiments

The surfaces were shown to be quasi perfectly flat prior the experiment but a major concern during the two experiments was to avoid the influence of potential imperfections. In addition to the control procedure that was implemented during the experiments (See Materials and Methods: General procedure), the homogeneity of the performance across the different plates on which the samples were glued was also tested. Four distinct plates were used in each experiment to present all the possible orders since the plates with Glass – Glass – PMMA and PMMA – PMMA – Glass could be used for presenting different orders of the samples. Thus, an imperfection on a plate could have impacted the responses for either one or two of the possible orders of presentation. In experiment 1, the performance was found to be different depending on the target material (Figure 9a.). We therefore investigated if this bias was due to an undetected imperfection or to a natural difference like, for example, a higher probability of a transient increase in the stickiness (stick and slip) for one of the materials. If the bias was due to an imperfection on a plate, it should have impacted the participants' answers for the scratched plate but repeated-measures ANOVA with Geisser-Greenhouse correction performed on all the possible orders where the target sample was PMMA ($F(1.262,13.88) = 0.806$, $p = 0.413$) and where the target sample was glass ($F(1.823,20.05) = 1.477$, $p = 0.25$) showed no inconsistency in the answers of participants (Supplementary Figure 2).



Supplementary Figure 2. Performance for each of the possible presentations of the stimuli in experiment 1. Performance (mean ± s.d.) was consistent across all possible orders where PMMA was the target sample (Left) and across all possible orders where glass was the target sample (Right).

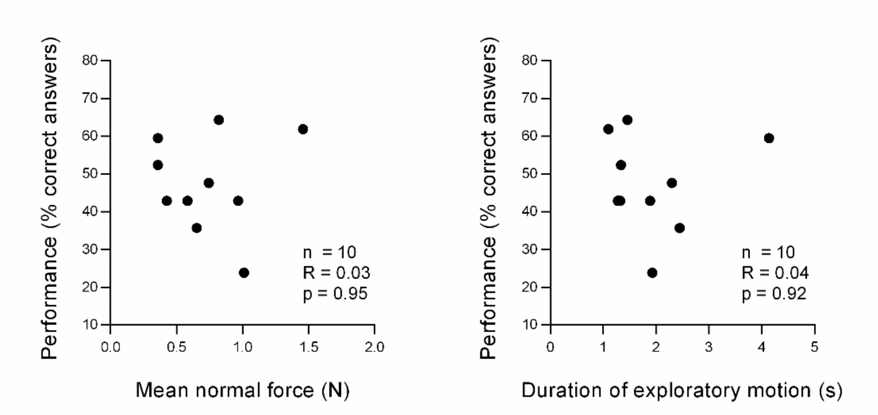
In experiment 2, performance was similar for glass and PMMA but a non-parametric Friedman test showed a lower performance when the target sample was located in the middle (χ^2 = 11.87, p = 0.0026). Thus, we tested if there was a discrepancy in the responses that would suggest the bias to be due to an imperfection rather than to the psychophysical criterion of the participants. Repeated-measures ANOVA with Geisser-Greenhouse correction was performed across all the plates where the target sample was at the distal or proximal location and showed no significant difference ($F(2.565,28.22) = 2.845$, p = 0.063). Wilcoxon matched-pairs signed rank test was performed between the two cases when the target sample was located in the middle and showed consistent answers (12 participants: N=8, W=1, p = 0.99) (Supplementary Figure 3).



Supplementary Figure 3. Performance for each of the possible presentations of the stimuli in experiment 2. Performance (mean ± s.d) was consistent across all cases where the target sample was in a distal or proximal location (Left) and across all cases where it was centrally located (Right).

3.6.3 Behavioural parameters in experiment 2

Explorations were constrained during experiment 2 but the participants had a large amount of behavioural freedom particularly in terms of exploration speed, normal force applied, and possible changes of strategy, which could influence the differences in contact mechanics between the two materials (Supplementary Figure 2). Despite the different strategies implemented by the participants, we did not find any influence of normal force (R = 0.03, p = 0.95; Pearson's correlation for n = 10) and mean duration of exploration (R = 0.04, p = 0.92; Pearson's correlation for n = 10). These results confirm the hypothesis that the capacity to discriminate relied on specific properties of the fingertip-surface interaction rather than on an optimal choice of exploring strategy.



Supplementary Figure 4. Normal force and mean duration of the exploration as a function of performance, related to Figure 10. Left: The specific normal forces used by the each participants while performing the task did not correlate with their performance. Right: The mean duration of the exploratory motion during the task similarly did not affect the participant's performance.

3.7 Acknowledgements

The authors thank Simon Johnson of Unilever, R&D for his help with finger tribology. This study was funded by the FP7 Marie Curie Initial Training Network PROTOTOUCH, grant agreement No. 317100. It was also supported by the European Research Council (FP7) ERC Advanced Grant (PATCH) to V.H. (No. 247300).

4 CHAPTER IV: Psychophysical Power Optimization of Friction Modulation for Tactile Interfaces

(Adapted from Sednaoui T, Vezzoli E, Gueorguiev D., Amberg M, Chappaz C, Semail B. Psychophysical Power Optimization of Friction Modulation for Tactile Interfaces. *Technical paper at the conference Eurohaptics* 2016, In Press)

4.1 Summary

Ultrasonic vibration and electrovibration can modulate the friction between a surface and a sliding finger. The power consumption of these devices is critical to their integration in modern mobile devices such as smartphones. This paper presents a simple control solution to reduce up to 68.8% this power consumption by taking advantage of the human perception limits.

4.2 Introduction

The last few years have seen the emergence of ubiquitous mobile devices and tactile interfaces. The abundance of these novel interfaces raised the interest in touch based human-machine interactions and highlighted the lack of natural touch feedback in the existing generation of tactile displays. The problem was partly responsible for the slow adoption of the technology among consumers. Currently, multiple solutions are being explored to deliver improved haptic feedback on existing mobile platforms such as smartphones or tablets; one such feedback technology, vibrotactile stimulation, is already incorporated on most platforms but only provides a general vibration sensation to the hand and finger of users (USA Brevet n° US7182691 B1, 2007). To improve upon this, tactile based solutions have been proposed in recent years such as electrovibration (Meyer et al., 2013) and Ultrasonic Lubrication (UL) (Amberg et al., 2011; Giraud et al., 2012; Sednaoui et al., 2015a). These technologies have very different means of action but ultimately affect the dynamic friction between the finger and the tactile plate in a similar manner (Vezzoli et al., 2015). Integration into mobile devices creates multiple challenges in both technologies. The power consumption is one of these challenges considering the already limited endurance of mobile devices.

Both UL and electrovibration technologies use their friction control capabilities to create a reproduction of simple textures. This reproduction is typically applied by alternating quickly states of high and low friction while the user moves its finger across the active surface (Meyer et al., 2013). In most cases, this switching is simply implemented by applying a square modulation signal to the friction control device (Giraud et al., 2013) Perception of a specific texture is driven by the spatial frequency pattern of this texture. This pattern can then be recreated in the time domain by modulating the active phases in function of the exploration speed. This study explores the possibility of reducing the duty cycle of such modulation while maintaining the same texture perception. Reducing the duty cycle of modulation affects the total active time and thus the final power consumption of the tactile device.

We chose an UL device to implement this study. This choice was made from due to two main factors. First an UL device presents higher power consumption in active state than electrovibration devices for a similar form factor. This is due mostly to continuous damping of the air against the vibrating plate (Messaoud et al., 2015). A second factor is that electrovibration presents a perception degradation when repeated sliding of the finger are performed. This is caused by the deposition of sweat that shields the finger from the electrical field (Kaczmarek et al., 2006).

The current paper demonstrates that power consumption in a friction modulation device can be reduced significantly by reducing the duty cycle of the modulation stimulation. A power reduction scheme is proposed and validated using psychophysics measures on five participants performing a discrimination task on an UL device. A wide range of modulation frequencies is tested to validate the proposed scheme across the frequency perception range of the human fingertip.

4.3 Experimental setup

4.3.1 Global system description

To perform this study, we developed a specific stimulator designed to deliver controlled and repeatable stimulations. First, the general experimental system is described and then the UL display that was specifically developed.

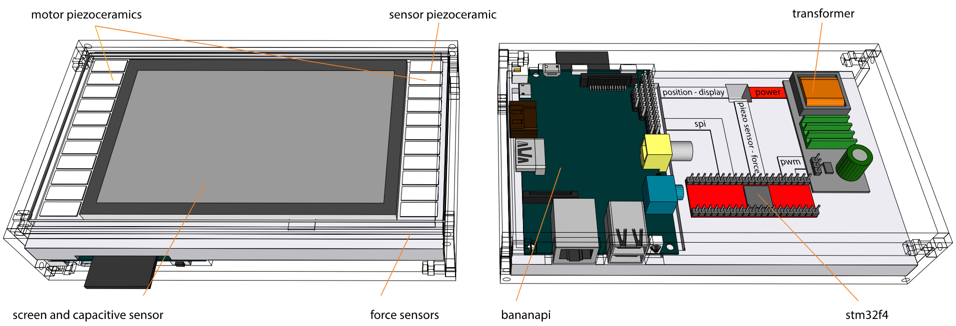


Figure 12. Device architecture

In order to control the modulation frequency and the vibration amplitude of the haptic plate, a new device was specifically developed. As seen in Figure 12, this system includes both visual and haptic feedback. Finger touch position is directly acquired using a capacitive touch screen. Computation and control of the experiment is separated in two parts: a “High level” signal using the banana pi (Shenzhen LeMaker Technology Co. Ltd, China) single board computer featuring a

1 GHz ARM Cortex-A7 dual-core CPU with 1 GB of ram. A “Low Level” signal generation is implemented in a separate DSP microcontroller (stm32f4, STMicroelectronics, France) running at 164MHz. In this setup “High level” computing refers to the display of the instruction to the user, selection of the haptic signal commands and storage of the results. The signal generation microcontroller for its part applies commands from the board computer to create the necessary waveforms for the friction modulation. The communication between the microcontroller and the single board pc is provided by an SPI bus working at 10 kHz. In order to insure the fastest amplitude rise time in this study, an external amplifier is used to drive the piezoceramic motors as in (Amberg et al., 2011).

The single board computer is connected to a 5 inches flat capacitive touch screen (Banana-LCD-5"-TS, Marel, China) providing the finger position input and display output, where the sampling frequency of the finger position is 62 Hz. This LCD display gives visual confirmation of the experiment goals during the measures. A second visual system using a computer screen is used to display comfortably the controls of the experiments to each participant.

4.3.2 Ultrasonic Vibrating Plate

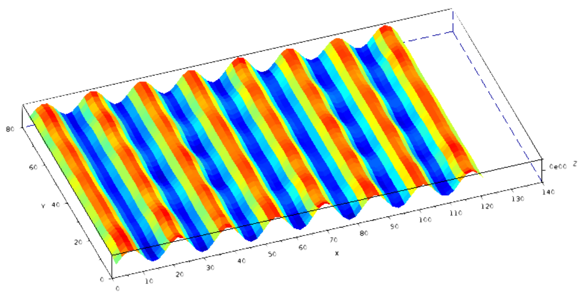


Figure 13. Cartography of the ultrasonic vibrating plate

The ultrasonic vibrating plate implemented in the device is specifically designed to provide the best modulation bandwidth. The glass plate measures 154x81x1.6 mm resonating at 60750 Hz, where the half length of the vibration mode is 8 mm. 22 piezoceramics, 14x6x0.5 mm, are mounted at the side of the plate along the extremum of deformation, 20 used as motors and 2 as vibration sensors. Their unglued electrode was cut along the nodal and each side connected to the amplifier to create a virtual mass on the glued face of the ceramic. The cartography of the vibration amplitude of the plate is reported in Figure 13.

Power consumption associated with reduction of the duty cycle has been measured with the help of a Tectronics oscilloscope and a current probe. A linear relationship was found between the consumed power and a duty cycle ranging from 5% to 95%.

4.4 Experimental protocol

This section presents the psychophysical protocols used in the two following experiments. A first experiment was conducted to determine the capacity of participants to distinguish differences in the duration of a single tactile stimulation. In a second experiment, an experimental protocol to measure the achievable duty cycle reduction for a range of modulation frequencies is presented.

In both experiments, the participants were interacting with the tactile device described in Section 2. Five subjects aged between 25 and 30 participated to this study (4 males and 1 female). The UL tactile interface sometimes makes a slight noise when alternating active and passive states. Therefore, to prevent any influence of this noise on the participant's perception, they had to wear noise reduction headphones and a white noise was also diffused in the room during the experiments. For each trial, the participants had to move their finger from left to right on the screen which generates a stimulation but were free to choose the force and speed of exploration. The participants had to lift their fingers from the plate after each sliding on the plate.

4.4.1 Minimum Signal Duration

The minimal signal duration discrimination experiment aim was to determine the capacity to perceive differences in the length of the friction reduction. From this psychometric function it was then possible to extract the just noticeable difference (JND) of signal duration for humans interacting with the UL tactile device. The experiment was based on a forced choice task with a constant pool of stimuli (constant stimuli method). The participants had to compare the length of two stimuli, displayed in sequential order. A reference value of signal duration was always randomly set as one of the two stimuli presented in the discrimination task. The other stimulus was a test value to compare against the baseline. The participants explored the two stimuli up to 3 times and was then asked to report which stimulus offered the “shortest” stimulation. They had to choose one of the signals even if not sure of the answer.

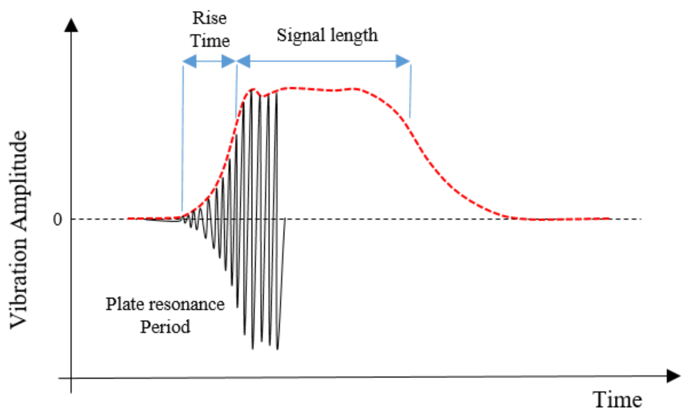


Figure 14. Voltage amplitude of the signal duration experiment

Test signals were presented in a pseudorandom order where one of the signals was always the baseline and the other selected from a list of five signal length calibrated in advance. The possible time durations were 1.6, 2.4, 3.2 and 4ms to be compared with a baseline of 0.8ms. The experiment was stopped after a signal of each length had been presented 10 times against the reference. Each of the five subjects was thus presented to a total of 40 signal comparisons.

4.4.2 Duty cycle modulation

The aim of the second experiment was to determine the maximum duty cycle reduction achievable while keeping the same perception of the modulation. The potential duty cycle reduction was assessed for multiples frequencies within the human perception range. To this end, this experiment was repeated on a range of modulation frequency for each participant.

For each set of modulation frequencies, the psychometric function and the JND of the duty cycle discrimination was determined. Similarly to the previous experiment, a constant stimuli method was used. The participants explored the two stimuli up to 3 times and were then asked to report which stimulus offered the "strongest" stimulation. They had to choose one of the signals even if not sure of the answer.

As in the first experiment, the test signals were presented in a pseudorandom order where one of the signals was always the reference and the other selected from a list of 4 duty cycles calibrated in advance. The list of possible duty cycles was 10%, 20%, 30%, and 40%, with the square 50% duty cycle used as the reference stimulus (See Figure 15). The experiment was once again stopped after each duty cycle was presented 10 times against the reference.

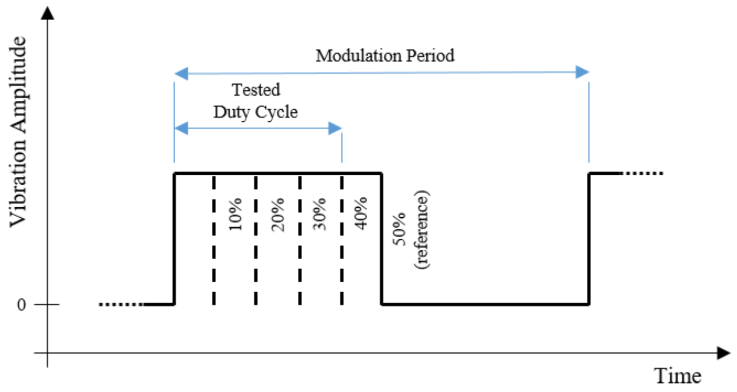


Figure 15. Reduction cases of the Duty Cycle.

The same protocol was implemented 4 times for different modulation frequencies: 10Hz, 20Hz, 40Hz and 80Hz. To prevent fatigue, the 4 experiments were divided in 2 sessions separated by a one-hour break. Each of the five subjects was thus presented to a total of 160 signal comparison tests to extract the 4 duty cycle psychometric functions and JND values.

4.4.3 Psychophysical analyses

In each task, the psychophysical threshold was evaluated by fitting a logistic psychometric function based on the method of maximum likelihood to the psychophysical performance of the participants. The fitting was implemented by using the version 1.81 of the Palamedes toolbox (Kingdom and Prins, 2009).

4.5 Results

4.5.1 Minimum Signal Length

Results from the five subjects are presented. All the answers from the five participants were averaged together and the standard deviation calculated. The data obtained during the trial are shown in Figure 16.

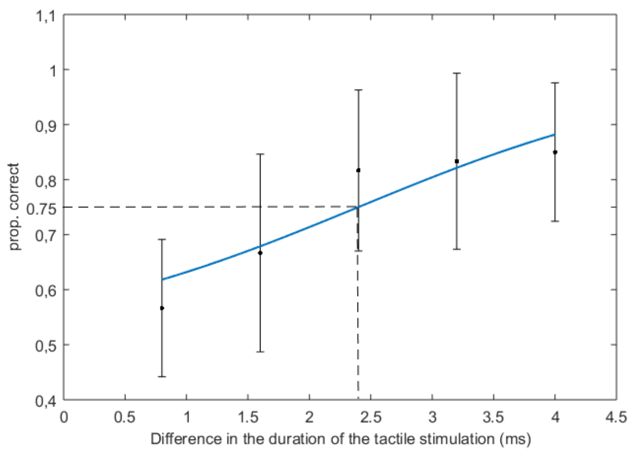


Figure 16. Just noticeable difference of signal length. Error bars represent the standard deviation and blue line is a fit of a logistic psychometric function to the result plot.

To compute the just noticeable difference (JND), which represents the minimum signal length difference that can be reliably discriminated, the percent of the time that the participants responded correctly as a function of the difference in the signal length was calculated. A logistic psychometric function bounded between 0.5 and 1 was fitted to the resulting plot. A value of 0.5 on the Y axis represents a situation where the participant performs at chance level. On the contrary a value of 1 represents 100% correct discrimination from the participant.

For a forced choice task with two alternatives, the JND is typically set as 75% of correct answers. We computed it by interception of the psychometric function at Y=0.75 and the overall JND for the five participants was therefore estimated at 2.45ms.

4.5.2 Duty Cycle Modulation

In this experiment, four modulation frequencies were explored in separate blocks. Similarly to the time length experiment, the JND, which represented minimum duty cycle that can be reliably discriminated from a reference duty cycle of 50%, was computed by estimating the interception point of a psychometric function fitted to the answers of the participants and a proportion of correct answers of 0.75.The overall JND's for the five subjects who participated in this experiment were calculated at a duty cycle of respectively 16.5, 17.5, 11 and 17.5% for modulation frequency of 10, 20, 40 and 80Hz (See Figure 17).

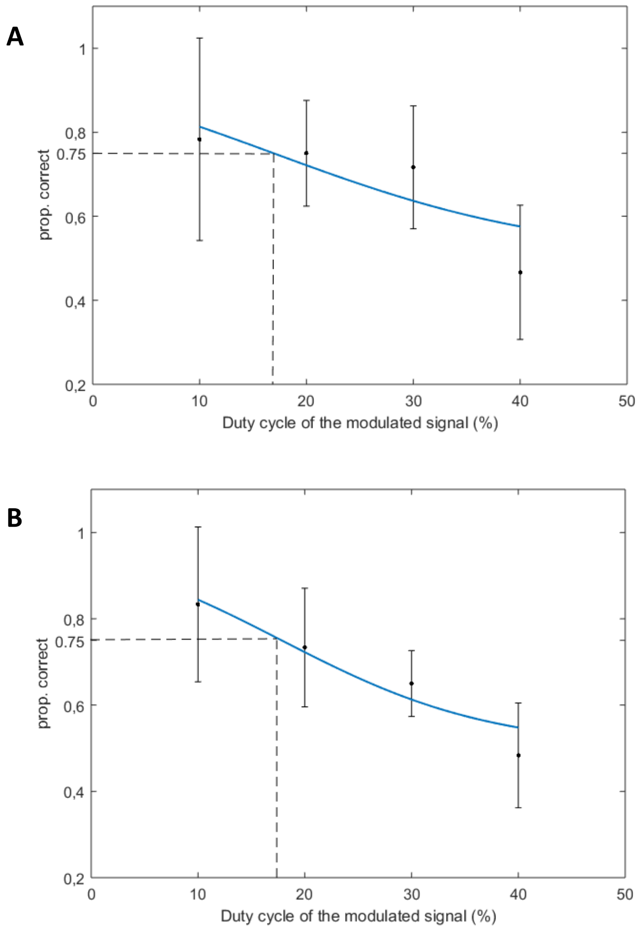


Figure 17. A) JND of duty cycle at 10 Hz modulation B) JND of duty cycle at 80 Hz modulation

4.1 Discussion

This section first discusses the impacts of the experiment's results on UL power consumption. A second part describes the improvements and future work to complete and validate the proposed control scheme.

4.1.1 Impact on energy consumption

The results presented in section 4.5.2 show that reducing the duty cycle of a friction modulation signal is not always perceivable by the participant. Moreover, these JND values represent a reduction relative to a standard duty cycle of 50% of respectively 67, 65, 78 and 65% for modulation frequency of 10, 20, 40 and 80Hz.

As described in section 4.3.2, the UL device power consumption is reduced linearly with the application of smaller duty cycles. The results show a stable reduction of the duty cycle across the studied frequency spectrum. The modulation frequency does not seem to impact the duty cycle JND.

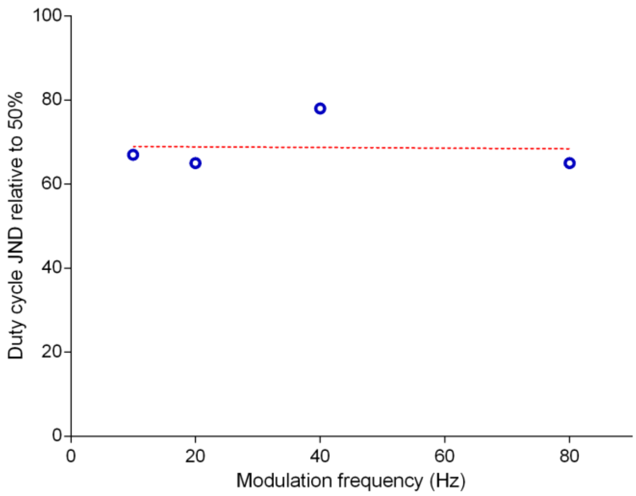


Figure 18. JND of the duty cycle in function of the modulation frequency. JND is relative to a standard duty cycle of 50%. Dotted line represents the mean JND across the spectrum.

An average of 68.8% power reduction is available across the 10 to 80Hz modulation frequency without perceivable difference to the participant. It is to be noted that this reduction of power consumption should be also similar for electrostatic devices since the usual approach is to apply an amplitude modulated sinusoidal voltage in active state.

The indistinguishability of signals under 2.45ms allow us to reduce a single pulse stimulation to the shortest possible without any difference to the tactile users. This limit could be used to reduce the power consumption in specific usage cases.

4.1.2 Perspectives

The JND of 17.5% found for 80Hz represent burst of 2.13ms which is consistent with the indistinguishability of signals under 2.45ms shown in section 4.5.1. This limit of indistinguishability could mean a modification of the relationship shown in Figure 18 for higher modulation frequencies. The range of modulation frequency (10 to 80Hz) in the current paper is limited by the time response of the haptic stimulator. To solve this issue a second haptic stimulator with a smaller time response will be designed to reach a modulation frequency closer to the 500Hz of human perception. This device will allow us to estimate the limits of human perception of the friction modulation and ultimately relate it to perceptual bandwidth of the fingertip mechanoreceptors.

The results presented in this paper are currently limited to 5 participants. These results will be validated in a subsequent study with a larger number of participants. Ultrasonic lubrication and electrovibration do not have the save power consumption while in active state. The current paper uses a device based on Ultrasonic lubrication as a proof of concept for the proposed texture simulation strategy. Further study will measure precisely the energy saving that can be expected for both technologies.

4.2 Conclusion

A general control scheme based on human perception to reduce power consumption in friction modulation devices is introduced. The results are validated using psychophysics measures on an ultrasonic lubrication device. A power reduction of up to 68.8% is confirmed for an ultrasonic device across the 10 to 80Hz range of modulation studied.

4.3 Acknowledgements

This work was founded by the FP7 Marie Curie Initial Training Network PROTOTOUCH, grant agreement No. 317100. This work has been supported by IRCICA USR 3380 Univ.Lille - CNRS (www.ircica.univ-lille1.fr)

4.4 Addendum to chapter IV

For the psychophysical evaluations performed in chapter three, the fitting of the psychometric function was implemented using a logistic function with a maximal asymptotic value of 1. This parametrization assumes that for highly over-threshold intensities of ultrasonic lubrication, the friction reduction is always perceived. However, the psychophysical results from the study conducted in chapter IV and in Annex II showed that even at high intensities, there is a consistent lapse rate around 5% that might be caused by natural friction fluctuations like stick-slip or sudden excess of sweat. Participants probably mistake these natural fluctuations for the signal that they are asked to detect and are hence biased by them.

Thus, we re-implemented the psychometric fitting with all parameter identical except for the lapse rate at high intensities, which was allowed to take values between 0 and 5% and replotted the psychometric function for the tested frequencies of modulation: 10 Hz, 20 Hz, 40 Hz and 80 Hz (See Figure 19). The results from this more accurate fitting are significantly different than previously and the reductions at threshold are respectively 40.6%, 57.2%, 78.8% and 59.6% (See Figure 20) compared to the reference displaying a U-shape rather than a straight line. It was hypothesised that differences in duty cycle would be more perceivable at low frequencies since the difference in the duration of the ultrasonic signal would play a more prominent role than at high frequencies. It is unclear why the reduction at threshold would decrease for 80 Hz compared to 40 Hz but the observed trend would need to be further validated for a larger pool of participants before performing a detailed analysis of the contact mechanics. However, differences probably stem out from the specificities of the mechanoreceptor's receptive fields and the respective contribution of the four psychophysical tactile channels.

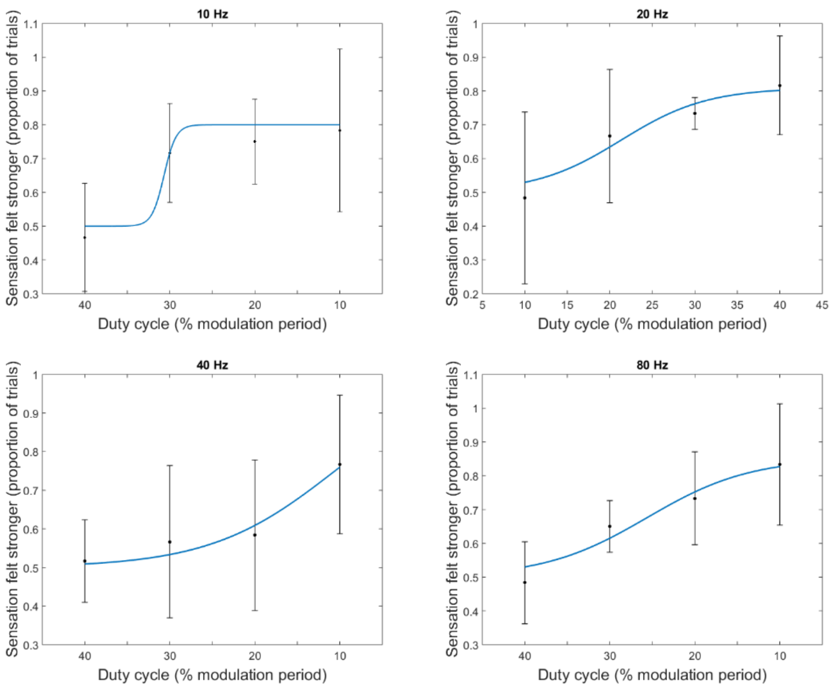


Figure 19. Psychometric functions associated with the discrimination rates of the shorter duty cycles (40%, 30%, 20% and 10%) from the reference standard (50%). Four conditions with different modulation frequencies have been tested: 10 Hz, 20 Hz, 40 Hz and 80 Hz.

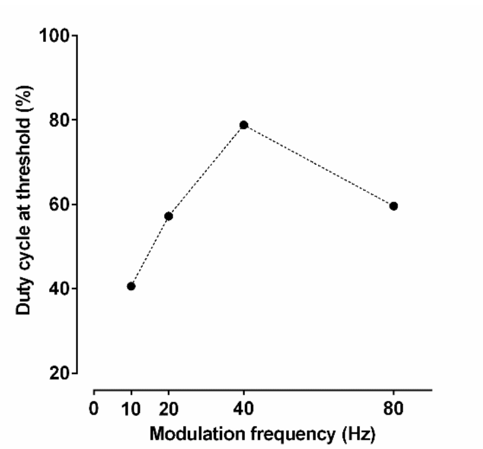


Figure 20. The reduction of the duty cycle at the psychophysical threshold is plotted against the modulation frequency and was found to follow a U-shape curve.

5 CHAPTER V: General discussion and perspectives

5.1 Peripheral versus central pathways

In the first experiment performed for this thesis, we were able to confirm the classic results on the vibrotactile adaptation of mechanoreceptors. Indeed, we were able to decrease selectively the sensitivity of the fast adapting type I and II mechanoreceptors to vibrotactile stimuli after 8 minutes of prolonged exposure to an over-threshold stimulus. We used two frequencies, 51 Hz and 251 Hz, and showed a stronger adaptation for 51 Hz, which adapted both FA-I and FA-II afferents while 251 Hz predominantly adapted the FA-II. Then, we performed several additional experiments by sending the adapting frequency directly to the median nerve through electrical stimulation in order to bypass the mechanoreceptors' transduction of the vibrations. The prolonged electrical stimulations did not affect the vibrotactile threshold, which supports the hypothesis that vibrotactile adaptation predominantly affects the transduction function of the mechanoreceptors.

5.1.1 Implications for tactile processing at cortical level

Adaptation has been extensively studied at peripheral level with identical testing and adapting stimuli. Thus, the role of vibrotactile adaptation to adapt the mechanosensitive afferents at peripheral level is well-know and documented (Bensmaia, 2005; Berglund and Berglund, 1970; Hahn, 1966; Hollins et al., 2001; Leung, 2005). Our study represented an attempt of using this technique to investigate peripheral and cortical determinants of vibrotactile adaptation. Its outcome supports the view that the somatosensory cortex is not a mere projection of the tactile coding at peripheral level but a different level of computation relying on functional features of the stimuli (Saal and Bensmaia, 2014).

A compelling result in favour of the peripheral hypothesis was that the electrical detection threshold remained unaffected after prolonged mechanical adaptation since it was a fair possibility that the electrical stimulus was too unnatural to trigger habituation in the neurons of the somatosensory cortex. However, the unchanged detection threshold of electrical stimulations confirms the hypothesis that vibrotactile adaptation mainly occurs in the mechano-transductory part of the afferents (Bensmaia, 2005) and that somatosensory neurons perform a qualitatively different processing than peripheral mechanosensitive afferents.

Based on these results, the use vibrotactile adaptation in future studies might be questioned since its influence at peripheral level is known and it does not seem to apply to central tactile processing. However, a couple of studies performed in the 90's found that adaptation can also influence higher-level tasks. They showed that thresholds for discrimination of frequencies and amplitudes were enhanced rather than impaired (Goble and Hollins, 1994, 1993). This is consistent with cortical neurons recruiting signals from many afferents of different types and performing better when afferents not involved in the task are adapted. A potential application of adaptation would therefore be to modulate the specific contribution of each afferent in order to alter the perception of higher level tactile features. This technique could complement electrophysiological studies of primates' somatosensory neurons, which are complex to undertake and face ethical constraints. It could be used to validate the observed cortical processing of the signals coming from peripheral afferents by reproducing the experiments under adaptation of specific afferent types.

5.2 The perceptual value of transient frictional cues

5.2.1 Implications for the neuroscience of touch

Out of the everyday observation that Glass and Plexiglas intuitively feel different while their surface properties are very similar. We were interested to find out if when the other haptic cues (compliance, density, thermal properties, visual aspect) are controlled, participants would still be able to discriminate between the surfaces. Participants found the task very difficult but their ability to discriminate was unquestionable, although no difference could be found in the dynamic coefficient of friction of the two materials. We found differences between the contact forces with the two materials only during the early stages of the exploratory motion. This suggests that the micro-slips, which occur when the fingertip starts its motion, contribute to our tactile experience of materials. The importance of initial forces is well-known in motor control where the capacity to dexterously perform the manipulations was shown to rely on rapid feedback loops (Nashed et al., 2012) while such a method has not yet been proposed to study tactile exploration. Moreover, our results are consistent with FA-I mechanosensitive afferents (which are the most numerous) responding predominantly during quick changes in friction (Johansson and Flanagan, 2009) while they respond less when the coefficient of dynamic friction is stabilized.

The perceptual importance of the onset of exploration and the proposed method for epoching tactile exploration in three distinct phases (loading, partial slip of the contact area and full sliding) open a new perspective for the investigation of the tactile exploration of textures. Textures are usually classified on the basis of their frequency spectra during stable exploration (Klöcker et al., 2013; Manfredi et al., 2014) but our results suggest that important cues are available at the onset of exploration, which are potentially important for tactile perception of textures. Epoch-specific analysis and classification of the signal could unravel new differences between the textures and new explanations for the subjective perceptual dimensionality of tactile experiences.

5.2.2 Implication for haptic technologies

Applications of friction modulation in tactile displays with haptic feedback usually focus on creating spatial areas or temporal intervals on the screens that correspond to various functions of the tactile display (button, different applications, error messages...). Current haptic displays are developed on the basis of the current knowledge of the stable dynamic tactile sensing of gratings and textures (Biet et al., 2008). In consequence, their design require from the user to use stable dynamic touch in order to experience the optimal sensation provided by the tactile display.

This approach overlooks the forming of the contact between the fingertip and the screen as well as the onset of the exploratory movement. Therefore, possibilities of fast and repeated interaction like tapping on interactive buttons are still limited. In this thesis, we showed that early frictional cues have perceptual value and could therefore be used to implement more efficient haptic feedback. In fact, such a technology is currently under development in the lab of Michael Wiertlewski who presented it at World Haptics 2015 (Monnoyer and Wiertlewski, 2015). Friction was undergoing fast modulation during the making of the skin-screen contact and created a sensation of tapping a physical button. This new type of haptic feedback shows that the human ability to sense frictional cues during the onset of haptic interaction can be used to develop novel and more efficient tactile technologies.

5.2.3 Perceptual optimization of a tactile display with haptic feedback

In chapter III, we performed psychophysical optimization of a newly developed tactile display (TD) with haptic feedback. A common pattern implemented on TD's are virtual gratings with different spatial or temporal periods; each period usually consists in 50% natural and 50% reduced tangential force. We hypothesized that for these stimuli the important perceptual parameters are the sharpness and amplitude of the frictional changes and the period of the virtual grating. Thus, we decreased by steps of 10% the duration of the intervals of reduced friction from 50% of the grating's period, which we took as reference, down to 10% of it. We tested if the modified virtual grating was perceptually equivalent to the reference. The results showed that reduced friction during 17% of the grating's period provides the same sensation as the reference (50% of reduced friction within one period). Since energy consumption was found to be linear, the virtual gratings with smaller intervals of reduced friction produced the same tactile sensation while using 50-70% less power. This kind of optimization is very useful for industrial applications of haptic feedback since saving energy is crucial to make a technology usable in portable devices.

This outcome highlights the role of a fundamental knowledge of the perceptual principles related to a technology to efficiently direct the development efforts. The next step is to characterize more accurately the complex mechanics occurring during the modulation of friction and assess their importance for tactile perception. A more complete understanding of the tactile perception of transient changes of friction will enable to deliver more natural haptic feedback at the edge of the virtual frictional patterns, which are currently overlooked.

5.3 Perspectives for the investigation of human perception of frictional cues

5.3.1 Creation of an integrated framework to study tactile interactions

Friction was until recently considered of a secondary importance for tactile perception compared to the surface topography and the temporal and spatial codes mediating it (Manfredi et al., 2014). However, smooth surfaces made of very different materials are not uncommon in our environment and we deal with them without difficulty in our everyday life. Thus, a better understanding of interactions with smooth surfaces is needed to complete our knowledge of human tactile perception. Several methods have recently been implemented to characterize the frictional properties of touch. Some of them are promising attempts to represent topography, vibrotaction and friction in a common framework (Meyer et al., 2016; Michael Wiertlewski et al., 2011). The development of such a framework has the potential to create a common theory for the different types of tactile interactions.

5.3.2 Future perspectives for friction modulating devices

A major reason for the limited knowledge of frictional properties was that it was technically challenging to study. Although the micro-design of a surface or well controlled vibrotaction bear their own challenges, it has been for a long time impossible to change the friction of a surface without introducing an external product at the interface (oil, talc…). The devices modulating the friction of materials with high spatial and temporal resolution are therefore becoming extremely useful research tools. At the start of the project, a shortcoming of these devices was that external factors like the specific properties of each finger or the temperature could influence the amplitude of vibration. It made the stimulation hard to reproduce reliably within a large pool of participants. The new version of the STIMTAC device, which was developed for the experiment in Annex II, include an internal controller for the amplitude of the ultrasonic vibration and well calibrated time-response of the plate. Thus, it became possible to calibrate a desired set of stimuli and reproduce them with a high precision for a large number of participants. In addition, different materials can be glued on the screen without altering its ability to modulate friction. It has therefore become a reliable tool to evaluate the parameters governing the human perception of frictional cues (amplitude of the change, duration, rate of modulation…). This new technology has already been used for the studies presented in chapter IV and Annex II of this thesis.

5.4 Future work following this PhD thesis

This PhD thesis provided new insight in the pathways processing tactile signal and our perception of frictional cues. The studies composing it answered interesting scientific questions and simultaneously opened new ideas and hypotheses. In Chapter II, the electrical and mechanical adaptation to pure frequencies was thoroughly investigated and showed no central component. Nevertheless, participants experienced paraesthesia and a decrease in the subjectively perceived magnitude. If I had to do a follow up study, I would focus on more natural adaptive and testing stimuli and on a psychophysical evaluation based either on the subjective perception of the intensity or on more cognitively demanding tasks. In Chapter III, we showed a correlation between the frictional differences at the onset of the exploratory movement, especially during partial slip, and capacity to discriminate. However, the one-dimensional force signal has the limitation of averaging the complex multi-dimensional patterns taking place in the contact area. A better understanding of the perceptual implications of partial slip in the contact area would require to record the same perceptual task with a high-speed camera located under the sample. The potential results of these future investigations could also contribute to explain the psychophysical results of the study presented in Chapter IV although these are still preliminary and need further validation with a larger number of participants.

5.5 Final remarks and perspectives for the field of touch

The field of touch has undergone several revolutions in the last 15 years. Many new perspectives were opened about temporal codes mediating touch, the resolution of tactile sensitivity, the importance of interfacial forces, remote coding in upper locations of the hand, functional selectivity of cortical neurons, the temporal scales impacting friction or novel cues for proprioception. Nevertheless, a large number of these studies do not include state of the art psychophysical assessment of the perceptual values of the phenomena that they investigate. This is probably due to the complexity of the equipment needed to deliver well-controlled haptic stimuli. Because of this technical complexity, many studies are performed in engineering labs, which have the technical expertise to develop the setups. On the other hand, they often do not have an easy access to human participants and lack in depth expertise of psychophysical methods. Therefore, further development of the field of touch will require more interdisciplinary and collaborative studies that combine engineering capacity and experimental skills in order to complement the precise measurements with the psychometrics related to these phenomena.

6 ANNEX I: Free tactile exploration optimizes frictional differences between smooth materials to improve their discriminability

(Adapted from the work-in-progress paper: *Free tactile exploration optimizes frictional differences between smooth materials to improve their discriminability*, presented at Haptics Symposium 2016 by David Gueorguiev, Séréna Bochereau, André Mouraux, Vincent Hayward and Jean-Louis Thonnard)

6.1 Summary

Touch is incredibly sensitive at capturing and transmitting the features of the textures with which we interact every day. While tactile discrimination of surfaces with differing geometry has been proven possible up to the nanoscale level, the capacity of the chemical properties of materials to affect tactile perception has been less studied. However, recent studies have shown that chemistry of the material can influence contact mechanics especially after a prolonged interaction. This led us to investigate the tactile perception of optically smooth surfaces made of glass and PMMA. Our results show that, for these two materials, the exploratory strategy has a significant impact on the interfacial friction and that the created differences contribute to the tactile sensation of the material.

6.2 Introduction

Tactile sensation plays a key role in our interaction with the world around us. We need to constantly assess the nature of the materials with which we are in contact in order to perform most of our everyday tasks. It is known that the fingertip is very sensitive to geometric features (Weber et al., 2013) and can sense surface features even at the nanometric level (Skedung et al., 2013). However, many materials that we manipulate daily like glass, plastic or synthetic fabrics are smooth yet feel different due to specific chemical properties that affect the friction at the interface between the finger and the surface (Dinç et al., 1991). There is evidence that these cues are used for perception (Smith and Scott, 1996) and that the local friction can evolve with time during tactile exploration because leading to phenomena like occlusion or stick-slip (Adams et al., 2013; Andre et al., 2011). The purpose of this work is to study the tactile perception of two smooth surfaces, one hydrophobic (PMMA) and one hydrophilic (glass) and to investigate if their perception and frictional properties are influenced by the exploratory strategy of the participants.

6.3 Material and Methods

6.3.1 Participants

Data were collected from 24 healthy volunteers aged between 22 and 52 (12 in experiment 1 and 12 in experiment 2). Written informed consent was obtained from each participant. Participants were blindfolded and white noise was played through headsets in order to mask auditory and visual cues. The study was approved by the local Ethics Committee.

6.3.2 Stimuli

The two material samples were made of ordinary glass and PMMA. Both optically flat materials were chosen for their differences in atomic structure and hydrophobicity. Glass has a hydrophilic amorphous non-crystalline solid atomic structure with a thermal diffusivity of 3.4×10^{-7} m^2/s and PMMA is a hydrophobic transparent polymer with a thermal diffusivity of 1.1×10^{-7} m^2/s. The temperature of the samples was kept identical by bonding them on 1.0 cm thick aluminum plates in order to even out their thermal properties (Jones and Berris, 2003).

The plates were fixated on specifically designed force transducers to measure the normal force (NF) and the tangential force (TF). In experiment 1, the plates were warmed at 33±0.9°C while in experiment 2, they were kept at 23.5±1.5°C. In both experiments, the contact forces between the finger and the samples were processed by using identical MATLAB scripts.

6.3.3 Psychophysics

The participants washed their hands with commercial liquid soap and waited five minutes before starting the task in order to stabilize the skin's frictional properties. The task comprised 42 consecutive trials, where three randomly placed samples were presented to the participant (either two samples of PMMA and one sample of glass or one sample of PMMA and two samples of glass). For each trial, participants were asked to explore the three samples and report which of the samples was different from the two others. In experiment 1, samples were to be explored with a single stroke from left to right but participants had the opportunity to repeat the constrained exploration up to five times by trial before reporting a judgment. In experiment 2, participants were able to freely explore each sample as many times as they wanted and in any order as long as they avoided static touch. The experiment was divided into three blocks of fourteen trials. Before and after each block, the humidity level of the fingertip was assessed with a corneometer (CM 825, Courage + Khazaka electronic GmbH, Germany).

6.4 Results

6.4.1 Psychophysical results

Performance at the discrimination task was significant in both experiments and despite a slight trend, no significant difference between the two experiments was found in the overall task performance (unpaired *t*-test, $p = 0.14$). We then sorted the trials by their target material and we observed that, in experiment 2, participants performed significantly better at identifying a sample of PMMA among two samples of glass as compared to identifying a sample of glass among two samples of PMMA (paired t-test: p-value = 0.0015) (Figure 1b). No such bias was observed in experiment 1 where exploration was constrained to distinct unidirectional strokes (Figure 1a). We checked for a possible imperfection of the plates that could have induced the bias but we did not find any.

The comparison between the fingertip's humidity of the participants from the two groups showed no difference between their distributions and could not explain the occurrence of a bias between the perception of the hydrophobic and hydrophilic material.

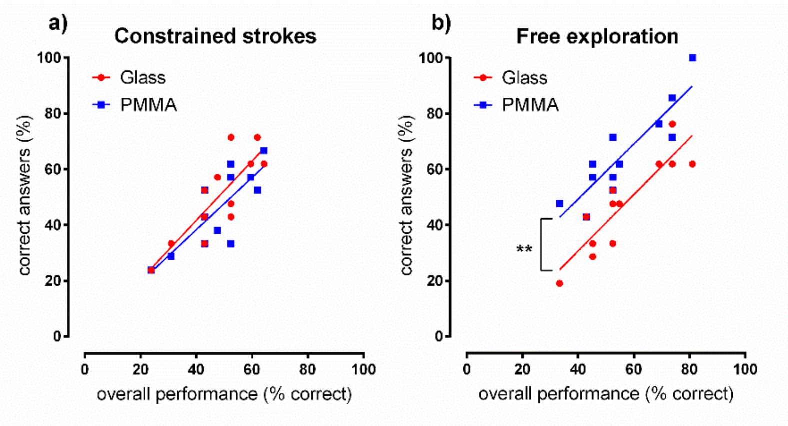


Figure 1. Material specific performance. a) In experiment 1, the target material of the trial does not influence the performance. b) The performance at the task in experiment 2 is significantly better when the target is PMMA (paired t-test: p = 0.0015).

6.4.2 Contact mechanics

The normal and tangential force data were analyzed for each exploration and the dynamic coefficient of friction (COF) was computed as the ratio between the two forces, for all trials of both experiments. Tactile exploration was considered as occurring when the NF was above 0.05 N. Then, for each trial we computed the mean of the COF and its variance throughout the exploration for both materials. When participants performed a constrained exploration (experiment 1), the COF of PMMA and glass showed no difference neither for the mean or the variance (Figure 2a). In contrast, when participants performed a free exploration of the two surfaces (experiment 2), both the mean and the variance of the COF were significantly different between the two materials (Wilcoxon paired signed-rank test $p < 0.001$) (Figure 2b), with PMMA displaying higher values than glass.

The observed perceptual bias during free exploration might therefore be triggered by the higher proportion of large COF values or large COF variance values for PMMA as compared to glass, thus making PMMA more salient. To study whether these differences in COF could explain the difference in the ability to discriminate the two textures in the two experiments, we removed the trials in which the exploration was characterized by COF mean or variance values greater than the median COF mean or variance. After removing trials showing greater COF mean values, the perceptual bias towards improved detection of PMMA in Experiment 1 was no longer significant (paired t-test: $p = 0.06$). In contrast, after removing trials showing greater COF variance, the bias remained similar (paired t-test: $p = 0.0006$). However, more refined analyses are necessary to better understand the relationship between the perception and the underlying forces. Furthermore, the possible contribution of the temperature of the plates needs to be more adequately addressed in an additional experiment.

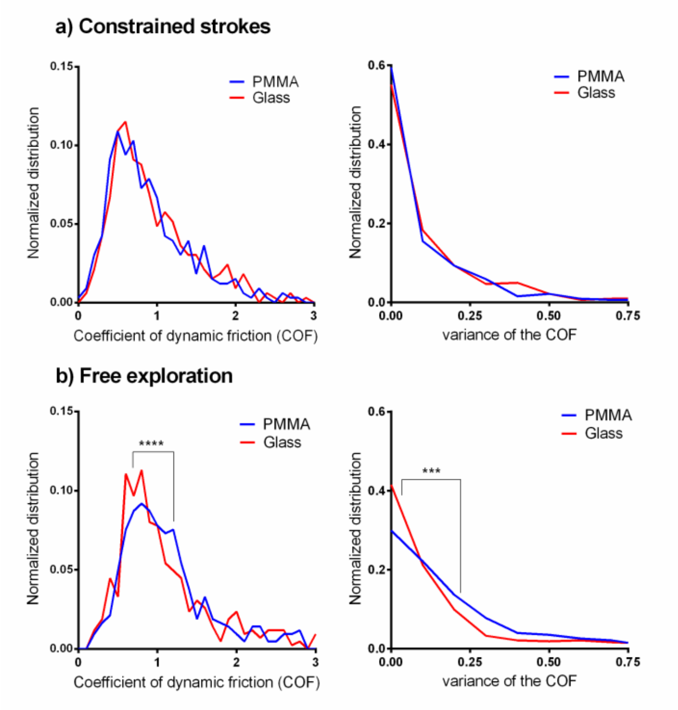


Figure 2. a) In experiment 1, the distributions of the COF and its variance are undistinguishable between the two materials b) in experiment 2, the two distribution differed both for the mean (Wicoxon matched-pairs signed-rank test $p < 0.0001$) and variance ($p = 0.0007$). The hydrophobic surface (PMMA) exhibited higher values than the hydrophilic one (glass).

6.5 Conclusion

These results confirm that the friction induced during tactile exploration of smooth materials can change during a prolonged tactile exploration. It is probable that most participants intuitively adopt a strategy that enables them to optimize the frictional differences between the fingertip and the materials during free exploration even if some additional investigation is still needed to validate this hypothesis.

7 ANNEX II: The human perception of transient frictional modulation

(Adapted from the work-in-progress paper: The human perception of transient modulation of friction, for Eurohaptics 2016 by David Gueorguiev, Eric Vezzoli, André Mouraux, Betty Lemaire-Semail and Jean-Louis Thonnard)

7.1 Summary

The frictional forces that we experience while exploring and manipulating everyday objects and textures around us has been repeatedly shown to be a crucial component of our tactile perception. In this study, we take advantage of transient pulses of ultrasonic vibration with stabilized amplitude delivered in controlled passive touch condition to study the human perception of subtle frictional cues. Our results show that humans are able to perceive very small transient changes in friction modulation. On average, the threshold corresponded to an 8% change in friction relative to baseline. However, thresholds differed by up to a factor three across participants.

7.2 Introduction

A more realistic haptic feedback will be implemented in new generation tactile devices. A high fidelity technique for tactile rendering is yet to be developed, and the request for this technique is ever-growing. Different approaches are available to produce tactile sensations on a user fingertip. Among them there is the modulation of the friction of an active surface for a sliding finger. Finger position tracking mechanism allows the generation of a spatio-temporal relationship leading to the generation of texture (Biet et al., 2008). The modulation involves ultrasonic vibrations to reduce the sliding friction between the contacting finger pad and the display (Sednaoui et al., 2015b). The effectiveness of the principle to modulate friction is not in doubt and has been preliminary estimated in a recent study (Samur et al., 2009), but a precise study on the influence of various parameter on the perception and friction modulation of this device has never been performed. This is essential to understand the technological requirements to provide an effective stimulation to the users and to test the validity of different proposed mechanisms. In this paper, the influence of amplitude of vibration and nature of explored surface to the human perception threshold will be investigated in controlled experimental conditions.

7.3 Materials and Methods

Data were first collected from 12 healthy volunteers aged between 27 and 53. Gaussian white noise was played at a comfortable listening level through headsets in order to mask auditory cues.

We used a full custom robotic platform designed to apply a controlled stimuli to the fingertip in passive touch condition similar to the one presented in (Moungou et al., n.d.). The subject's index finger was fixed in a support that maintains a constant angle of approximately 20° between the finger and the stimulating plate, which is a typical angle adopted during grasping and tactile exploration. An ATI Nano 43 (ATI, USA) load cell was mounted on the robot and served for controlling the normal force applied by the robot as well as for recording the interfacial forces occurring during the presentation of the stimuli against the fingertip.

The friction was modulated with a novel tactile display integrated with the acquisition and control chain of the robot. The display is based on a modified version of the STIMTAC (Amberg et al., 2011), where the full body of stimulator has been modified to be mounted on the force sensor of the robot and the vibration amplitude of the device was controlled in closed loop. The implemented control ensures the stability of the vibration with a resolution of 50 nm with different surfaces glued and a vibration rise time of 1.5 ms. For this study, three materials were used at the skin-plate interface in separate blocks: the bare aluminum plate of the device, a glued polypropylene (PP) sheet and a glued polyurethane (PU) sheet. These materials were chosen to investigate the effect of different frictional properties of the materials on the participant's capacity to sense the modulation of the tangential force. Aluminum (hydrophilic) and PP (hydrophobic) have similar dynamic coefficients of dynamic friction (CF) but differ by their bonding of water molecules while PU has typically a higher CF and is hydrophobic.

The study was made in passive touch conditions. The robotic platform was programed to deliver a precise stimulation of the fingertip. The stimulation consisted in a sliding of 5 cm at a speed of 2.0 cm/s and with a constant force of 0.7 N against the fingertip of the right index finger, which was kept at the precise same location by the finger holder of the robotic platform. At each trial, the platform performed two consecutive sliding against the finger. In one of the passages (randomly chosen), ultrasonic vibrations were displayed for two intervals of 100ms, which were programmed to precisely start at 22 mm and 25 mm of sliding (See Figure 1). Participants had to perform a forced-choice task to find out in which of the passages was the signal. The stimulation levels were 0.1, 0.2, 0.3, 0.5, 0.7 µm and each of them were pseudo-randomized and presented 10 times within a 50 trials long session. The 75% jnd was then computed by fitting a logistic psychometric function to the proportion of correct response compared to the level of stimulation. The fitting was done using PALAMEDES toolbox (Kingdom and Prins, 2009). The relative reduction of friction was computed for each trial by comparing the ratio between the tangential force (TF) averaged over the 100 ms preceding the start of each of the two ultrasonic pulse and the corresponding averaged TF over following interval with reduced friction.

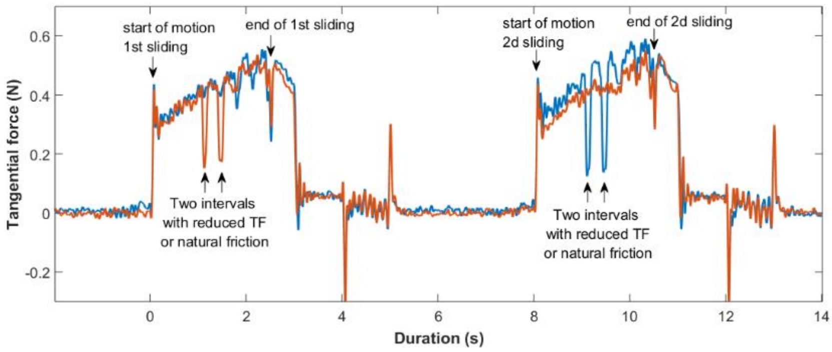


Figure 1. Participants performed a forced-choice task in which they had to decide which of two consecutive trials contained the transient change in friction. The tactile display slided against the finger twice per trial. The transient reduction of tangential force, which participants had to detect, was applied either in the first sliding (red trace) or in the second one (blue trace).

7.4 Preliminary results

7.4.1 The 75% just noticeable difference of the amplitude of vibration

For each of the three materials used in the experiment, we evaluated the 75% jnd for all participants in order to obtain an estimate of the human ability to perceive applied modulations of friction. We first computed the mean thresholds for each material separately and found out the average a 75% jnd for the amplitudes of ultrasonic vibration to be respectively 0.24 ± 0.15 µm, 0.27 ± 0.09 µm and 0.31 ± 0.11 µm (mean ± s.d.) for the aluminium, polypropylene and polyurethane (See Figure 2). We then ran a non-parametric 1-way ANOVA test between the three different conditions justified by the non-normal distribution of the thresholds. Surprisingly, despite the different properties of the three materials, the thresholds did not differ depending on the interfacial material (Friedman test: $\chi^2 = 3.957$, $p = 0.14$).

7.4.2 Computing the relative reduction of TF at the threshold

We then mapped the amplitude of vibration at the threshold to the corresponding relative reduction of tangential force. The value of the relative reduction of friction at the threshold vibration amplitude was obtained by intercepting it with the actual reduction of TF obtained by linear interpolation of the average reduction of TF recorded for the nearest levels of vibration up and down the threshold value.

The results show that, at the threshold, the percentage of the TF's relative reduction is 8.4 $\pm$ 6 % for aluminum, 6.9 $\pm$ 4.1 % for polypropylene and 8.0 $\pm$ 4.6 % for polyurethane.

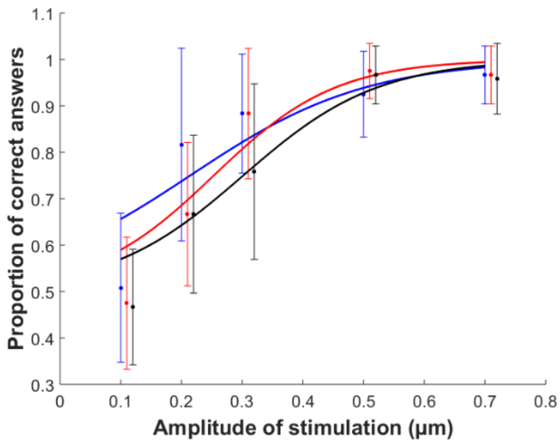


Figure 2. Psychometric curves and corresponding error bars for aluminium (blue), polypropylene (red) and polyurethane (black) fitted to the proportion of correct answers for each stimulation level (mean $\pm$ s.d.). The error bars are slightly shifted for better visibility.

7.5 Conclusion

Although it is known that the frictional properties of surfaces are well perceived during tactile exploration (Smith and Scott, 1996), very little is known about the minimal modulation of friction necessary to elicit a difference in tactile perception. In this study, participants demonstrated an extremely fine discrimination of ultrasonically induced transient frictional cues with different surface materials. A mean discrimination of the 8% of the frictional value was perceived by the users.

8 References

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