THE SOOTHING FUNCTION OF TOUCH:
EXPERIMENTAL AND NEUROIMAGING STUDIES

Mariana von Mohr Ballina

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I, Mariana von Mohr Ballina, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Abstract

Social bonding and support are important for human wellbeing. Close social bonds have long been known to serve safety and distress-alleviating functions. Interestingly, evidence from non-human mammals suggests that it is not the mere presence of conspecifics but rather certain active behaviours that are important for affective regulation. However, little is known about how active interpersonal supportive behaviours can buffer physical and psychological threat (e.g., pain) in human mammals. Recent evidence suggests that a specific type of dynamic, low-pressure touch that is associated with the activation of a particular type of peripheral touch receptor may be a particularly effective form of active social support. This type of touch is termed affective touch and this thesis aimed to examine its role on the social buffering of pain.

Three experimental studies examined the modulatory role of affective touch on different forms of bodily and psychological threat, including social pain due to ostracism (Study 1), physical pain delivered by a laser device (Study 2), and the immediate space surrounding the body critical for triggering defensive reactions in the face of threat (Study 3). Given that the perception of bodily threat depends on prior beliefs about interpersonal relating, we examined whether the effects in study 2 and 3 were moderated by attachment style. On this basis, one experimental study also examined whether sensitivity to affective touch itself depends on individual differences in attachment style (Study 4). A fifth study presented a novel way to assess affective touch accuracy and meta-cognitive awareness (Study 5).

Findings suggest that affective touch is a potent form of active social support, capable of attenuating pain. However, such effects were moderated by attachment style and depend on social context. Findings are discussed within a recent, Bayesian predictive coding theory of brain function, namely the Free Energy Principle, that allows to put forward a unifying model of bottom-up and top-down determinants of pain and affective touch, while emphasizing the interdependence of perception, action and relevance of social factors.

Impact Statement

This work has provided significant behavioral and neurophysiological insights into the social modulation of pain. Such novel findings were generated by combining methods from normally independent domains of psychology and neuroscience, namely social psychology, cognitive neuroscience and the psychophysics of tactile perception. As such the scientific gains of this work are expected to be high and far-reaching in the aforementioned disciplines, but also more broadly in neuroscience, psychiatry and the humanities. Indeed, solely the first peer-reviewed publication arising from this thesis was well received by both the scientific and public community, being among the 100 most read articles published in *Scientific Reports – Nature* in 2017, a year that the journal published more than 24,000 articles, and receiving significant, international media attention, including a live interview at Sky News.

More generally, this thesis has provided the necessary neural and behavioral data to extend this line of work to clinical populations, with the potential of leading to new treatments and prevention programmes using embodied forms of social support. In fact, the affective-motivational aspects of CT-optimal affective touch have begun to be applied to the perception and potential treatment of eating disorders. In addition, the current work can have substantial impact on the field of mood disorders, including depression and anxiety, where this form of social support can potentially attenuate associated psychological and physiological reactions.

This work further highlights the critical role of tactile interactions in our daily life. This is particularly important given that our social world is becoming increasingly visual and digital and as such, it is easy to forget the power of touch in human relations.

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Peer-reviewed publications arising from this thesis to date

von Mohr, M., Krahé, C., Beck, B., & Fotopoulou, A. (2018). The social buffering of pain by affective touch: A laser-evoked potentials study in romantic couples. *Social cognitive and affective neuroscience*. *13*(11), 1121-1130.

von Mohr, M., & Fotopoulou, A. (2018). The cutaneous borders of interoception: active and social inference on pain and pleasure on the skin. In M. Tsakiris & H. De Preester (Eds.), *The interoceptive mind: from homeostasis to awareness*.

Krahé, C.*, **von Mohr, M.*,** Gentsch, A., Guy, L., Vari, C., Nolte, T., & Fotopoulou, A. (2018). Sensitivity to CT-optimal, Affective Touch Depends on Adult Attachment Style. *Scientific reports*, *8*(1), 14544.

von Mohr, M., Kirsch, P. L., & Fotopoulou, A. (2017). The Soothing Function of Touch: Affective Touch Reduces Feelings of Social Exclusion. *Scientific Reports*. *7*: 13516

Chapter 1

Introduction

1.1 Overview of this chapter

Although there are many ways to provide active support, recent experimental studies (Kirsch et al., 2017) and corresponding theoretical reviews (Fotopoulou & Tsakiris, 2017; Morrison, 2016) suggest that a particular type of relatively slow, dynamic, low force stroking touch is a particularly effective and salient embodied form of communicating active, social support. Critically, this specific type of touch is thought of as being primarily mediated by a separate, specific neurophysiological system, namely the C-Tactile (CT) system, and termed ‘affective touch’ given its positive affective value well tuned to CT activation (McGlone, Wessberg, & Olausson, 2014). Accordingly, the present thesis aimed to examine the buffering role of affective touch on three different forms of bodily and physical threat: The first corresponds to social pain due to ostracism; the second to physical pain administered by a laser device; and the third to the perception of approaching stimuli in peripersonal space, which is considered critical for triggering defensive behaviors. Nevertheless, given that both the perception of pain as well as the perception of social support depends on prior beliefs about interpersonal relating, this thesis also took individual differences in attachment style into account. To address these aims, the current thesis used methods from experimental psychology and social cognitive neuroscience, and drew on a variety of research traditions to combine some of their insights in a novel interdisciplinary way. The following sections of this introductory chapter will first briefly outline the current literature on physical and social pain, as well as different socio-contextual factors that have been shown to modulate it (section 1.2). Next, it will review the current literature on the sensory, affective and social aspects of affective touch (section 1.3). Finally, it will describe recent evidence on how individual differences in dispositional factors that can modulate both the perception of pain and social support (section 1.4). The chapter ends with a summary of the specific objectives of the thesis based on the main aims, and an outline of the following chapters (section 1.5).

1.2 The concept of pain in psychology and neuroscience

Pain is typically defined as "an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage" (International Association for the Study of Pain, 1979). In fields such as psychology and social neuroscience, pain is typically conceptualized as comprising sensory and affective-motivational dimensions (e.g., see Brooks & Tracey, 2005; Auvray, Myin, & Spence, 2010 for reviews) Accordingly, these two components of pain are commonly assessed using visual scales (or verbal labels) measuring pain intensity and feelings of unpleasantness/motivated actions to alleviate these feelings, respectively. In addition, recent postulations suggest an overlap between the physical and social pain system, with social pain implicating brain regions typically associated with the affective component of physical pain (Eisenberger, Lieberman, & Williams, 2003). Importantly, as it will be explored in the following sections, socially supportive behaviors can influence both social and physical pain. These insights, together with literature on the perception of immediate space surrounding the body, which is critical for triggering defensive behaviors in the face of bodily and psychological threat, will be reviewed below.

1.2.1 The peripheral and central neurophysiology of physical pain

Before reviewing this material, it seems appropriate to stress that here we will focus on the nociceptive aspect of cutaneous pain perception (i.e., the neural encoding and processing of actual or potential tissue damage) and not visceral, joint or muscle pain. While most research into the basis of cutaneous pain has been conducted on conscious humans and surrogate animal models (see Namer & Handwerker, 2009 for a review), our understanding has been obstructed given the difficulties inherent to study such processes in humans. Nevertheless, recent advances in neurophysiological methods, in combination with psychophysical measurements, have proved valuable into our understanding of nociceptors (i.e., peripherally localized neurons sensitive to noxious stimuli) in non-human and human mammals.

Surrogate animal models and human studies have revealed that nociceptors are distinctive afferent units rather than the extremes of a single class of receptors with a continuum of features (reviewed by Marks, Ringkamp, Campbell, & Raja, 2006). While low-threshold, mechanoreceptive, or thermoreceptive afferent neurons cannot discriminate reliably between noxious and non- noxious (innocuous) stimulation, nociceptors can (Bessou, Burgess, Perl, & Taylor, 1971). These two classes of fibers also differ in their termination patterns in the spinal cord (Sugiura, Lee, & Perl, 1986) their membrane constituents (Caterina, Schumacher, Timinaga, & Rosen, 1997) and properties, including their action potential shape (Ritter & Mendell, 1992). Broadly, nociceptors can be divided into two types: A- (most in the Aδ- range) and C- fibers, which are mediated by myelinated fast (5–30 m/s) and unmyelinated slow (0.4–1.4m/s) conductive axons (Dubin & Patapoutian, 2010), corresponding to initial fast-onset pain (sharp pain sensation) and slow second pain (pervasive burning pain sensation), respectively. Nociceptors, particularly in musculoskeletal tissue, have been mostly thought to be electrically ‘silent’, transmitting all or no action potentials only when excited, and thus give rise to pain (Marks et al., 2006).

Different pathways on how the nociceptor is conveyed to the CNS have been suggested, including different spinal neural features and their functional role. First, an afferent volley is produced upon the activation of the nociceptor. The nociceptive volley travels along the periphery and enters the dorsal horn of the spinal cord (Brooks & Tracey, 2005) and mostly terminates in laminae I where they synapse with relay neurons and local interneurons important for signal modification (see Dubin & Patapoutian, 2010 for the specific role of laminae I, IV, and V in relation to A- and C-fibers). Via spinal ascending pathways (e.g., spinothalamic and spinoreticular tract) the relay neurons project to the thalamus and brainstem, which in turn project to large distributed brain networks (Dubin & Patapoutian, 2010). However, a different type of multimodal spinal neurons located deeper in the dorsal horn, namely the wide dynamic range (WDR) neurons, has also been implicated in nociceptive and pain-related mechanisms (Perl, 2007).

More generally, peripheral neurophysiological specificity does not seem to lead to a direct relation between nociception and conscious pain perception. While the activation of nociceptors and nociceptive pathways can lead to pain (Marks et al., 2006), it is also known that nociceptors can be active in the absence of pain perception and pain can occur without known nociceptive activity. Indeed, there have been observations of a lack of reported pain by soldiers during battle, despite severe injuries (see Perl, 2007), as well as experimental evidence suggesting that pain perception varies with psychological state and context (Head & Holmes, 1911; Melzack, Wall, & Ty, 1982). In fact, since the proposal of the influential “gate control theory" (inhibition of nociceptive excitatory signalling at the level of the spinal cord), and more recent insights regarding the heightened sensitivity of afferent signals at the same level, known as "central sensitization," it is widely accepted that although much pain is a consequence of stimulation of peripheral nociceptors, the CNS plays a major role in the processing of noxious sensations (Melzack & Wall, 1965).

Furthermore, more potent neuroscientific methods in recent decades have provided corroborating evidence for the critical, active role of the brain in the processing of noxious sensations (Ploghaus et al., 1999; Ploner, Freund, & Schnitzler, 1999; Rainville, Duncan, Price, Carrier, & Bushnell, 1997). For example, novel cortical stimulation studies have qualified Penfield's inability to detect 'pain cortical areas' (Mazzola, Isnard, Peyron, & Mauguire, 2012), functional neuroimaging studies indicate that noxious stimulation involves large distributed brain networks (J. Brooks & Tracey, 2005; Talbot et al., 1991). The so-called pain matrix has been subdivided into a medial and lateral pain system, based on their respective projection sites from the thalamic structures to the cortex. The lateral pain system involves the S1 and secondary somatosensory cortex (S2) and is thought to play a role in the sensory-discriminative aspect of pain (i.e. where is the stimulus and how intense it is?), whereas the medial pain system, including areas such as the anterior cingulate cortex (ACC), the insula, and the amygdala, is thought to be involved in the affective-cognitive aspect of pain. However, the insular cortex plays a role in facilitating the integration of information between the lateral and medial pain systems (Brooks & Tracey, 2005) and some studies suggest that the functional role of these areas may not be pain-specific but rather relating to the processing of all sensory-salient events (i.e., 'salience network'; see Legrain, Iannetti, Plaghki, & Mouraux, 2011). Moreover, the nervous system plays a critical role in regulating pain signalling. The existence of a descending pain modulatory system was early postulated by Head & Holmes (1911) and a theoretical framework was later on proposed with the "gate control theory" (Melzack & Wall, 1965). Current views of pain also indicate that ascending nociceptive information is modulated by top-down descending circuitries (see Brooks & Tracey, 2005 for a review). Hence, scientific and health organizations such as the International Association for the Study of Pain stress the difference between nociception and pain.

1.2.2 The affective, cognitive and social modulation of physical pain

As mentioned above, the relationship between the intensity of noxious stimulus and its conscious perception is highly variable. Indeed several factors such as the psychological state of the individual or social-contextual factors can modulate pain (Head & Holmes, 1911; Melzack et al., 1982), and under certain conditions even block the perception of pain when the noxious stimulus is delivered. Consequently, there has been growing interest into the top-down factors that can modulate pain perception. In particular, neuroscience evidence suggests that cognitive, affective and social factors modulate our perception of cutaneous pain. Thus, in this section we will review this literature on pain. Although cognitive, affective and social-contextual factors will be tackled separately, it's worthwhile mentioning that such factors rarely occur in isolation, which consequently also complicates our understanding of such processes as well as their underlying neural mechanisms.

With respect to the cognitive aspect of pain modulation, one of the most frequently studied psychological variables is attention (see Villemure & Bushnell, 2002 for an excellent review). The role of attention on pain is most commonly manipulated by asking the subject to attend another sensory modality (e.g., visual, auditory), which distracts them from the painful stimuli. Not surprisingly, research has consistently found that distraction reduces pain experience while increasing activation in brain regions typically implicated in the medial pain system, as well as reducing activation in the thalamus and insula (Brooks, Nurmikko, Bimson, Singh, & Roberts, 2002; Longe et al., 2001; Petrovic, Petersson, Ghatan, Stone-Elander, & Ingvar, 2000). However, it should be noticed that the influence of attention on pain is a complex matter, given that pain itself modifies an individual's attention and particularly, re-directs it to the actual or potential threat to our body. Indeed, as mentioned above, the pain matrix has been recently suggested to detect environmental threat to the body in response to sensory salient-events (Legrain et al., 2011). Thus, distracting a subject's attention from the noxious stimuli could thereby simply attenuate its saliency and hence its magnitude.

Relatedly, research has also examined the effects of pain expectation about the upcoming noxious stimuli. Such expectations may help an individual to adjust sensory, cognitive and motor systems in order to optimally process the noxious stimuli in terms of neural and behavioural responses (Katja Wiech, Ploner, & Tracey, 2008). Critically, much of the individual variation in how people perceive the noxious stimuli depends on prior experiences as well as predictions about the stimulus, which are then used to interpret the upcoming afferent information. In this manner, pairing environmental cues with the sensory noxious event plays a key role in how we predict and process the upcoming sensation. For example, neuroimaging studies have manipulated the anticipation of pain by pairing non-noxious and noxious stimuli with different coloured lights and thus have the subjects learn and expect different types of stimuli depending on the signalled coloured light (e.g., Ploghaus et al., 1999) as well as examining what happens when expectations of pain are violated by signalling high-level pain when in fact the intensity was low and vice versa (e.g., Keltner, 2006; Koyama, McHaffie, Laurienti, & Coghill, 2005). Collectively, a series of studies suggest that the expectation period between cue (e.g., coloured light) and noxious stimulus increases activity in brain regions typically activated by pain itself, i.e., SI, ACC, insula, thalamus, PAG (M. Fairhurst, Wiech, Dunckley, & Tracey, 2007; Ploghaus et al., 1999; Porro et al., 2002). Furthermore, expectations in which there is a high level of certainty regarding the stimulus activate descending control systems to attenuate pain, whereas in contrast, uncertainty increases pain (Ploghaus, Becerra, Borras, & Borsook, 2003). Moreover, expectations of low- but application of high-intensity stimulus, is associated with reduced activation in many brain regions implicated in pain processing (i.e., somatosensory cortex, insula and ACC), suggesting that neural processing underlying pain experience can be shaped by prior knowledge of the stimulus (Koyama et al., 2005). Finally, studies have also begun to investigate violations in expectations and how the brain learns to adjust and predict pain based on prior successful and unsuccessful learning trials (Ploghaus et al., 2000). Together, these lines of work suggest that expectations are constantly compared (and updated) to the bottom-up sensory information, which may ultimately influence our perception of pain.

In addition to attention and anticipatory factors, other psychological factors such as mood and emotional states have been shown to modulate pain. Research has mostly investigated the modulatory role of emotion on pain by using manipulations to prime (negative and positive) mood and affective states, such as viewing pictures, listening to music or watching films (Villemure & Bushnell, 2002). In general, manipulations that have a positive effect on mood or affective states (e.g., happy faces, pleasant music) have been found to reduce pain perception. On the other hand, manipulations that prime negative mood or affective states have been found to increase pain perception (De Wied & Verbaten, 2001; Meagher, Arnau, & Rhudy, 2001; Weisenberg, Raz, & Hener, 1998). It has been suggested that, like other modalities such as attention, the affective modulation of pain engages a descending regulatory circuitry to modulate ascending nociceptive information at the spinal level (Melzack & Wall, 1965; Villemure & Bushnell, 2002). Studies have begun to examine this notion by having participants view affective and neutral pictures while measuring pain and nociceptive flexion reflexes in response to predictable and unpredictable electric shocks to the sural nerve (Rhudy, Williams, McCabe, Nguyên, & Rambo, 2005; Rhudy, Williams, McCabe, Rambo, & Russell, 2006). Findings from these studies provided evidence for the hypothesis that emotional picture-viewing engages the descending modulation of spinal nociception, although mostly in relation to unpredictable, rather than predictable, noxious stimuli.

Furthermore, as systematically reviewed elsewhere (Decety & Fotopoulou, 2015; Krahé, Springer, Weinman, & Fotopoulou, 2013), social-contextual factors have also been shown to modulate pain in both clinical contexts and the laboratory. In clinical pain populations, the literature suggests either a correlation between social support and lower pain intensity (López-Martínez, Esteve-Zarazaga, & Ramírez-Maestre, 2008), or conversely, a correlation between social support and pain level (Kerns et al., 1997) and behaviours (Gil, Keefe, Crisson, & Van Dalfsen, 1987). Although several models have been suggested to account for such differences in the literature (e.g., operant conditioning perspectives, Jolliffe & Nicholas, 2004; pain catastrophising, Sullivan et al., 2001), several confounders could have influenced the above mixed findings given the lack of experimental control in clinical settings. By contrast, experimentally induced pain in healthy subjects provides us the opportunity to disentangle the influence of different social variables of interest (Krahé et al., 2013). Based on the literature on experimentally induced pain, it is thought that interpersonal social cues may signal safety or threat of the environment or stimulus itself, which ultimately influences our perception of pain (Krahé et al., 2013). Supportive of this notion, research suggests that viewing pictures of one’s partner, relative to strangers or objects, attenuates pain, with greater neural activity in regions associated with signaling safety (i.e., ventromedial prefrontal cortex; Eisenberger et al., 2011) and reward (nucleus accumbens; Younger et al., 2010) found only in the partner-picture conditions. Important to this thesis, studies have also compared the modulatory effects of holding the hand of a partner, relative to a stranger's or object/no hand, on impending threat or pain (Coan, Schaefer, & Davidson, 2006; Master et al., 2009). These latter studies evidence that holding the hand of a partner reduces unpleasant feelings of pain (Master et al., 2009) and activates higher-order brain regions associated with emotion regulation and emotion-related homeostatic functions in the anticipation of pain (e.g., right dorsal prefrontal cortex, superior colliculus, anterior cingulate cortex; Coan et al., 2006). Similarly, a recent study shows that handholding during pain increases brain-to-brain coupling, being correlated with pain analgesia and the observer's empathetic accuracy (Goldstein et al., 2018). While these studies point to potential higher-order affective regulation, recent laser-evoked potential studies further suggest that higher-order processes modulate pain by influencing the salience of stimuli threatening the body (Krahé et al., 2015). However, simultaneous manipulations of social touch (e.g. hand-holding) and pain as in the studies mentioned above (e.g., Coan et al., 2006; Goldstein et al., 2018), do not allow precise inferences about the mechanisms of pain modulation, given the well-known analgesic effects of touch on pain (Liljencrantz et al., 2017; Mancini et al., 2015) and the fact that these studies cannot control for skin-to-skin touch parameters (e.g. pressure of handholding, movement, sweating, temperature) or distraction effects.

1.2.3 Social and physical pain overlap

Similar to 'physical pain', growing interest in fields such as psychology and social cognitive neuroscience has risen in response to 'social pain'. Such interest is based on the notion that, as social species, the mammalian need for social proximity, attachment and a sense of belonging to a group has an adaptive and evolutionary value in terms of survival and reproductive success (Brewer, 2004; Eisenberger, 2012b). Consequently, the exclusion of an individual by other group members (i.e., ostracism) may induce strong negative reactions (see Williams, 2007; Williams, 2009 for a review). In fact, long-term isolation, rejection and loneliness have been associated with both physical and psychological negative health outcomes (Steptoe, Shankar, Demakakos, & Wardle, 2013) and even small-scale social exclusion results in a powerful aversive experience. Accordingly, 'social pain' has been defined as the "unpleasant experience associated with actual or potential damage to one's sense of social connection or social value" (Eisenberger, 2012b, p. 421). Below we briefly outline current literature arguing for an overlap between the physical and social pain system.

From an evolutionary perspective, social pain has been suggested to work as a social threat detection system to promote social proximity and bonding (Eisenberger, 2012a, 2012b; Nelson & Panksepp, 1998). Specifically, it has been proposed that the physical pain system has been co-opted to signal when social relationships, primal to survival, may be in threat (Nelson & Panksepp, 1998). Consequently, social pain constitutes an adaptive way in which severe social separations are prevented (Nelson & Panksepp, 1998). In line with this thinking, physical and social pain may be processed by some of the same neural circuitry. Supportive of this notion, research suggests that experiences of social pain activate brain regions that are commonly implicated in the affective processing of physical pain (Eisenberger et al. 2012a, 2012b).

One of the most common paradigms to manipulate social exclusion in an experimental setting consists of the Cyberball paradigm (Williams, Cheung, & Choi, 2000). The Cyberball paradigm consists of a virtual paradigm involving a ball-tossing game, in which participants are led to believe that they are playing with two other 'real' people but these are in fact, programmed. After a few ball throws, participants stop receiving the ball from the other two players (exclusion condition). The Cyberball paradigm has been found to impact an individual's physical state, including skin temperature and heart rate (Gunther Moor, Crone, & van der Molen, 2010; IJzerman et al., 2012), as well as his/her psychological state. Importantly, using the Cyberball paradigm, Eisenberger and colleagues (2003) found increased activity in the dorsal anterior cingulate cortex (dACC) and the anterior insula (AI) –brain regions associated with the affective component of physical pain– following Cyberball-exclusion, as compared to Cyberball-inclusion. These findings therefore imply an overlap between neural regions implicated in both physical and social pain (Eisenberger, 2012a, 2012b; Eisenberger et al., 2003). Consistent with the notion of a physical-social pain overlap, research further suggests that social-contextual factors that decrease physical pain (Master et al., 2009; Younger et al., 2010) also decrease social pain (Teng & Chen, 2012) and vice versa (Bernstein & Claypool, 2012; Brown, Schrag, & Trimble, 2005). Similarly, individual differences in sensitivity to social pain also correlate with individual differences in sensitivity to physical pain (see

Eisenberger, 2012b for a review). Critically, the physical and social pain system are likely mediated by similar neurochemicals.

The earliest evidence of an overlap between the physical and social pain system comes from the role of opioids, which as will be discussed below in more detail, are also thought to contribute to social attachment (Nelson & Panksepp, 1998b). Opioids, such as morphine, are best known for having analgesic effects and their role in physical pain processing. However, cumulative evidence indicates that in addition to their pain-relieving effects, opioids also reduce separation distress. For instance, opioids have been shown to reduce behaviors related with the distress of social separation, such as pup cries in response to being separated from their mother (Nelson & Panksepp, 1998; Eisenberger, 2012a, 2012b). Thus, evidence suggests shared opioid-related activity between physical and social pain processes.

Concurrently, endogenous opioids play a key role in social attachment, as they seem to be implicated in regulating social separation as well as in the pleasure associated with social connection (Nelson & Panksepp, 1998). In addition to reducing separation distress, endogenous opioids have been found to possess rewarding effects (Belluzzi & Stein, 1977) and to be released in response to social contact (Blass & Fitzgerald, 1988; D'Amato & Pavone, 1996; Smotherman & Robinson, 1992; Smotherman, Simonik, Andersen, & Robinson, 1993). Given its rewarding effects, it has been presumed that attempts of social connection are sought in order to increase the experience of reward associated with opioid release. Consistent with this notion, evidence suggests that opioid receptor antagonists increase grooming behavior, which index attempts of social connection in rodents (Fabre-Nys, Meller, & Keverne, 1982). By contrast, opioid receptor agonists have been found to reduce the time that rodents spend in close proximity with conspecifics (Herman & Panksepp, 1978; J Panksepp, Herman, Conner, Bishop, & Scott, 1978), likely due to opioids acting as a substitute for social connection and its rewarding effects. On this basis, it has been suggested that opioid substrates help maintain proximity with others, with high opioid receptor activity eliciting comfort upon reunion.

Similar to opioid mechanisms, oxytocin plays an important role in the formation and maintenance of social bonds (Insel & Young, 2001; Insel, 1992; Nelson & Panksepp, 1998). Rodent studies conducted in the past three to four decades support the notion that oxytocin central projections (rather than oxytocin peripheral or hormonal effects) are involved in reducing separation distress (Insel & Shapiro, 1992;

Insel & Winslow, 1991), released in response to social contact (Uvnas-Moberg, Bruzelius, Alster, & Lundeberg, 1993) and modulate affiliative behavior (e.g., Forsling, 1986; Insel & Shapiro, 1992; Pedersen & Prange, 1979).Therefore, oxytocin may also contribute to social attachment. Importantly, both oxytocin and opioids are released in response to social contact, which does not only reinforce social connection but also reduce separation distress (Nelson & Panksepp, 1998). It’s worthwhile noticing that these rodent studies have mostly assessed social contact by looking at pro-social tactile stimulation by conspecifics (e.g., mostly grooming behavior) and milk transfer. Thus, one may presume that pro-social touch by conspecifics plays an important role in reducing separation distress and motivating social connection, mediated by opioid mechanisms and oxytocinergic pathways. Other neurobiological pathways are likely to play a role but are beyond the scope of this chapter.

Although human research into the social modulation of experimentally induced social pain remains in its infancy, one may predict that social connection and support can buffer the distressing effects of ostracism. Social support has known beneficial effects on distressing life events (Park, Wilson, & Myung, 2004) as well as physical health (Ditzen & Heinrichs, 2014; Uchino, 2006). Animal models suggest that the buffering effects of social support include the regulation of stress-related activity in the autonomic nervous system and hypothalamic-pituitary-adrenal (HPA) axis (Hostinar, Sullivan, & Gunnar, 2014). Similarly, in humans, social supportive behaviours following stress conditions seem to attenuate multiple stress systems, including the autonomic nervous system and HPA-axis (see Ditzen & Heinrichs, 2014 for a comprehensive review), possibly mediated by neuropeptides involved in social bonding and affiliative behavior, including oxytocin (Heinrichs, Baumgartner, Kirschbaum, & Ehlert, 2003). Further, as reviewed above, neuroimaging studies from neighboring topics indicate that social support reduces activity in brain regions implicated in emotion and homeostatic regulation (i.e., anterior cingulate cortex, dorsolateral and ventrolateral prefrontal cortex; Coan et al., 2006; Eisenberger, Taylor, Gable, Hilmert, & Lieberman, 2007). Moreover, cues of social support from a partner reduce physical pain (Eisenberger et al., 2011; Younger et al., 2010). Together, these lines of research suggest that neural and hormonal responses to threat cues are minimized when social support is provided (Decety & Fotopoulou, 2015). Consequently, it is likely that social support may also buffer ostracism-related effects.

However, this question has received very little attention in science.

Specifically, while self-reported supportive daily life interactions have been shown to diminish neuroendocrine stress responses to social stressors as well as decrease activity in the dACC following ostracism (Eisenberger et al., 2007), to date, only two studies have directly examined the buffering effects of social support on ostracism. Specifically, these studies suggest that the presence of a friend in high self-esteem individuals (Teng & Chen, 2012), or supportive versus non-supportive texts (Onoda et al., 2009), reduce feelings of distress caused by social exclusion. With respect to touch as a form of social support, only one study to date has examined the role of touch on ostracism. Specifically, this study suggests that touching a teddy bear mitigates feelings of social exclusion to increase pro-social behaviour, with positive emotions mediating such effects (Tai, Zheng, & Narayanan, 2011). However, given the tight link between touch among conspecifics and social bonding (Nelson & Panksepp, 1998; Suvilehto, Glerean, Dunbar, Hari, & Nummenmaa, 2015), further research is needed to examine whether receiving supportive touch may buffer feelings of distress caused by ostracism.

1.2.4 Defensive reactions in the space surrounding the body

During conditions of bodily threat or psychological stress, such as the anticipated pain from a sharp object approaching one’s face, one’s body may induce action to mobilize withdrawal or act upon the threatening stimulus. The effective piloting of the body to avoid or manipulate threatening stimuli requires an integrated neural representation of the body and of the space surrounding the body (Holmes & Spence, 2004). Specifically, peripersonal space (PPS), defined as the immediate space surrounding the body (Giacomo Rizzolatti, Fadiga, Fogassi, & Gallese, 1997), is thought to be critical for triggering defensive or approaching behaviors, given that objects within this space can be grabbed and thus manipulated, whereas objects beyond this space (termed extrapersonal space) cannot (Previc, 1998). It therefore makes sense that PPS is processed in a different ways than extrapersonal space, particularly as objects that are closest to, and moving towards the body, could implicate threat and avoiding them must be a primary goal for all organisms fighting for survival. Consequently, our perception of our PPS integrates multiple sensory systems (see Holmes & Spence, 2004 for a review), so that multisensory information about objects that are close to our bodies are reachable and can be acted upon.

The neural representation of PPS consists of a network of interacting subcortical and cortical brain regions. To represent the space around the body, one must first locate the position of one's body across different postures and analyse the spatial relationship between parts of the body and nearby objects (Holmes & Spence, 2004). This process requires the integration of proprioceptive, as well as exteroceptive (e.g., tactile, visual) information. In particular, neurons that respond to both visual and tactile stimuli (i.e., bimodal neurons) have been suggested to code the peripersonal space in a frame of reference centered on the part of the body. Indeed, these bimodal neurons have been found in cortical (i.e., ventral premotal cortex, ventral intraparietal area, and parietal area 7b, Duhamel, Colby, & Goldberg, 1998; Rizzolatti, Scandolara, Matelli, & Gentilucci, 1981) as well as subcortical brain areas (i.e., putamen; Graziano & Gross, 1994), and respond to tactile stimuli located on a specific part of the body and to visual stimuli presented proximally to the same body part. In addition, given that the brain areas that contain these bimodal neurons are located in, or connected to, motor areas (Cooke & Graziano, 2004; G. Rizzolatti, Luppino, & Matelli, 1998) hints to this visuo-tactile system being involved in the representation of space and bodily position in order to plan movements in response to stimuli within the peripersonal space.

Given the importance of the space surrounding the body in detecting and acting upon threatening stimuli close to the body, studies have examined the role of physical (e.g., de Haan, Smit, Van der Stigchel, & Dijkerman, 2016; Lloyd, Morrison, & Roberts, 2006) and psychological threat (e.g., social exclusion; Ambrosini, Blomberg, Mandrigin, & Costantini, 2014) on PPS. For example, a recent study investigated the role of threatening stimuli on visuo-tactile interactions surrounding PPS (e.g., de Haan et al., 2016), finding that tactile reactions closer to the body are faster when they see a spider (i.e., threatening stimuli) as compared to a butterfly (non-thretening stimuli). Interestingly, however, such effects were only present in individuals who were afraid of spiders, supportive of the idea that visuo-tactile interactions in the space close to the body are important for defensive purposes and maintaining bodily integrity.

However, given that we live in an ever-changing social environment, our PPS representation grows or shrinks to optimize the processing of self-relevant events, which depends on the social context (e.g., Noel, Pfeiffer, Blanke, & Serino, 2015; see also Hall, 1966, 1968). Indeed, the boundaries of PPS have been shown to shrink when subjects face another individual, consistent with the notion that PPS can be conceived as a space of interaction critical for triggering defensive or approaching behaviours (Teneggi, Canzoneri, Di Pellegrino, & Serino, 2013). Such effects on PPS boundaries further depend on the social perception we have about others. For instance, a recent study has shown that when facing another person, the social perception that we have about this person (i.e., believing the other is moral versus immoral) influences PPS representation. Specifically, it was found that when facing an immoral person, PPS boundaries are extended (Pellencin, Paladino, Herbelin, & Serino, 2018). Thus, social perception of others affects the multisensory representation of the space between self and other. Interestingly, interpersonal interactions with others have also been shown to modulate PPS boundaries. Specifically, being treated fairly (versus unfairly) by another person in an economic game, has been shown to extend PPS boundaries to that same person, suggesting that it is not only the presence or beliefs about the other person, but the nature of the interaction with another person that influences PPS (Teneggi et al., 2013). However, to date, no study has examined whether supportive interpersonal behaviors, such as active supportive touch, modulate PPS boundaries.

1.3 The role of touch as active, embodied social support

As reviewed above, different aspects of pain are modulated by social-contextual factors, with socially supportive and interpersonal behaviors playing a prominent role. The buffering role of pain by social support is based on the idea that as social species, mammals, including humans, have adapted to the presence and active care of other conspecifics, so that our ability to form and regulate emotions is constituted on the basis of social interactions (Atzil & Barrett, 2017; Beckes & Coan, 2011; Coan, 2011; Fotopoulou & Tsakiris, 2017). As such, it is not surprising that recent neuroimaging studies have shown an attenuation of neural responses typically implicated in affective regulation (e.g. dorsolateral prefrontal cortex, anterior insula), when social support by a close other (e.g., hand-holding by a romantic partner versus a stranger) is provided in the face of physical threat (e.g., Coan et al., 2006), including pain (e.g., Eisenberger et al., 2011; Krahé et al., 2015). Nevertheless, most of this research has focused on passive forms of social support (i.e., static manipulations such as hand-holding, others presence, viewing pictures of one’s partner, touching a teddy bear, etc.) and consequently, the explanatory power of these manipulations is restricted in two important ways. The first restriction is that studies have mostly focused on passive support from a support provider versus control conditions of absence of such support, e.g., presence versus absence (Krahé et al., 2015), static hand-holding versus no or stranger hand-holding (Coan et al., 2006; Goldstein, Weissman-Fogel, Dumas, & Shamay-Tsoory, 2018), viewing pictures of one's partner versus a stranger (Eisenberger et al., 2011). However, these manipulations of passive social support are subject to several confounds such as social distraction, comfort and familiarity. Moreover, behavioural studies on passive and active support have been found to have opposite psychological effects on pain (see Krahé & Fotopoulou, 2018; Krahé et al., 2013 for reviews). For example, pure 'presence' conditions have yielded mixed results, possibly due to lack of information about the intentions, whereas clear signals of support and possibility for action seem to consistently attenuate pain.

The second restriction is that many of these studies have focused on verbal or visual communication of support (e.g., supportive text messages, viewing pictures of one's partner), or on passive forms of embodied support (e.g., partner presence, handholding), while largely neglecting one important way to communicate support, namely via embodied forms of active support such as dynamic touch. Social touch is thought to serve as a foundation for affiliative behavior and can be divided into three main categories: simple, protracted and dynamic (Morrison, Löken, & Olausson, 2010). Specifically, simple touch involves brief, intentional contact to a relatively restricted location during social interactions (e.g., tapping someone on the shoulder); protracted touch involves longer skin-to-skin contact between individuals, typically with a larger amount of pressure than simple touch (e.g., hand-holding, hugs, cuddling); finally, dynamic touch involves continuous movement on the skin from one point to another (e.g., stroking, caressing, and even rubbing; Morrison et al., 2010). The precise mechanisms by which these different types of social touch regulate pain have begun to be examined, although in some cases these overlap. On the one hand for example, the role of simple touch, particularly when administered concomitant with noxious stimulation, has been shown to attenuate nociceptive responses (Mancini et al., 2015), with such effects likely mediated by a subcortical gating of ascending nociceptive input as measured by the laser blink reflex (Mancini et al., 2015). On the other hand, the role of protracted touch, such as handholding, has also been shown to attenuate pain (e.g., Coan et al., 2006; Goldstein et al., 2018), with such effects linked to higher-order affective regulation. Nevertheless, using such static manipulations of embodied social support are not only subject to confounds mentioned in the first restriction, but may not allow precise inferences to be made about the mechanisms of pain modulation. For instance, is social touch such as handholding attenuating pain because it is delivered concomitantly with noxious stimulation and therefore attenuating pain due to interactions between nociceptive and tactile pathways at the spinal level? Or because it is accompanied by positive feelings, such as fondness and support? Or simply because, cognitively, one knows that handholding is a socially supportive, good thing (i.e., similar to other forms of support such as supportive text messages, it involves declarative pre-existing knowledge)? By contrast, one could employ dynamic stroking touch that can signal active care from others, without the subject's explicit knowledge that is a socially 'good thing' (see more below).

In general, social touch is thought to possess positive hedonic value (although clearly this value depends on the specific context, i.e., touch may not always be welcome or pleasant), in order to promote affiliative and prosocial behavior (see Morrison et al., 2010 for the social touch hypothesis). For example, the effects of touch in social interactions have been shown to increase the liking of a person (Burgoon, Walther, & Baesler, 1992; Fischer et al., 1976; Hornik, 1992) as well as generosity and compliance (Crusco & Wetzel, 1984; Hornik, 1992; Joule & Guéguen, 2007). Critically, within these different types of social touch, dynamic touch in particular plays a unique role in the formation and maintenance of social bonding. This dynamic type of touch is homologue to grooming in non-human mammals, such as primates. In primates, grooming not only serves a hygiene purpose but it also serves as a form of bonding and reinforcing alliances (Dunbar, 1997; Dunbar, 2010). Grooming is typically observed within close conspecifics, such as in maternal behavior, with neurotransmitters involved in social bonding mediating such effects. For instance, the administration of oxytocin into the cerebrospinal fluid of knockout mice results in increased grooming behavior (Amico et al., 2004). Similarly, opioids play a central role, with evidence suggesting that opioid receptor antagonists increase grooming behavior in rodents (Fabre-Nys et al., 1982), and opioid receptor blockade results in increased solicitations for grooming in primates (Keverne, Martensz, & Tuite, 1989; Martel, Nevison, Simpson, & Keverne, 1995; see more below). In humans, evidence suggests that grooming plays a central role in close relationships and bonding. For instance, a recent study suggests that in romantic couples, self-reports of mutual grooming are positively correlated with relationship quality and previous experiences of familial affection (Nelson & Geher, 2007).

Given that touch is critical for social interactions, it makes sense that at least some forms of social touch are mediated by specific neurophysiological pathways (Morrison et al., 2010). In particular, a large body of research has begun to investigate the peripheral and central neurophysiology underpinning dynamic touch. Specifically, evidence suggests that a specific type of slow (at 1-10 cm/s velocities), light-pressure (≈0.4N), dynamic touch (moving along the skin) is mediated by a separate, specific neurophysiological system, namely the CT system (McGlone et al., 2014). This specific type of touch is well tuned to optimal CT activation and such activation is expected to give rise to pleasant sensations, therefore the term 'affective touch' will be used hereafter. There is reason to suspect that CT input can inhibit C-nociceptive signaling in the dorsal horn (Lu & Perl, 2003), particularly when the touch is administered concurrently or in close temporal proximity with the noxious stimuli (Liljencrantz et al., 2017), indicating pain modulation at lower levels, i.e., before it reaches the brain. However, one may speculate that affective touch can also modulate pain at higher levels of the neurocognitive hierarchy as it specifically signals pleasant emotions and communicates social support (Kirsch et al., 2017), without the need for any explicit labelling by words or pictures. Accordingly, affective touch can be seen as a unique form of embodied active support, and such manipulation allows addressing several of the aforementioned restrictions (e.g., can be done offline by the same touch provider and by merely manipulating the velocity of the touch; see section 1.5 for more details). The following subsections will briefly outline the current literature on the sensation, affective and social-motivational aspects surrounding affective touch.

1.3.1 The peripheral neurophysiology of affective touch

Although research has mostly conceptualized the cutaneous senses to serve a primary discriminative role (Mountcastle, 2005), with the skin being stimulated by low-threshold mechanoreceptors (LTMs) innervated by myelinated Aβ-afferent fibres to enable fast conduction and rapid central processing, there are different sensory afferent fibres innervating the human skin. Moreover, the sense of touch does not only possess sensory and perceptual consequences, but may also have an affective component (e.g., see section 1.2 for a similar discussion on pain and C fibres). Recent research suggests that slow conducting unmyelinated afferent CT fibres mediate the affective component of innocuous touch (McGlone et al., 2014). These C fiber tactile afferents were first identified in a cat in 1939 by showing low spike heights while using the skin-nerve preparation technique, although initially associated with ‘tickling’ sensations (Zotterman, 1939). More recently, low threshold mechanosensitive C fibres (C-LTMs; detected by cutaneous sensory neurons, i.e., C low threshold mechanoreceptors, C-LTMRs), which are identified by conduction velocity and spike polarity, have been found in the hairy skin of rodents and primates (Bessou et al., 1971; Leem, Willis, & Chung, 1993). Employing a genetic labelling method in mice, C-LTMRs were later found to form longitudinal lanceolate endings around hair follicles (Li et al., 2011). Unlike other molecularly defined mechanosensory C fibers, a subgroup of C-LTRMs (i.e., MrgPRB4+ neurons) do not respond to mechanical stimulation of the skin in an ex-vivo preparation (Vrontou et al., 2013). Moreover, pharmacogenetic activation of MrgPRB4+ neurons promotes conditioned place-preference, indicating that CLTMs process the rewarding properties of touch (Tzschentke, 2007). C-LTMs are now acknowledged to also exist in human skin, termed as CT afferents (Johansson & Vallbo, 1979; Vallbo et al., 1993; Vallbo, Olausson, & Wessberg, 1999). CTs have different characteristics than myelinated fast conducting Aβ-fibres associated with discriminative touch, including their conduction axon velocity (0.6-1.3 m/s) and skin location (i.e., found in hairy but not glabrous skin). Although little is known about the exact terminal morphology of CTs, studies show high arborisation of C fibre terminals at the dermis-epidermis level (Cauna, 1973).

Microneurography studies have provided valuable insight into the neurophysiological characteristics that activate CT afferents (McGlone et al., 2014). CTs are highly sensitive mechanoreceptors responding to stimuli that are clearly innocuous, such as slow stroking with the experimenter’s fingertips or a soft brush and fatigue quickly (i.e., decreased responsiveness to repeated stimulation of the receptive field within 5s) (Nordin, 1990; Vallbo et al., 1999). Specifically, it has been found that CTs firing rate is distinct from myelinated afferents, reflecting an inverted U-shaped relationship between the stroking velocity and mean firing rate with the most vigorous responses being at 1-10 cm/s. That is, CTs show strong responses to slow (1–10 cm/s) stroking, but poor response to fast (30 cm/s) or much slower stroking (0.1 cm/s) (Löken, Wessberg, Morrison, McGlone, & Olausson, 2009).

Moreover, subjective responses of perceived pleasantness in response to stroking also showed an inverted U-shape relationship, with the highest pleasantness responses being found at 1-10 cm/s stroking velocities (Löken et al., 2009), indicating that CT afferents carry a positive hedonic quality (i.e., pleasantness). Furthermore, in addition to CTs responding optimally to such stroking velocities, they are also temperature sensitive. CTs are preferentially discharged in response to 32 degrees Celsius, the typical skin temperature (R. Ackerley et al., 2014). However, one of the main difficulties in our understanding of selective CT stimulation is related to the fact that to date, we cannot stimulate CT fibres without stimulating Aβ-fibres in healthy subjects. Nevertheless, insights have been provided from patients with sensory neuronopathy (Olausson et al., 2002; Olausson et al., 2008). Given that sensory neuronopathy affects myelinated but not unmyelinated fibres, these patients are thought to lack Aβ afferents while their CTs afferents may remain intact. Interestingly, research has shown that CT stimulation in these patients activated the insula (i.e., the preferential cortical target for CT afferents; see more below), but not somatosensory regions associated with the sensory discriminative processing of touch (Olausson et al., 2002). On the other hand, these patients were able to detect, although poorly, slow brushing on the forearm (where CTs are abundant), which was accompanied by sympathetic skin response (Olausson et al., 2008). Given the sensory discriminative properties associated with Aβ-fibres and the lack thereof in these patients, it is possible to presume that while CT touch may not be involved in the discriminative aspects of touch, some somatotopical organization occurs in the insular cortex (Olausson et al., 2008; see also Bjornsdotter et al., 2009). Moreover, patients with hereditary sensory and autonomic neuropathy type V, i.e., presenting a reduction in density of thin and unmyelinated nerve, including CT afferents, perceived slow brushing on the forearm as less pleasant than controls, with such tactile stimulation not modulating activity in the posterior insula cortex – a target for CT afferents (Morrison et al., 2011; see more below). Together, these findings suggest that CT afferents follow a separate neurophysiological route than Aβ mediated discriminative touch.

Although our knowledge on how CTs peripheral information reaches spinal, brainstem and cortical areas in humans remains scarce, meaningful insights regarding the spinal processing of CTs have been obtained from animal studies and C-LTMS/C-LTMRs. Mice studies suggest that central projections of the unmyelinated C-LTMS enter the laminae II of the dorsal horn; wherein the population of spinal neurons include vertical neurons with axons arborizing in lamina I, where they would synapse with secondary afferent neurons (see McGlone et al., 2014 for a review). Furthermore, there could be different classes of spinal neurons responsive to gentle touch, including WDR neurons (Andrew, 2010), with a separate line of research using mice genetic tools suggesting the dorsal horn as the key initial focus for integration of Aβ and C- LTMRs (Abraira & Ginty, 2013). In humans and monkeys, it has been proposed that secondary afferent neurons in the lamina I then project to higher centres such as the insula via spinothalamic pathways (McGlone et al., 2014). Taken together, these lines of inquiry suggest that there are different pathways through which CT peripheral information is conveyed to higher centers, although these pathways may likely vary across species.

Nevertheless, given that CTs are thought to carry positive affective value and follow the lamina I spinothalamocortical pathway, portrayed as the long-missing afferent underlying distinct conscious affective feelings, affective touch has recently been re-classified as part of interoception (Craig, 2002). Such re-classification of affective touch (together with other sensory modalities such as pain and itch) can be traced back to a wider interest, starting on the nineteenth century, in mapping and classifying the senses with reference to criteria such as the nature of the stimulus, anatomy and location of receptors across body parts, the pathways to and the representation of the signal at the central nervous system (CNS), as well as the quality of the experience. This interest led to a number of classifications of the senses; for example, in exteroceptive (their receptive field "lies freely open to the numberless vicissitudes and agencies of the environment" Sherrington, 1910, p. 132), interoceptive (sensory receptors located within the body and primarily in the viscera), and proprioceptive sensations (receptors in muscles, tendons, and joints detecting position and movement of the body). Since this influential classification (see Ceunen, Vlaeyen, & Van Diest, 2016 for a review), exteroceptive and proprioceptive systems have received far more attention than interoceptive modalities. However, this has changed in the two last decades. On the one hand, theories and studies in affective neuroscience (e.g., Damasio, 2010) have brought to the foreground William James' idea that interoceptive sensations (although primarily the viscera) may lie at the heart of our emotions and self-awareness (e.g., see somatic marker hypothesis). On the other hand, progress in anatomy and physiology has urged certain researchers (e.g.

Craig, 2002) to propose alternative classifi cations of the senses that include a moreencompassing definition of interoception as the sense of the physiological condition of the entire body, not just the viscera.

Specifically, Bud Craig's proposal (2002, 2003) suggests that the primate brain has evolved a direct sensory pathway to the thalamus that provides a modality-specific representation of various individual aspects of the physiological condition of the body (i.e., interoception re-defined). This pathway is thought to originate in lamina I of the spinal dorsal horn and in the nucleus of the solitary tract in the caudal medulla, and to represent the afferent inputs from sympathetic (somatic) and parasympathetic nerves, respectively, and to terminate with a posterior-to-anterior somatotopic organization in a specific thalamic structure (the posterior and basal parts of the ventral medial nucleus, Craig, 2002). He has further proposed that the functional role of this pathway is to represent the sensory aspects of homeostatic emotions (Craig, 2003, 2008) and their accompanying motivations (represented in the ACC) that serve to maintain the body in relative stability despite ongoing internal and external changes. This proposal brings the concept of interoception into a tight relation to the notion of homeostasis (Cannon, 1929), so that interoception is the sensory representation of the physiological condition of the whole body allowing homeostatic, and ultimately 'allostatic' control (i.e. self-initiated temporary change in homeostatic imperatives to prepare for a predicted external change). In other words, interoceptive signals (e.g., hunger, thirst, itch, cool, warm, pain, affective touch, etc.) provide information regarding current homeostatic levels (e.g. HPA dysregulation in the case of bodily threat), which are used as motivations to steer action (e.g. seek comfort and support from others). This definition of interoception, which subsumes cutaneous pain, and affective touch, differs greatly from the classic association of these modalities with exteroception and particularly discriminatory touch.

1.3.2 The hedonic value of affective touch

As mentioned above, subjective responses of perceived pleasantness in response to stroking have been highly correlated with CT stimulation, with the highest pleasantness responses being found at 1-10 cm/s stroking velocities (Löken et al., 2009), indicating that CT afferents carry a positive hedonic quality. However, as with other sensory modalities, the ascending signals from the periphery are processed and modulated by several top-down factors (e.g., predictions based on prior experiences about the touch, contextual information about the touch provider, psychological and emotional state) before the subjective experience of pleasure is consolidated (D. M. Ellingsen, Leknes, Løseth, Wessberg, & Olausson, 2016). Consequently, although several methods have been developed to measure the perceived pleasantness of affective touch, such insights are limited by several confounding variables. Yet, our understanding of how CT stimulation is processed in the brain has been facilitated by recent insights from social cognitive neuroscience. Below we briefly describe the current measures used to assess the affectivity of touch as well as some insights provided by neuroimaging research about the central processing of affective touch.

A growing body of research has focused on quantifying the sensory and emotional aspects of touch (Ackerley, Carlsson, Wester, Olausson, & Backlund Wasling, 2014; Ackerley, Saar, McGlone, & Backlund Wasling, 2014; Essick, James, & McGlone, 1999; Guest et al., 2011; McGlone et al., 2012). For example, Guest et al. (2011) developed and validated a descriptive scale for touch perception, namely the Touch Perception Task (TPT), consisting of sensory and emotional descriptors. Interestingly, using the TPT, it has been found that stroking the forearm (CT-skin) led to higher ratings of emotional descriptors, whereas stroking the palm (non-CT skin) led to higher sensory descriptors (McGlone et al., 2012). Similarly, using different materials (i.e., soft brush, fur, sandpaper) has been shown to lead to higher emotional content on the forearm versus the palm and cheek (Ackerley, 2014). Nevertheless, such measure has not been used to assess the emotional attributes of touch at different speeds, which as aforementioned play an important role in both CTs firing rate and perceived pleasantness; perhaps because it would be difficult to use descriptors when the only changing variable is the velocity of the touch. Instead, research on the field has mostly focused on the use of subjective ratings of perceived pleasantness, including visual analogue scales (VAS; e.g., Ellingsen et al., 2014; Morrison, Bjornsdotter, & Olausson, 2011; Sehlstedt et al., 2016) and verbal reports using a likert-type scale (e.g., Crucianelli, Metcalf, Fotopoulou, & Jenkinson, 2013; Von Mohr, Kirsch, & Fotopoulou, 2017)on a continuous pleasantness dimension (e.g., scales ranging from not pleasant at all to extremely pleasant).

Employing subjective pleasantness ratings, it has been consistently found that people rate stroking at CT-optimal speeds as more pleasant than stroking at non-CT optimal speeds (e.g., Morrison, Bjornsdotter & Olausson, 2011; Ellingsen et al., 2014; Sehlstedt et al., 2016) – with such finding replicated also using different means to administer the touch (i.e., robot versus person; Triscoli, Olausson, Sailer, Ignell, & Croy, 2013). However, mixed results have been found when stroking the palm, where no CTs have been found. Specifically, although some studies find differences in perceived pleasantness between CT-innervated skin (e.g., forearm) versus non-CT innervated skin (e.g., palm) when gentle CT-optimal stroking is applied (Löken et al., 2009; Essick, James, & McGlone, 2009), many others do not (e.g., Gentsch, Panagiotopoulou, & Fotopoulou, 2015; Löken, Evert, & Wessberg, 2011; McGlone et al., 2012). Consequently, it is thought that such effects on the palm are likely due to secondary reinforcement, wherein top-down processes associated with expectations of pleasantness linked to relatively slow stroking also leads to increased perception of pleasantness even when delivered to non-CT skin (McGlone et al., 2014). However, if this is the case, subjective pleasantness ratings may not be sufficient to discriminate between bottom-up sensory mechanisms (CT afferent signalling in response to touch at CT optimal speeds in CT skin) and top-down cognitive mechanisms (learned expectations linked to touch at CT optimal speeds) that may lead to the experience of pleasantness on the skin. Thus, novel ways to measure the perceived pleasantness of the touch are needed.

Despite subjective measures not being optimal for disentangling between bottom-up versus top-down pleasantness feelings on CT and non-CT skin sites at CT-optimal speeds, neuroimaging evidence has shown that such tactile stimulation is differently processed on the brain. For example, a recent study suggests that tactile stimulation at slow CT-optimal speeds in the forearm is associated with increased activity in brain regions implicated in emotional processing (e.g., posterior insular cortex; mid-anterior orbitofrontal cortex). In contrast, slow CT-optimal tactile stimulation in the palm is associated with increased activity in the somatosensory cortex, consistent with non-affective discriminatory tactile processing (McGlone et al., 2012). Critically, there were no differences in pleasantness ratings between skin areas. Thus, pleasantly rated touch from hairy skin, mediated by CT afferents, is differently processed in the brain than also pleasantly rated touch from glabrous skin, mediated by Aβ afferents.

More generally, a growing body of research has characterised an affective touch network that appears to bypass the S1 (associated with the discriminative aspects of somatisation, including touch; c.f., Gazzola et al., 2012; McCabe, Rolls, Bilderbeck, & McGlone, 2008) by activating brain regions implicated in the cognitive-affective aspects of the touch, such as the posterior superior temporal sulcus, medial prefrontal cortex OFC and ACC (Gordon et al., 2013). Specifically, although CT-optimal touch also activates the primary somatosensory cortex in healthy subjects, correlations with pleasantness ratings have only been reported in the insula and the OFC (McCabe et al., 2008; Kress et al., 2011). Moreover, using fMRI and transcranial magnetic stimulation, evidence suggests that discrimination and intensity ratings predict activation in the S1, whereas pleasantness ratings predicted activation in the ACC (associated with the affective-motivational aspects of touch) but not the S1 (Case et al., 2016). Further, while investigating the cortical areas that represent affective touch, painful touch and neutral touch, studies have also found increased activity in the OFC in response to pleasant and painful touch, as compared to neutral touch, highlighting the role of the OFC on the affective aspects of the touch (Rolls et al., 2003). In contrast, the somatosensory cortex was less activated by pleasant and painful touch, relative to neutral touch (Rolls et al., 2003). Importantly, slow gentle touch on CT skin has also been shown to activate the insula (e.g., Gordon et al., 2013; Olausson et al., 2002), although the insula also plays a critical role in integrating sensory-discriminative and affective-cognitive aspects of the touch (McCabe et al., 2008; Rolls, 2010).

However, as aforementioned, the perceived affectivity of the touch may also be influenced by top-down factors relating to contextual information about the touch provider. Specifically, when someone touches us, we make predictions about the person giving the touch, as well as his/her intentions, which gives us useful information about the touch and consequently, may change our hedonic experience of the touch (Ellingsen et al., 2016). For instance, research suggests that male individuals who were led to believe they were being touched in the leg in a caress-like manner by a male rated the touch as less pleasant than when they thought they were being touched by a female (Gazzola et al., 2012). Moreover, in this study, the OFC and S1 were differently activated by the perceived sex of the caresser (Gazzola et al., 2012). Furthermore, subjects viewing emotional smiling faces, relative to frowning faces, rated the touch as more pleasant (see also Crucianelli, Cardi, Treasure, Jenkinson, & Fotopoulou, 2016), supporting the notion that affective-social factors may influence the hedonic value of touch experience. Relatedly, concomitant caress-like affective touch shaped social impressions of the emotional faces, leading to neutral and smiling faces seeming more attractive and friendly. Such effects were more powerful when intranasal oxytocin, a neuropeptive implicated in social affiliation and attachment (Feldman, 2012), was administered (Ellingsen et al., 2014). Similarly, post-conditioning faces paired with CT vs. non-CT touch are judged as more approachable, as well as decreased heart rate deceleration (Pawling, Trotter, McGlone, & Walker, 2017). Finally, simply expecting an improvement on the pleasantness of the touch, i.e., using an intranasal spray with the subjects thinking it might contain oxytocin and hence have positive effects on the touch, placebo effects have been shown to increase the perceived pleasantness of gentle stroking as well as increase activity in brain circuits involved in emotional appraisal (Ellingsen et al., 2013). Thus, social top-down contributions may influence the meaning and hedonic value of the touch.

1.3.3 Social and motivational aspects associated with affective touch

In addition to the top-down effects that may determine the perception of affective touch, affective touch itself may have effects on other physiological and social-cognitive domains. Crucially, such effects of affective touch on other domains may exist since early in development. For instance, recent evidence suggests that infants as young as nine months show selective behavioural and physiological sensitivity to stroking touch at CT-optimal speeds as compared to similar but non CT-optimal speeds (< 1cm/s and > 10cm/s) (Fairhurst, Löken, & Grossmann, 2014). Indeed, the notion that the neural substrate for detecting pleasure associated with this kind of touch develops early has been supported by recent findings suggesting that gentle touch at CT-optimal speeds in newborns leads to increased activity in brain regions associated with the socio-affective processing of touch (i.e., postcentral gyrus, Tuulari et al., 2017; and insular cortex, Jönsson et al., 2018; Tuulari et al., 2017). A recent behavioural study further found that this type of touch helps infants tune to social signals, such as faces, more than other types of touch (Della Longa, Gliga, & Farroni, 2017). These findings support the idea that the CT system may form part of a dedicated modality conveying affective and affiliative aspects of social touch and thus promoting the development of self-awareness and affect regulation in early development (Fotopoulou & Tsakiris, 2017). Importantly, the effects of affective touch in social affiliation and support extend to adulthood. For instance, slow touch at CT-optimal speeds has been shown to communicate social support more distinctively than faster (at non-CT optimal speeds but otherwise identical) touch, even when people receive this kind of touch by a stranger while blindfolded and without any other information (Kirsch et al., 2017). Moreover, there is evidence suggesting that interpersonal stroking touch is targeted to CT afferent activation (Croy et al., 2016). For example, if couples are left to freely choose the speed at which they touch each other, they tend to choose CT optimal velocities. These same effects are found for stroking a baby, but not for stroking an artificial arm. Specifically, stroking velocities were significantly faster for the artificial arm (outside the CT range), relative to the baby and partner conditions (Croy et al., 2016). Thus, the functional role of this system has been linked to prosocial functions, and particularly the communication of social support and intimacy (Kirsch et al., 2017; see also Ellingsen et al., 2016; Morrison, 2016 for reviews).

In addition to these prosocial functions, there is mounting evidence for the impact of affective touch on affective regulatory function. For example, relatively slow touch at CT-optimal versus non-CT optimal speeds reduces autonomic arousal, such as and skin conductance (Olausson et al., 2008) and heart rate activity (Fairhurst et al., 2014; Pawling, Cannon, McGlone, & Walker, 2017). Previous studies have also reported that interpersonal, social touch in general leads to an increase in parasympathetic activity (e.g., reduced heart rate activity and blood pressure; e.g., Ditzen et al., 2007; Grewen, Girdler, Amico, & Light, 2005; Light, Grewen, & Amico, 2005). Neurochemically, this reduction in arousal in response to interpersonal touch is thought to be mediated by the release of oxytocin (Uvnäs-Moberg, Handlin, & Petersson, 2014), a neuropeptide hormone that facilitates sensory and psychological processes critical for pro-social behaviour (Insel & Young, 2001; Liu & Wang, 2003). Indirect support for the involvement of oxytocin in affiliative touch behaviour comes from primate studies. In rhesus monkeys, engagement in social grooming behaviours has been correlated with cerebrospinal fluid (Winslow, Noble, Lyons, Sterk, & Insel, 2003) and plasma (Maestripieri, Hoffman, Anderson, Carter, & Higley, 2009) oxytocin levels. Similarly, increased levels of oxytocin have been reported following grooming events in chimpanzees, which interestingly was mediated by the strength of the bond between the grooming partners (Crockford et al., 2013). Moreover, the central effects of oxytocin on prosocial behaviour have been attributed to its ability to promote sensitivity to socially relevant cues and inhibit HPA responsivity to stressors (Lee, Mouraux, & Iannetti, 2009). Together, these findings suggest that the role of affiliative tactile interactions on autonomic arousal may be mediated by oxytocin, which also plays a central role in social bonding. Although the nature of the precise cutaneous nerves underlying such effects remains largely unknown, recent theoretical postulations have argued for the potential role of CT afferents as the cutaneous mediators of oxytocin release during affiliative tactile interactions (Susannah C. Walker, Trotter, Swaney, Marshall, & Mcglone, 2017). Critically, such effects may extend to pain, with animal (e.g., Eliava et al., 2016) and human (e.g., Paloyelis et al., 2016) studies suggesting that oxytocin possesses analgesic effects (see Walker et al., 2017 for a review).

Similar to oxytocin, endogenous opioids may mediate the motivational and rewarding effects of tactile interactions (Walker & McGlone, 2013), including CT stimuli (Ellingsen et al., 2016). As mentioned above endogenous opioids play a central role in social attachment, being implicated in regulating social separation (see section 1.2.3) as well as increased receipt and seeking of social tactile contact, including grooming. For example, acute doses of naloxone (i.e., opioid antagonist) to rhesus monkeys leads to increased seeking of grooming from their companions but not their peers (Martel et al., 1995), with this particular behaviour thought to be due to naloxone blocking the positive affect associated with social contact and consequently, leading to solicit comfort via increased social grooming. Moreover, mixed findings with respect to the directionality of effects regarding μ-opioid receptors (MOR) on affiliative touch behaviour (i.e., increasing or reducing touch behaviour) have led to speculation that such effects may be state and motivational dependant (see the 'state-dependent μ-opioid modulation of social motivation' model; Loseth, Ellingsen, & Leknes, 2014). For instance, studies showing that enhanced MOR signalling in rodent and primate infants leads to a decrease in affiliative touch behaviour can be explained by a state of distress following social separation and thus, highly motivated for social contact. In contrast, studies showing that enhanced MOR signalling leads to an increase in affiliative touch behaviour can be explained by most of these studies being conducted in adolescents and adult rodents, who may have more motivation for social exploration and less need for relief. In this manner, by providing relief from distress, social contact may lead to MOR activation and thus reduce contact seeking, whereas MOR signalling disruption may lead to increased contact seeking (see Ellingsen et al., 2016 and Loseth et al., 2014 for reviews). Critically, as mentioned in section 1.2.3, endogenous opioids have been strongly implicated in both physical and social pain, with opioid receptors mostly concentrated in brain areas related to pain and affect

(Baumgartner et al., 2006). As such one may speculate that affective touch may play a central role in modulating pain, with opioids being one potential neurochemical mechanism that mediates such effects. Indeed, although research is needed to examine the nature of the cutaneous nerves underlying such effects, recent evidence on healthy subjects has shown that opioid blockade may lead to an increase of perceived pleasantness in response to slow CT-optimal touch (Case et al., 2016). Other neurochemical mechanisms (e.g., serotonin, cannabinoids, dopamine) are likely to play a role in the social and motivation aspects associated with affective touch but are beyond the scope of this chapter.

1.4 The role of dispositional factors in the experience of pain and social support

As mentioned in section 1.2, the International Association for the Study of Pain (1994) has defined pain an inherently a subjective experience. Thus, personality dispositional factors in how individuals perceive pain, as well as others, may shape pain perception. In particular, as reviewed elsewhere (Krahé et al., 2013), experimental research has shown that pain is modulated by social context and interpersonal interactive behaviors, which in turn may depend on the individual's prior beliefs about interpersonal relations. This section outlines current literature on one key personality factor that has been associated with the perception of pain in a social context, namely attachment style.

Attachment theory is one of the most influential theories of the development of close social relationships (Bowlby, 1969; Bowlby, 1977). Its key tenet is that infants have an innate drive to form a close bond with their primary caregivers to ensure their survival and well-being in times of threat. In particular, signals of threat to the internal condition of the body, including cold, pain and hunger, are thought to activate attachment behaviors that lead to closeness with the caregiver (Bowlby, 1969, 1997). Thus, according to attachment theory, support and interactive behaviors with the caregiver, also termed 'attachment partner', is the primary way of coping with threat (in the wider sense). Importantly, Bowlby's original focus was on physical 'proximity seeking' as the primary behavioural coping strategy, and a central aspect of proximal caregiving during threat is touch. Indeed, this is a similar point that Harlow's classic monkey studies on the 'soft' surrogate, artificial mothers made. That is, touch and proximity to softness, i.e., 'contact comfort', even if it is artificial softness as in built-in ‘soft’ (made out of cloth) surrogate mother, is a proxy for the mammalian need for social attachment (Harlow & Zimmermann, 1958).

In the past few decades, however, the emphasis in attachment research has been influenced by the additional, cognitive hypothesis that differences in the responsiveness and availability of caregivers to the infant’s attachment needs lead to the development of internal working models of social relating and associated affect regulation strategies (Main, Kaplan, & Cassidy, 1985). These working models are described as affective-cognitive schemas, termed ‘attachment representations’ or most generally referred to as attachment styles, which are transferred from parental figures to close relationships (Hazan & Shaver, 1987) and remain relatively stable across the life span (Waters, Merrick, Treboux, Crowell, & Albersheim, 2000). The development of attachment styles depends on feelings of availability and responsiveness from the attachment figure. For example, secure attachment is characterized by positive views of self and other, and the belief that one can turn to others for support and those others will be responsive (Mikulincer, Shaver, Sapir-Lavid, & Avihou-Kanza, 2009). However, if early interactions are characterised by unreliability and unresposiveness, an insecure attachment may result. Insecurely-attached individuals may not perceive their attachment partner to be supportive (Collins & Feeney, 2004) and instead, may use secondary coping strategies (see Mikulincer, Shaver, & Pereg, 2003; Shaver & Mikulincer, 2002).

Two main subtypes of insecure attachment have been described, namely attachment avoidance and attachment anxiety, each using different coping strategies. Attachment anxiety is characterized by fear of abandonment and extreme need for emotional closeness, over-dependence on others, negative views of self, positive views of others, and high emotional reactivity. Anxiously attached individuals employ ‘hyperactivating’ strategies, such as heightened monitoring of threats in the social environment (Shaver & Mikulincer, 2002) and consequently, may tend to exaggerate the threat of pain (Wilson & Ruben, 2011). By contrast, attachment avoidance is characterized by a need for emotional distance, resistance to trusting and depending on others, positive views of self, negative views of others, and suppression of emotion (Shaver & Mikulincer, 2002). Avoidantly attached individuals employ ‘deactivating’ strategies and consequently, may suppress the magnitude of pain and prefer to deal with pain on their own rather than to rely on others for support (Wilson & Ruben, 2011).

Individual differences in attachment style have been linked directly with the perception of pain and related reactions (e.g., Hurter, Paloyelis, Amanda, & Fotopoulou, 2014; Meredith, Ownsworth, & Strong, 2008; Sambo, Howard, Kopelman, Williams, & Fotopoulou, 2010). Moreover, in the clinical pain literature, insecure attachment has been proposed as a vulnerability factor for developing chronic pain (Meredith et al., 2008). Recently, differences in attachment style have been shown to influence the effects of interpersonal variables on subjective, behavioral, physiological and neural responses to pain. For example, higher attachment anxiety has been associated with reduced pain when there is provision of social empathy (Sambo et al., 2010) or affective touch (Krahé, Drabek, Paloyelis, & Fotopoulou, 2016). Conversely, higher attachment avoidance has been associated with increased pain when there is social presence (irrespective of their empathy level; Sambo et al. 2010) or affective touch (Krahé et al., 2016). However, given that the perception of pain depends on social context (see Krahé et al., 2013 for a review), future research is needed to examine how differences in attachment style influence the effects of interpersonal variables on pain differently in contexts in which social attachment has already been established. For example, will differences in attachment style will still play a role when the support is provided by a romantic partner? Alternatively, evidence suggests that the perception and search for support is also influenced by attachment style (e.g., Florian, Mikulincer, Bucholtz, 1995; Priel & Shamai, 1995). Thus, could our perception of tactile interpersonal variables themselves, such as affective touch, be influenced by differences in attachment style?

1.5 Outline of the thesis

Given recent evidence suggesting that affective touch may be a particularly effective form of active social support, this thesis aimed to examine its role on the social buffering of pain. Distinct from other types of touch, affective touch is mediated by a specific neurophysiological CT pathway and may possess hedonic value (i.e., feelings of pleasantness) as well as playing a unique role in social bonding and affiliation. Given the critical role of active care from others, including tactile interactions, in regulating our emotions, one may presume that interpersonal affective touch can regulate pain. Yet, as reviewed above (see section 1.3), whilst research has begun to examine the potential analgesic effects of affective touch, it has mostly focused on lower levels of pain regulation. On the other hand, as reviewed in section 1.2, the pain literature suggests that supportive interpersonal behaviors may attenuate pain in a top-down fashion. However, this literature has mostly focused on passive forms of social support, including touch (see section 1.3). Furthermore, there is a need for research to examine the role of active socially supportive touch in different aspects of pain (as reviewed in section 1.2). Therefore, in a series of empirical studies, reported in Chapter 2, 3 and 4, the current thesis examined the role of affective touch as a form of active social support on three different aspects of pain. Importantly, in these studies, our tactile manipulation of affective touch consisted of administering gentle stroking (at CT-optimal speeds) that is typically judged as pleasant and socially supportive, compared to faster or slower stroking (at non-CT optimal speeds) but otherwise identical touch, without providing any kind of feedback (e.g., visual, auditory) about its affective or social meaning. In addition, the touch was delivered in temporal asynchrony to the pain manipulation (e.g., nociceptive stimuli, cyberball task) in order to avoid concurrent multisensory effects at spinal and supra-spinal levels or/and distraction effects. These empirical studies are outlined below:

Study 1: The buffering of social pain by affective touch. As reviewed in section 1.2.3, active interpersonal touch may play a unique role in the formation of social bonds and attenuating separation distress. Thus, in this study (reported in Chapter 2), I used the Cyberball task (see section 1.2.3) to manipulate feelings of social exclusion, a form of social pain. Following social exclusion, slow affective CT-optimal touch (at CT optimal speeds) or fast, non-CT optimal touch (at non CT optimal speeds) was delivered to the participants. Using these manipulations, I investigated whether slow, affective touch would lessen the distress caused by social exclusion.

Study 2: The social buffering of physical pain by affective touch. As reviewed in section 1.2.2, the social modulation of pain depends on the particular social context. Thus, this study (reported in Chapter 3) aimed to build upon a recent laser-evoked potentials study examining the modulation of pain by affective touch and attachment style (Krahé et al., 2016) in the context of a romantic relationship. I used a laser device to deliver noxious stimuli. Prior to the impending noxious stimuli, the romantic partner administered affective CT-optimal touch (at CT optimal speeds) or non-CT optimal touch (at non CT optimal speeds) to the participant. Using these manipulations, I investigated whether slow, affective touch attenuates subjective and neural responses to pain in a context in which social attachment is already established.

Study 3: The role of affective touch on the perception of PPS. As reviewed in section 1.2.3, the space surrounding the body is critical for triggering defensive or approaching behaviors. Thus, in this study (reported in Chapter 4), I used a well-validated visuo-tactile interaction task to measure the extent of PPS representation in a social and non-social context. Prior to the visuo-tactile interaction stimuli, participants received affective CT-optimal touch (at CT optimal speeds) or non-CT optimal touch (at non CT optimal speeds). Using these manipulations, I investigated whether slow, affective touch facilitates approaching behaviors by reducing the segregation between extrapersonal and peripersonal space.

However, given that the perception of bodily threat may depend on prior beliefs about interpersonal relating (see section 1.4), I examined whether the effects in study 2 and 3 were moderated by attachment style. Nevertheless, as reviewed above, recent evidence suggests that the perception of socially supportive variables is also influenced by differences in attachment style. On this basis, the current thesis also examined whether the perceived affectivity of affective touch itself depends on attachment style. This empirical study is outlined below:

Study 4: Affective touch and attachment style. As reviewed in section 1.3.2, the perceived pleasantness of the touch depends on top-down factors such as social context. However, as a social sensory modality, another top-down factor that could influence the perception of affective touch is attachment style. Thus, in this study (reported in Chapter 5) I examined whether individual differences in attachment styles relate to the perception of affective touch. I used the Adult Attachment Interview and a well-validated self-report questionnaire of close relationships to measure implicit and explicit representations of attachment style, respectively. Pleasantness ratings in response to affective, CT-optimal (at CT optimal speeds) and non-CT optimal touch (at non CT optimal speeds) were also collected. Using these measures, I examined whether the sensitivity to affective touch depends on adult attachment style.

Finally, given the need to develop new measures to assess the affectivity of touch (see section 1.3.2), a fifth study presented a novel way to assess affective touch accuracy and meta-cognitive awareness:

> *Study 5: Affective touch dimensions – from sensitivity to awareness.* As reviewed in section 1.3.2, our current measures to assess the subjective, perceived pleasantness of the touch are not able to differentiate between bottom-up and top-down processes. Thus, in this study (reported in Chapter 6), I aimed to go beyond prior investigations by combining for the first time CT stimulation with signal detection theory to provide a novel way to measure affective touch sensitivity and awareness.

Overall, the current thesis aimed to provide insight into the social modulation of threat, including physical and psychological pain, as well as the perception of peripersonal space by affective touch, while also taking into account individual differences in attachment style that may not only influence such effects but also impact the perception of affective touch alone. A general discussion about the pattern of findings arising from this thesis will be discussed in Chapter 7. Specifically, findings will be discussed within a recent, Bayesian predictive coding of brain function, namely the Free Energy Principle, that allows to put forward a unifying model of bottom-up and top-down determinants of pain and affective touch, while emphasizing the interdependence of perception, action and relevance of social factors.

Chapter 2

The Soothing Function of Touch: Affective Touch Reduces Feelings of Social Exclusion

2.1 Introduction

As mentioned in Chapter 1, mammals have a well-recognized need for social proximity and attachment. Consequently, it is not surprising that some of the most distressing life experiences involve the dissolution of social bonds. Long-term isolation, rejection and loneliness have been associated with physical and psychological negative health outcomes (Steptoe et al., 2013). Even small-scale social exclusion (i.e., ostracism) using a computerised ball-tossing game to manipulate social exclusion in an experimental setting (i.e., the Cyberball paradigm; Williams, Cheung, & Choi, 2000) has been found to induce strong negative reactions, including effects in affect, cognition and physiology (Williams, 2009). Given the importance of social proximity and attachment to survival, threats to social connection could be as harmful to our wellbeing as threats to physical safety, such as pain. Even more, it has been proposed that the physical pain system has been co-opted to signal when social relationships are in threat (Eisenberger, 2012b; Nelson & Panksepp, 1998), with neuroimaging evidence suggesting an overlap in brain regions implicated in the affective component of physical pain and ostracism, namely the dACC and anterior insula (Eisenberger et al., 2003, but see Cacioppo et al., 2013; Legrain et al., 2011). In this sense, ostracism may activate a threat detection system that is experienced as a 'social pain' to promote re-connection and social proximity and bonding (Eisenberger, 2012b; Nelson & Panksepp, 1998). Indeed, research suggests that social exclusion motivates individuals to seek interpersonal reconnection (Chester, DeWall, & Pond, 2016; Maner, DeWall, Baumeister, & Schaller, 2007). Thus, the present Chapter aimed to study the soothing effects of affective touch on ostracism. Specifically, affective touch is conceptualized here as a form of active social support (see Chapter 1, section 1.3).

As reviewed in Chapter 1 (see section 1.2.3), social support has known beneficial effects on distressing life events (Park, Wilson, and Lee, 2004) as well as physical health (Ditzen & Heinrichs, 2014; Uchino, 2006). Social supportive behaviours following stress conditions seem to attenuate multiple stress systems, including the autonomic nervous system and HPA-axis (Ditzen & Heinrichs, 2014), possibly mediated by neuropeptides involved in social bonding and affiliative behavior, including oxytocin (Heinrichs et al., 2003). Social support has also been shown to reduce physical pain (Eisenberger et al., 2011; Younger et al., 2010), and reduce activation in brain regions implicated in emotion and homeostatic regulation (i.e., anterior cingulate cortex, dorsolateral and ventrolateral prefrontal cortex; Coan et al., 2006; Eisenberger et al., 2007). However, the examination of social support on the buffering of social pain, such as ostracism, remains in its infancy. Specifically, while self-reported supportive daily life interactions have been shown to diminish neuroendocrine stress responses to social stressors as well as decrease activity in the dACC following ostracism (Eisenberger et al., 2007), to date, only two studies have directly examined the buffering effects of social support on ostracism. These studies suggest that the presence of a friend in high self-esteem individuals (Teng & Chen, 2012), or supportive versus non-supportive texts (Onoda et al., 2009), reduce feelings of distress caused by social exclusion. However, as systematically reviewed elsewhere (Krahé, Springer, Weinman, & Fotopoulou, 2013), experimental manipulations of actual or primed supportive social presence have poor explanatory power, as they entail many confounds such as familiarity, attention and social desirability effects. For example, comparing support conditions of a friend versus a stranger (e.g., Teng & Chen, 2012) entails confounds such as familiarity and social desirability effects. Similarly, receiving supportive versus non-supportive texts (e.g. Onoda et al., 2009), is susceptible to distraction and social desirability effects, as one typically knows, cognitively, that it is a positive, socially good thing. One way through which we can study the effects of social support with greater validity, specificity and experimental control is by focusing on comparable conditions of embodied social support (Coan et al., 2006; Decety & Fotopoulou, 2014), and particularly affective, social touch that conveys social support (Hertenstein, Keltner, App, Bulleit, & Jaskolka, 2006; Kirsch et al., 2017).

Manipulations of affective touch are also theoretically important, as touch seems to have a unique contribution to the formation of social bonds (Brauer, Xiao, Poulain, Friederici, & Schirmer, 2016; Suvilehto et al., 2015). In non-human mammals, tactile stimulation by conspecifics has analgesic and stress-alleviating effects (Korosi & Baram, 2010) mediated by neurobiological pathways involved in social bonding (Nelson & Panksepp, 1998). Similar beneficial effects are increasingly studied in humans. For instance, touch-based interventions can improve clinical outcomes in patients with fibromyalgia, rheumatoid arthritis and pre-term infants (Field, 2014; Hathaway et al., 2015). Furthermore, social touch is known as a stress buffer, playing a critical regulatory role in the body's responses, including cortisol and heart rate responses (Ditzen et al., 2007), to acute life stressors, which ultimately promotes social connection (Morrison, 2016). Supportive of this notion, a recent study suggests that touching a teddy bear mitigates feelings of social exclusion to increase pro-social behaviour (Tai, Zheng, & Narayanan, 2011). Although further research is needed to fully investigate the mechanisms underlying the buffering effects of touch in humans, it has been proposed that social, affective touch works as a potent interpersonal homeostatic regulator, particularly during early development (Fotopoulou & Tsakiris, 2017). According to some theorists such social, homeostatic regulation may involve primarily thermoregulatory processes (IJzerman et al., 2015; Morrison, 2016).

With respect to affective touch in particular, no study to date has examined its role on the modulation of social pain. Nevertheless, evidence suggests a relationship between slow, CT touch and pain. For instance, gentle slow touch, likely activating CT fibres, increases μ-opioid system activity (Nummenmaa et al., 2016), which is involved in pain regulation and social connection (Nelson & Panksepp, 1998), whereas opioid blockade modulates the perception of pleasantness of slow CT-optimal touch (Case et al., 2016). Further, recent studies on pain suggest that slow CT-optimal touch modulates subjective (Liljencrantz et al., 2017) and neural responses to noxious stimulation (Krahé, Drabek, Paloyelis, & Fotopoulou, 2016). However, it remains unknown, whether slow CT-optimal affective touch may affect the distress, or 'social pain' associated with ostracism (Eisenberger, 2012b). As outlined in Chapter 1, this kind of dynamic, slow touch is associated with neurophysiological specificity (Ellingsen, Leknes, Løseth, Wessberg, & Olausson, 2015; McGlone et al., 2014) and conveys social support (Kirsch et al., 2017). Thus, we can contrast affective slow touch, that is though of as being primarily mediated by the CT system and is typically perceived as pleasant and socially supportive, with faster touch, but otherwise identical touch, that is known not to activate the CT system optimally and is typically judged to feel ‘neutral’ and without a specificity in communicating social intentions. Accordingly, this affective touch manipulation affords experimental control and validity regarding different conditions of social support, while also allowing interpretations of neurophysiological relevance.

Accordingly, the present study employed a well-validated paradigm, namely the Cyberball task (Williams et al., 2000), to manipulate ostracism in eighty-four healthy females. Following social exclusion, slow affective CT touch (at CT optimal speeds) was delivered to half of the participants, while fast non-CT touch (at non CT optimal speeds) was delivered to the other half. Using these manipulations, this study investigated the hypothesis that slow, affective CT touch would lessen the distress caused by ostracism more than fast, non-CT touch.

2.2 Methods

2.2.1 Participants

Eighty-four females were recruited via the University College London (UCL) Psychology Subject Pool and were compensated for their participation with £8 or 1 credit. The sample size was determined based on prior power calculations (Cohen’s d set at 0.4; G*Power 3.1) in accordance with the average effect sizes reported in experimental social psychology (Richard, Bond, & Stokes-Zoota, 2003) and other social experimental studies manipulating touch in relation to physical or social pain (e.g., Tai et al., 2011). The UCL ethics committee approved this study and the experiment was conducted in accordance with the Declaration of Helsinki. Only females were recruited to control for gender effects related to touch (Gazzola et al., 2012; Suvilehto et al., 2015). Participants were excluded if they reported a history or current psychiatric or/and neurological condition. As presented in Table 2.1, there were no significant differences between the groups on age, ethnicity, education or any other demographic variable.

Table 2.1
Demographic characteristics for participants allocated to the slow and fast group. Age, BMI and mood are presented as mean (standard deviation).

	Slow Touch Group (n=42)		Fast Touch Group (n=42)		*T*	*p*
Age (in years)	22.21 (2.10)		22.86 (3.06)		-1.12	.27
BMI	20.84 (2.43)		21.44 (3.66)		-.88	.38
Missing	2		1			
	N	%	N	%	X^2	*p*
Relationship Status					.43	.51
In a relationship	21	50	24	57.1		
Single	21	50	18	42.9		
Ethnicity					4.23	.65
Caucasian	10	23.8	6	14.3		
Asian-British/Asian	23	54.8	29	69		
Mixed/Multi-racial	3	7.1	3	7.1		
Arabic	1	2.4	0	0		
Hispanic/Latino	2	4.8	1	2.4		
Black/ Black British	1	2.4	0	0		
Other	2	4.8	3	6		
Highest Level of Education Completed					.39	.82
High School	16	38.1	16	38.1		
Bachelor's Degree	20	47.6	18	42.9		
Master's Degree	6	14.3	8	19		
Sexual Orientation					.13	.94
Heterosexual	36	85.7	37	88.1		
Homosexual	1	2.4	1	2.4		
Bisexual	5	11.9	4	9.5		

2.2.2 Design

This study employed a 2 (ostracism: inclusion/baseline vs. exclusion; within-subjects factor) x 2 (touch velocity: slow vs. fast; between-subjects factor) mixed design, using the Cyberball paradigm to manipulate ostracism (Williams et al., 2000) and randomly assigning participants to a slow touch (n=42) or, a fast touch group (n=42) to manipulate affective social support following exclusion. This mixed design, with a between-subjects manipulation of affective touch was judged as necessary, given that the Cyberball paradigm cannot be implemented optimally in repeated measures design (pilot studies indeed revealed that subjects were 'suspecting' the rejection/exclusion manipulations when these were repeated). Hence, all participants completed the inclusion/baseline and exclusion conditions. However, as far as the between-group manipulation goes, I needed a baseline measure without any between-group manipulation in order to make sure there were no baseline differences across groups. Thus, the between-group manipulation only took place following the exclusion, but not inclusion/baseline, condition. The main measure included the Need-threat scale, as well as manipulation checks conducted on affect, the Cyberball task and perceived pleasantness of the touch (see below).

2.2.3 Procedure and materials

Upon obtaining written informed consent, participants were told they would be playing an online ball-tossing game against two other participants (who were in fact computer-generated) in order to measure their mental visualization skills (Williams et al., 2000). Participants could throw to whomever they wished, and they believed the other "players" could do so as well. Participants' photographs were taken to maintain the deception. Two adjacent stroking areas, each measuring 9 cm x 4 cm, were then marked on the participant's left forearm in order to alternate between tactile stimulation sites and minimise habituation (McGlone et al., 2012).

Participants first completed computerized demographic questionnaires. Participants then played the Cyberball-inclusion game for approximately 2-3 minutes. This corresponded to a 30 ball-tosses game, where all players received equal number of ball-tosses. Upon completion, participants rated twenty-items (e.g., 'I felt I belonged to the group', 'I felt liked'; corresponding to the 'Need-threat scale'; Jamieson, Harkins, & Williams, 2010). The need-threat scale is an index of four fundamental needs often threatened by ostracism, namely: belonging, self-esteem, meaningful existence and control. Given that ostracism is an interpersonally aversive behavior unique in that, compared to physical or verbal altercations, it can threaten these particular needs (Williams, 2009). For example, ostracism can affect the sense of social connection (i.e., belonging), it can lead to rumination about why people are ignoring and excluding them (i.e., self-esteem), lack any ability to engage the source of the ostracism being unilateral (i.e., control) and elicit feelings of invisilbility, similar to not existing or being dead (i.e., meaningful existence) (Williams, 2002, 2009). Participants' responses were averaged across each need subscale to yield an averaged total index of need-threat level (Cronbach α =.87), with lower scores indicating greater threat. This was the main self-report measure of the effects of ostracism in this study, as in most studies using this paradigm (e.g., Durlik & Tsakiris, 2015; Jamieson et al., 2010; Teng & Chen, 2012).

Following a 10-minute break of Sudoku-like activities, participants played the Cyberball-Exclusion game for 2-3 minutes; they received the ball 2 initial times, while they were excluded in the remaining ball-tosses. Upon completion, participants were blindfolded. The experimenter stroked the participant's marked skin areas for 70 seconds with a soft brush (Natural hair Blush Brush, No. 7, The Boots Company) in either: CT-optimal speed (3cm/s; slow touch group) or non CT-optimal speed (18 cm/s; fast touch group), as in previous studies by our group (Crucianelli et al., 2013; Gentsch et al., 2015; Krahé et al., 2016). The experimenter was trained to deliver the touch at these two different speeds. Following tactile stimulation, participants filled out the main measure of ostracism, namely the Need-threat scale. As before, participants' responses were averaged across each subscale to yield an averaged total index of need-threat level (Cronbach α =.73), with lower scores indicating greater effects of ostracism (see Figure 2.1 for a schematic representation of the study procedure).

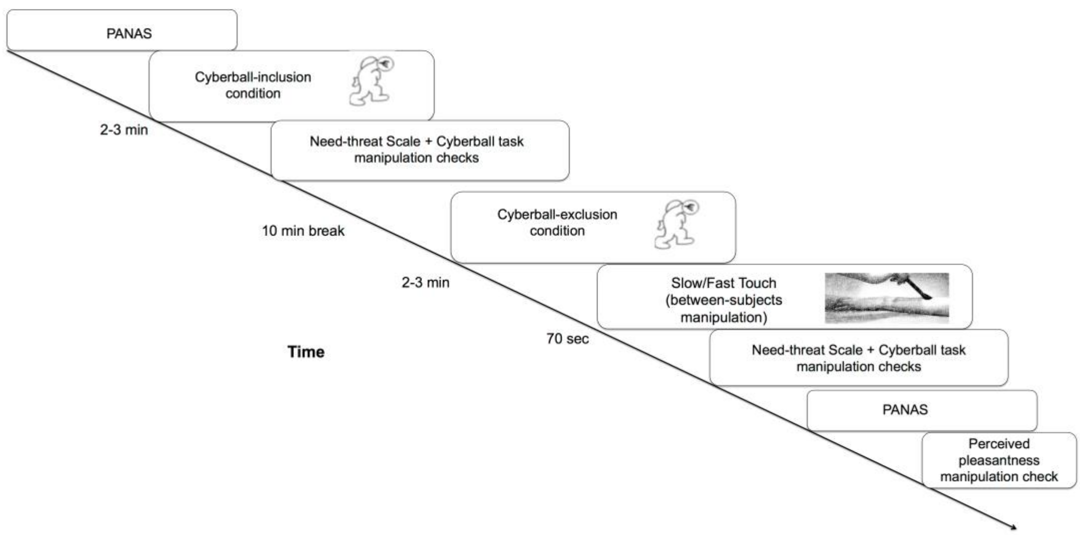


Figure 2.1: Schematic representation of study procedure. All participants completed the same experimental procedure, in the exception of receiving slow or fast touch after the Cyberball exclusion condition, depending on their assigned group. PANAS,

Positive and Negative Affect Schedule, was completed at the beginning of the experiment as well as after the cyberball exlusion and touch manipulation; Slow touch (3 cm/s); Fast touch (18 cm/s) between-subjects manipulation lasted 70 seconds.

2.2.4 Manipulation checks

2.2.4.1 Affect. The Positive Affect and Negative Affect Schedule (PANAS; Watson, Clark, & Tellegen, 1988) was used to assess potential changes in affect as in many previous studies using the Cyberball paradigm (e.g., Pfundmair, Aydin, Frey, & Echterhoff, 2014; Q. Zhang et al., 2017). The PANAS includes two affect scales, one affect scale measures positive affect and the other one measures negative affect. This measure has twenty items in total (ten items per scale), rated on a continuous five-point scale, ranging from ‘not at all’ to ‘extremely’. Scores for positive and negative affect items were summed, separately, yielding a total score for each affect scale. Higher scores indicate high (positive or negative) affect. Affect ratings were collected at the beginning of the experiment, as well as upon completion of the Need-Threat scale following the Cyberball-Exclusion game and touch manipulation (at the very end).

2.2.4.2 Cyberball task. Two types of manipulation checks were conducted on the Cyberball task, namely, exclusion perception and attention checks. First, upon completion of the Cyberball task and need-threat scale, participants reported whether they perceived having been ‘excluded’ and ‘ignored’ during the game in order to assess whether they had experienced the Cyberball task as intended. This manipulation measure, used in most previous studies using the Cyberball paradigms (e.g., Jamieson et al., 2010; Zadro, Williams, & Richardson, 2004), is separate from the main dependent variable of interest (i.e., the need-threat scale; see Jamieson et al., 2010) as it assesses the perception of ostracism rather than feelings of ostracism associated with the Cyberball game. These manipulation check items were rated on a continuous 5-point scale, ranging from ‘not at all’ to ‘extremely’. Consistent with prior research (Durlik & Tsakiris, 2015), to ensure the validity of the Cyberball task we examined whether our participants experienced the task as intended, i.e. they felt excluded in the excluded condition. Thus, the two items assessing how ignored and excluded participants felt were averaged and cases with scores 2 SD above/below the overall mean were excluded from main analyses. Five and one participants for the fast and slow touch group, respectively, did not meet this criteria and were excluded from further analyses. Second, participants also reported an estimate on the percentage of ball tosses they received during the Cyberball game to ensure they were paying attention. No participants were excluded on this basis (scores 2 SD above/below the overall mean).

2.2.4.3 Perceived Pleasantness. At the end of the experiment, we collected pleasantness ratings of slow, affective CT optimal and fast, neutral non CT optimal touch from both groups to make sure that participants perceived slow touch as more pleasant than fast touch, irrespective of their assigned group, in accordance with prior literature (Ackerley, Carlsson, et al., 2014; Löken et al., 2009). We used a soft brush (Natural hair Blush Brush, No. 7, The Boots Company) to administer 16 randomized trials of 3-second tactile stimulation at CT-optimal (3 cm/s) and non CT-optimal (18 cm/s) speeds to the participant's previously marked forearm skin areas. Note that these CT and non-CT speeds are the same speeds administered in the touch manipulation following the exclusion condition. After each trial, participants were asked to rate the pleasantness of the touch by using a scale ranging from 0 'not at all pleasant' to 100 'extremely pleasant'. CT optimal slow and non-CT optimal fast touch ratings were averaged separately for each participant, creating fast touch and slow touch pleasantness averaged rating scores for each participant.

2.2.5 Statistical analyses

Data exploration confirmed that the continuous variables of interest were normally distributed. Moreover, tests of normality (i.e., Kolmigorov-Smirnov, Shapiro-Wilk) were conducted on this data. In spite of data being normally distributed, the assumption of homogeneity of variance throughout grouped data was violated in the inclusion condition ($p < 0.05$ on the Levene's test), but not the exclusion condition ($p > 0.05$ on the Levene's test), need-threat total scores. Given that group sizes were relatively equal (ratio of the larger to smallest group being less than 1.5) and thus the F statistic may be robust to this assumption, parametric tests were employed and reported. Nevertheless, analyses on the need-threat total scores were also conducted by using non-parametric tests (i.e., Wilcoxon Signed Rank and Mann-Whitney U on difference scores) to make sure that these results were replicated, which in fact, yielded the same pattern of results. Statistical analyses were conducted on a final sample of seventy-eight participants (slow touch group: forty-one participants; fast touch group: thirty-seven participants). Welch tests with adjusted degrees of freedom (df) to correct for unequal variances were employed when t-test analyses indicated that equal variances were not assumed (i.e., Levene's test for equality of variances p<.05). Effect sizes are presented as partial eta-squared ($\eta 2_{partial}$). A .01 $\eta 2_{partial}$ represents a small effect size, .06 $\eta 2_{partial}$ represents a medium effect size and 0.14 $\eta 2_{partial}$ represents a large effect size (Cohen, 1988).

2.3 Results

To examine the effects of slow, CT-optimal versus fast, non-CT optimal touch on ostracism, we measured participant's need-threat level (i.e., need-threat scale; Jamieson et al., 2010) following the inclusion and exclusion condition and touch manipulations. Across the groups, participants reported more need-threat in the Cyberball exclusion (*M*=1.88, *SD*=.41), as compared to the inclusion/baseline (*M*=3.63, *SD*=.62), $F(1,76)=479.50$, $p<.001$, $\eta^2_{partial}=.86$. There was no effect of group, $F(1,76)=.38$, $p=.540$, $\eta^2_{partial}=.01$. As predicted, the ostracism condition interacted with the group, $F(1,76)=4.48$, $p=.038$, $\eta^2_{partial}=.06$. Post-hoc tests, using Bonferroni adjusted alpha levels of .025 per test (.05/2), showed that while threat levels between the groups did not differ at baseline (i.e., inclusion/baseline condition), $t(63.69)=-.81$, $p=.422$, Cohen's $d=.18$, there was a significant group difference in the exclusion condition, following touch manipulation. Specifically, participants that received slow touch (*M*=1.99, *SD*=.42) post-ostracism reported less need-threat than those that received fast touch (*M*=1.76, *SD*=.37), $t(76)=2.46$, $p=.016$, Cohen's $d=.56$ (see Figure 2.2).

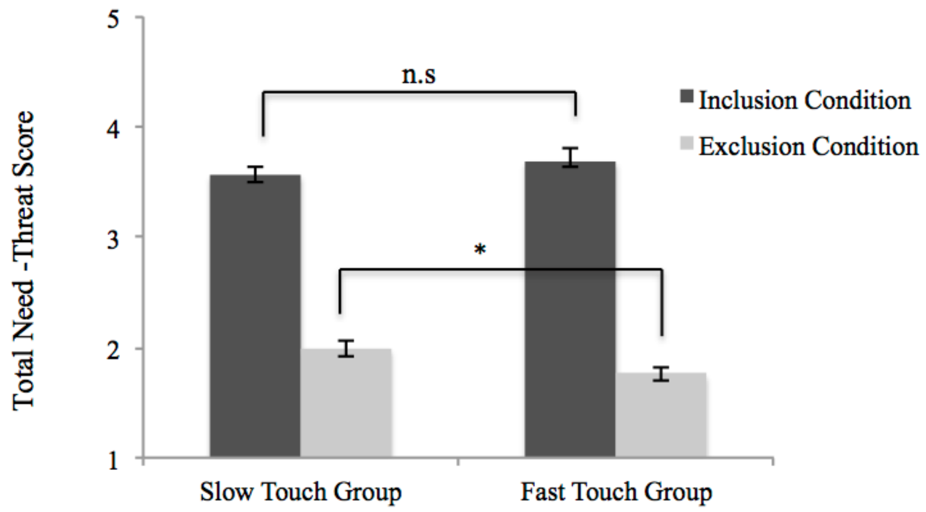


Figure 2.2: Inclusion and exclusion total need-threat score of the slow and fast touch group on a continuous 5-point scale. Lower scores indicate greater need-threat, i.e., more distress. Error bars denote ± standard error of the mean for illustration purposes. Asterisks indicate significant differences ($p < 0.025$) and n.s. indicate non-significant differences.

2.3.1 Manipulation checks

Across the groups, participants reported decreased positive affect (M=23.24, SD=7.81), but no differences in negative affect (M=15.87, SD=5.13), following the exclusion condition, as compared to baseline measures (positive affect: M=29.13, SD=7.13; negative affect: M=15.42, SD=5.34, respectively), $F(1,76)=68.17$, $p<.001$, $\eta^2_{partial}=.47$; $F(1,76)=.46$, $p=.499$, $\eta^2_{partial}=.01$, respectively. Importantly, positive and negative affect did not differ by the assigned touch group of the participants, $F(1,76)=.19$, $p=.661$, $\eta^2_{partial=}.01$; $F(1,76)=.13$, $p=.715$, $\eta^2_{partial=}.01$, respectively; nor did touch group interact with the ostracism condition, $F(1,76)=.2.42$, $p=.124$, $\eta^2_{partial=}.03$; $F(1,76)=1.18$, $p=.280$, $\eta^2_{partial=}.02$, respectively. Together, these results suggest that while social exclusion decreased positive affect, the type of touch received by the participants did not have a moderating effect on either positive or negative general affect following social exclusion.

Overall analyses conducted on the cyberball task manipulation check scores suggested that the manipulation of ostracism was effective. Participants reported having been excluded and ignored to a greater extent in the exclusion (M=4.53, SD=.61) as compared to the inclusion condition (M=1.40, SD=.57), $F(1,76)=1165.16$, $p<.001$, $\eta^2_{partial}=.94$. In addition to these manipulation checks, participants were also asked to estimate the percentage of ball-tosses that they received during the game to ensure they were paying attention to the task. As expected, participants reported receiving a lower percentage of ball-tosses during the exclusion (M=5.59%, SD=7.67%), as compared to the inclusion condition (M=32.35%, SD=8.93%), $F(1,76)= 724.39$, $p<.001$, $\eta^2_{partial}=.91$. Furthermore, group did not interact with the ostracism condition on the ostracism and attention manipulation checks, $F(1,76)=.95$, $p=.332$, $\eta^2_{partial}=.01$, $F(1,76)=.02$, $p=.895$, $\eta^2_{partial}=.00$, respectively, indicating that participants perceived the cyberball games in a similar manner, irrespective of their assigned group.

Analyses conducted on the pleasantness ratings scores of both type of touch (CT and non-CT optimal touch) suggested that CT and non-CT touch was perceived as expected in both groups. Participants perceived slow touch (*M*=67.68, *SD*=16.22) as more pleasant than fast touch (*M*=51.07, *SD*=13.45), $F(1,76)=67.69$, $p<.001$, $\eta^2_{partial}=.47$. Importantly, group did not interact with touch velocity, $F(1,76)=2.19$, $p=.143$, $\eta^2_{partial}=.03$, indicating that slow CT touch was perceived as more pleasant than fast non-CT touch, irrespective of the assigned group and hence our manipulations were successful in terms of perceived pleasantness of touch.

2.4 Discussion

This Chapter investigated the effects of slow, affective touch on the subjective effects of social exclusion or, ostracism, a form of social pain. Given the importance of social support and in particular, embodied social support (Coan et al., 2006; Decety & Fotopoulou, 2014), in buffering negative experiences, we predicted that slow affective touch would lessen the distress caused by ostracism. Consistent with prior research (Jamieson et al., 2010; Williams, 2009; Zadro et al., 2004), we found that people report more distress following conditions of social exclusion. However, contrary to past research (Leary, 2015; Williams, 2002), we found no differences in negative affect following conditions of social exclusion. Indeed, given that ostracism is a negative experience it can lead to an increase in negative affect in addition to threatening fundamental needs (Williams, 2009). There is some controversy, however, and it is worth noticing that for some studies, affect is not altered (e.g., Twenge et al., 2002; Zadro et al., 2004), possibly indicating affective numbness in cases in which the participant is left without any recourse for re-inclusion (Twenge et al., 2003). In our study, however, participants received touch following the ostracism manipulation, possibly indicating that the mere presence of another individual providing touch, i.e., social reconnection, may attenuate the negative affect elicited by social exclusion (Maner et al., 2007; Tai et al., 2011). Nevertheless, our main finding was that this distress, as measured by the need-threat scale, was significantly lessened in a group that received slow, affective touch following the ostracism manipulation, as compared to a fast, 'neutral' touch group, although neither manipulation was sufficient to totally eliminate the effects of social exclusion.

The current findings supported our predictions. Slow touch (CT-optimal speed), which was perceived as more pleasant than fast touch (non-CT optimal), was able to buffer to a degree the effects of interpersonal threatening experiences such as ostracism. Moreover, we found that affective touch did not have a more general effect on improving affect post-exclusion. Instead, it appears that affective touch is particularly effective in reducing feelings of social exclusion. Whereas one can assume that many other affective modulations may reduce the effects of social exclusion, e.g. reading a happy versus a sad story, the present findings are important because the only variable manipulated was the velocity of touch between individuals. Thus, many general and cognitive factors, e.g. social proximity, social desirability, attention, general mood effects, can be excluded as candidate explanations of our effect. Instead, our finding suggests that a unique type of embodied, tactile interaction between individuals is capable of modulating the subjective effects of social exclusion. These findings are consistent with research pointing to the role of touch in the formation of social bonds (Brauer et al., 2016; Suvilehto et al., 2015; Gentsch et al., 2015), as well as the findings that social exclusion can motivate interpersonal reconnection (Chester et al., 2016; Maner et al., 2007), including touch (Tai et al., 2011). Our findings therefore extend prior research indicating that touch leads to seeking interpersonal connection and pro-social behaviour following social exclusion (Tai et al., 2011), and suggest that particularly this type of dynamic slow touch, which is associated with neurophysiological specificity and conveys social support (Francis McGlone et al., 2014; Ellingsen et al., 2015; Kirsch et al., 2017)', buffers ostracism-related effects.

These findings add to the growing literature on the overlap between the physical and social pain system reviewed in Chapter 1 (section 1.2.3). Recent studies have found that CT-optimal touch reduces subjective (Liljencrantz et al., 2017) and neural responses to noxious stimulation (Krahé et al., 2016). The current study suggests that CT-optimal, affective touch affects the ‘social pain’ associated with ostracism, at least in the short run. These findings thereby support the notion that factors that influence physical pain may also modulate social pain, consistent with the physical-social pain overlap hypothesis (Eisenberger, 2012b).

More generally, the present findings corroborate and extend prior research on the beneficial effects of social support, and particularly embodied social support, on threat and stressful life events. While past research suggests that social support possesses stress-protective effects on social stressors, including social exclusion and correlated activity in the dACC (Eisenberger et al., 2007), such studies did not directly assess the actual role of social support in buffering ostracism-related effects. Subsequently, a recent study has shown that receiving supportive text messages during social exclusion leads to increased activity in left prefrontal areas as well as changes in activity in the ventral ACC during both social exclusion and support, suggesting a possible neurocognitive regulatory mechanism underlying cognitive-emotional support (Onoda et al., 2009). Moreover, one study assessed the buffering effects of the presence of a friend (versus a stranger) on the distress caused by ostracism (Teng & Chen, 2012). However, as aforementioned, these manipulations may entail many confounds. Thus, here we employed comparable conditions of embodied social support, namely slow, CT touch versus fast, non-CT touch, to minimise potential familiarity and social desirability confounds (Coan et al., 2006; Decety & Fotopoulou, 2014; Krahé et al., 2013). Embodied social support has been shown to reduce activity in brain regions implicated in emotion regulation when in threat, thereby pointing to the pivotal role of physical contact with others in how we cope with stressors (Coan et al., 2006). Thus, our findings extend existing literature by suggesting that embodied social support may not only buffer threats to physical safety (Coan et al., 2006), but also threats to social connection, e.g., ostracism. Future research is needed to examine whether such effects are associated with automatic changes in bodily state (e.g., visceral/autonomic), in line with Damasio's 'somatic marker hypothesis'.

2.4.1 Limitations, strengths and future directions

To the best of our knowledge, this is the first time that a sensory affective manipulation has been shown to buffer ostracism-related effects. However, the present findings should be considered in light of study limitations and directions for future research. First, a mixed design was employed, with a between-subjects manipulation of affective touch, which may thus entail potential individual variability confounds. Nevertheless, such between-subjects manipulation of touch was deemed necessary as a result of pilot studies suggesting that the Cyberball paradigm could not be optimally implemented in a repeated measures design (i.e., subjects suspected of the rejection manipulations when these were repeated). Second, only women were tested to control for gender effects related to touch (Suvilehto et al., 2015; Gazzola et al., 2012). However, it's worth mentioning that men and women seem to differentially benefit from verbal and tactile support (Ditzen et al., 2007; Heinrichs et al., 2003;

Kirschbaum, Klauer, Filipp, & Hellhammer, 1995). Thus, future studies should investigate whether the present results extend to men.

Third, although using comparable conditions of embodied social support has great methodological advantages (e.g., there are no pre-existing conscious beliefs about the velocity of the touch, can be tested against control conditions that involve the same support provider, etc.), it may in turn raise other experimental inquiries associated with this type of social support. For instance, are these modulatory effects on ostracism mediated by bottom-up physiological mechanisms or top-down learned expectations of pleasantness and support linked with this specific type of touch? Indeed, as reviewed in Chapter 1, the pleasantness and support associated with affective touch depend not only on bottom-up CT afferent signaling but are also influenced by learned expectations and social context. Specifically, as far as support is concerned, bottom-up mechanisms reflect sensory signals input processing (in this case CT-afferent signaling in response to slow touch in CT skin), whereas top-down mechanisms reflect higher cognitive processes (including learned expectations linked to a stimuli, in this case social support to slow touch, even though such process does not need to entail declarative preexisting knowledge, i.e., might have been learned behaviorally; Kirsch et al., 2017). Similarly, as far as pleasantness is concerned, bottom-up mechanisms reflect sensory signals input processing (in this case CT-afferent signaling in response to slow touch in CT skin), whereas top-down mechanisms reflect higher cognitive processes pertaining to pleasure (including learned expectations linked to the valence of the tactile stimuli, even though, as above, such process does not need to entail declarative preexisting knowledge, see Gentsch et al., 2015; McGlone et al., 2014) that may influence how (sensory-tactile) stimuli are experienced (Ellingsen et al., 2015). Consequently, affective touch experience involves a complex interplay between bottom-up and top-down processes. Future investigations examining the effects of touch at contrasting velocities (slow versus fast) in CT (e.g., forearm) versus non-CT (e.g., palm) skin are needed to provide insight into the separate involvement of bottom-up CT-afferent signaling and top-down expectations of support in the face of ostracism.

Furthermore, as reviewed in Chapter 1 (section 1.4), higher order top-down processes (e.g., individual differences in attachment style and social context) may influence our perception of social support, including affective touch, and consequently, our psychological responses to stress (Ditzen et al., 2008) and even pain. Interestingly, research suggests attachment style moderates the effects of slow affective touch on noxious stimulation (Krahé et al., 2016). Concurrently, such effects depend on social contextual factors (e.g., touch by romantic partners, see Chapter 3). Thus, it is possible that these top-down factors may not only modulate the effects of affective touch on physical pain but also on social pain. The role of individual differences in attachment style was not pursued in the current study given the mixed design employed in this study. Specifically, this mixed design, with a between-subjects manipulation of affective touch, would make problematic any inferences about the influences of attachment style on our effects of social exclusion by touch. Thus, future research is needed to examine potential dispositional and contextual factors at play, perhaps using a different design and paradigm to investigate the former.

Fourth, an ongoing challenge for social cognitive neuroscience is to balance the need for an ecologically valid social environment with the need for experimental control (Schilbach, Timmermans, & Reddy, 2012). The present study employed the Cyberball paradigm. While the Cyberball task is a well-validated paradigm that has consistently been shown to elicit strong negative reactions (Williams, 2007; Williams, 2009), it is well known that one of its main limitations is the lack of ecological validity. In terms of ecological validity, this methodological approach misses key mechanisms of everyday social interactions, including a broad array of contexts, verbal and non-verbal interactions and interpretations of self and other (Parsons, 2015; Schilbach et al., 2012). One way to increase both experimental control and ecological validity could be to employ virtual reality (Campbell et al., 2009) to elicit feelings of social exclusion. Advances in virtual technology may offer platforms in which three-dimensional objects are presented in a dynamic and controlled manner, while also immersing the individual in simulations that create a sense of 'being there', thus enhancing ecological validity in an experimentally controlled setting (Parsons, 2015). However, the present study did not employ virtual reality technology given its potential drawbacks in terms of cost, specialist technology skills required and the lack of psychometric validation for eliciting feelings of social exclusion.

Further, in accordance with prior research in the field (e.g., Gordon et al., 2013; Krahé et al., 2016), the present study employed cosmetic-like soft brushes to deliver the touch, which is clearly not the same as receiving skin-to-skin tactile stimulation and therefore, such technique could have missed essential mechanisms of everyday socio-tactile interactions that may convey support. In other words, gentle skin-to-skin touch plays a key role in social bonding as well as conveys social support (Field, 2010; Hertenstain et al., 2006) and the use of soft brushes, which do not necessarily reflect everyday social interactions, is likely to elicit different sensory-affective responses associated with social support. However, using cosmetic-like soft brushes to deliver the touch, as compared to skin-to-skin contact, allowed us greater experimental control – factors ranging from variations in skin temperature, sweating rates of the person delivering the touch to potential feelings of awkwardness of the person receiving skin-to-skin touch by a stranger could play a major role in how an individual interprets this kind of embodied social support. Moreover, soft, hairy like materials are frequently used in toys and gadgets as proxies for social support and affiliation, and pet stroking studies have showed that petting, and particularly stroking (Vormbrock & Grossberg, 1988), hairy animals, i.e., dogs, attenuates transient physiological and psychological responses such as blood pressure, heart-rate and state anxiety (Baun, Bergstrom, Langston, & Thoma, 1984; Jenkins, 1986; Vormbrock & Grossberg, 1988; Wilson, 1987). Similarly, in monkeys, it has been shown that touch and proximity to softness, i.e., 'contact comfort', even if it is artificial softness as in a built-in 'soft' (made out of cloth) surrogate mother, is a proxy for the mammalian need for social attachment (Harry F. Harlow & Zimmerman, 1959). Thus future research should examine whether skin-to-skin contact, as compared to human and robot-based tactile stimulation by the use of soft brushes, may elicit different responses to feelings of ostracism.

Relatedly, the current study delivered the touch following the manipulation of social exclusion. This was done for two main reasons. The first, to increase ecological validity (e.g., it is more likely to receive social support after you have been socially excluded, rather than before). The second, because our hypothesis was related to examining whether affective touch can *buffer* feelings of distress caused by ostracism, which has been associated with seeking interpersonal re-connection (i.e., soothing touch). However, future research should examine whether administering CT vs. non-CT touch prior to social exclusion yields similar results. Indeed, this latter 'conditioning' hypothesis would be in line with recent evidence suggesting that post-conditioning of social stimuli with CT-targeted touch increases 'approaching' behaviour (Pawling et al., 2017).

Finally, other interactive mechanisms, such as thermoregulation, could mediate the buffering effects of affective touch. Interestingly, social exclusion is associated with an experience of 'coldness', e.g., leads to lower room temperatures estimations while increasing desire for warm food or drinks (Zhong & Leonardelli, 2008) Conversely, CT afferents respond optimally to dynamic touch around 32 °C (Vallbo et al., 1999), (Ackerley, Wasling, et al., 2014) and thus, affective touch in this context may also provide some kind of 'warm' embodied support. Indeed, mammalian physical contact with conspecifics involves social thermoregulatory processes, which rely on thermosensory and somatosensory pathways in response to slow touch (IJzerman et al., 2015; Morrison, 2016). Given the functional and anatomical proximity of C thermoregulatory and mechanosensitive C afferents, it is possible that CT afferents may mediate circuits important for thermoregulatory behaviours (Morrison, 2016), including social exclusion. Future research is needed to examine whether social thermoregulatory mechanisms mediate the present effects.

Despite these limitations, the present study corroborates and extends prior literature on the regulatory function of slow, affective touch. It demonstrates for the first time that slow, affective touch, as compared to fast, 'neutral' touch, can lessen to a certain degree the distress caused by ostracism, a form of social pain. These findings point to the soothing function of affective touch, particularly in the context of social separation or rejection. Future research is needed to specify the neurophysiological mechanisms involved.

Chapter 3

The Social Buffering of Pain by Affective Touch: A Laser-evoked Potentials Study in Romantic Couples

3.1 Introduction

In Chapter 2 we saw that affective touch reduces feelings caused by social exclusion, a form of social pain. Such findings were consistent with the growing literature on the overlap between the physical and social pain system reviewed in Chapter 1, given recent evidence suggesting that affective touch also attenuates physical pain (Krahé et al., 2016; Liljencrantz et al., 2017). However, the perception of support in the face of pain is influenced by social context (see Chapter 1, section 1.2). Thus, the present Chapter aimed to examine the social buffering of physical pain by affective touch in a social context in which attachment is already established, namely in the context of a romantic relationship. Examining the role of affective touch in this particular context is important because close social bonds, or attachment relationships, have been long known to serve safety and distress-alleviating functions (Bowlby, 1969; Mikulincer et al., 2003). In addition, evidence from non-human mammals further suggests that it is not the mere presence of conspecifics but rather certain active behaviours (e.g., tactile contact, grooming, licking by conspecifics) that are important for affective regulation (e.g., Nelson & Panksepp, 1998).

Given the above evidence, recent proposals suggest that mammals, including humans, have adapted to the presence and active care of other conspecifics, so that our ability to form and regulate emotions (Atzil & Barrett, 2017) and our sense of selfhood (Fotopoulou & Tsakiris, 2017) are constituted on the basis of early social interactions. Thus, according to such theories, social proximity and active social support constitutes the default assumption of the human brain (i.e., social baseline theory; Beckes & Coan, 2011; Coan, 2011) or inherited ‘priors’ in predictive coding accounts (Decety & Fotopoulou, 2015). An ensuing prediction of such theories is that individuals employ fewer higher-order, self-regulatory psychological and neural processes when faced with threats in socially supportive contexts than when alone (Coan, 2011; Eisenberger et al., 2007). Indeed, functional neuroimaging studies have shown an attenuation of neural responses typically implicated in affective regulation (e.g. dorsolateral prefrontal cortex, anterior insula), when social support by a close other (e.g., hand-holding by a romantic partner versus a stranger) is provided in the face of physical threat (Coan et al., 2006), including pain (Eisenberger et al., 2011; Krahé et al., 2015).

However, the explanatory potential of these neuroimaging studies is restricted in two important ways that we aim to address in this study. The first restriction is that such studies have mostly focused on passive support of one's partner versus control conditions of absence of such support, e.g., presence versus absence (Krahé et al., 2015), static hand-holding versus no or stranger hand-holding (Coan et al., 2006; Goldstein et al., 2018), viewing pictures of one's partner versus a stranger (Eisenberger et al., 2011). In contrast, there are no neuroscientific studies on active forms of social support from one's partner, even though in behavioural studies passive and active support have been found to have opposite psychological effects on pain (Krahé & Fotopoulou, 2018; Krahé et al., 2013). Moreover, comparisons between supportive versus non-supportive actions (i.e., active support) of the same support provider have greater experimental control and hence explanatory power than many of the manipulations of the above studies, given that they are not subject to confounds such as social distraction, comfort and familiarity. Accordingly, in this study we aimed to examine for the first time the effects of different forms of tactile active social support by one's romantic partner on pain.

Although there are many ways to provide active support, here we employed slow affective touch given it has been shown to be a particularly effective and salient embodied form of communicating active, social support (see Chapter 1 also for its neurophysiological specificity and affective valence). Importantly, this type of touch allows us to address the second major restriction of the existing neuroimaging studies on partner support during pain. Namely, simultaneous manipulations of social touch (e.g. hand-holding) and pain as in previous studies (e.g., Goldstein et al., 2018; see also Coan et al., 2006), does not allow precise inferences about the mechanisms of pain modulation, given evidence suggesting touch-induced analgesia (Liljencrantz et al., 2017; Mancini et al., 2015) and the fact that these studies cannot control for skin-to-skin touch parameters (e.g. pressure of handholding, movement, sweating, temperature) or distraction effects. In contrast, one could control for all these confounds and their interactions by comparing slow touch, that is known to be primarily mediated by the CT-system and is typically perceived as pleasant, with faster but otherwise identical touch, that is known to not activate the CT system optimally and is typically judged to feel ‘neutral’. Specifically, given that slow, CT-optimal touch can specifically signal positive emotions and social support (Kirsch et al., 2017; von Mohr et al, 2017), this manipulation can be done off-line, i.e. not simultaneously with, but before the noxious stimulation, to signal a socially supportive context to the individual about to receive pain.

Indeed, a recent laser-evoked potentials (LEP) study found that individual differences in adult attachment style (see Chapter 1, section 1.4) determine how a stranger’s slow CT-optimal affective touch (versus faster and rated as emotionally neutral but otherwise identical touch), applied before noxious stimulation, affects early responses to noxious stimuli, namely the N1 component (Krahé et al., 2016). However, it remains possible that slow affective touch provided by a romantic partner, where social trust and attachment is already established, might also impact higher-order pain regulation, as captured by later LEP components, i.e. the N2-P2 complex. A romantic partner’s slow affective touch can be more powerful as affective touch is central to intimate, romantic relationships (Suvilehto et al., 2015) and the regulatory role of touch seems to be mediated by psychological intimacy (Debrot, Schoebi, Perrez, & Horn, 2013).

Therefore, the present study goes beyond previous research to investigate the effects of a form of active social support, namely affective touch, on subjective and neural responses to pain in the context of a romantic relationship. Healthy women received slow, CT-optimal touch by their partners versus faster, CT non-optimal touch, followed by laser-evoked noxious stimulation, without any other communication between partners. We measured self-reported pain as well as deflections in the ongoing electroencephalogram (EEG) time-locked to transient noxious radiant heat stimulation, namely the N1 and N2-P2 components (Plaghki & Mouraux, 2005), that can tease apart different stages of pain processing: The N1 consists of an early deflection peaking around 160 ms post-stimulus onset and is thought to reflect early sensory (nociceptive) processing preceding conscious awareness (Lee et al., 2009; Valentini et al., 2012), whereas the N2-P2 comprises a later biphasic complex peaking around 200-350 ms post-stimulus onset and is considered to reflect the salience associated with a conscious experience of pain (Lee et al., 2009; Mouraux & Iannetti, 2009). Using these methods, we sought to test two main hypotheses. First, we hypothesized that slow versus fast touch would attenuate subjective pain ratings and laser-evoked potentials reflecting both early and later stages of cortical pain processing, namely the N1 and N2-P2 local peak amplitudes. Second, we expected such effects to be moderated by individual differences in adult attachment style as in previous studies on social support and pain (as described in Chapter 1) in that affective touch should have the largest effect in individuals with higher attachment anxiety (who fear of rejection and seek clear signals of support) and the smallest effect in individuals with higher attachment avoidance (who prefer to cope with threat alone).

3.2 Methods

3.2.1 Participants

Thirty-two couples in a romantic relationship were recruited. We experimentally induced pain in the women (henceforth ‘participants’), while their partners delivered the (slow CT optimal, fast non-CT optimal) touch. Participants were included if they were right-handed and had been in their current relationship for over a year. The mean age of participants and their partners was M=24.53 (SD=3.78) and M=26.31 (SD=4.65), respectively, and had been in their current relationship for M=34.38 months (SD=26.24). Participants indicated they were Asian/Asian British (40.63%), White/Caucasian (31.25%), Hispanic/Latin-American (18.75%) and Multi-racial/other (9.38%). Couples were heterosexual (84.38%) and homosexual (15.62%). Participants were included if they were right-handed, 18-30 years old, had been in their current relationship for over a year, had no history of chronic pain, psychiatric or neurological disorder, had a depression severity score <9 (PHQ-9 questionnaire; Kroenke, Spitzer, & Williams, 2001), and had no tattoos or skin irritation/disease on the forearms or hands. The UCL research ethics committee approved this study and the experiment was conducted in accordance with the Declaration of Helsinki.

3.2.2 Design

Our within-subjects design comprised two experimental conditions: slow touch (3 cm/s; affective CT-optimal touch) and fast touch (18 cm/s; neutral, non-CT optimal) administered by the partner – with the order of these conditions counterbalanced across participants. Outcome measures were subjective pain ratings and N1, N2 and P2 local peak amplitudes. The moderating effect of adult attachment style was examined using a questionnaire that measures the degree of attachment anxiety and avoidance that individuals may experience in close, adult romantic relationships (Experiences in Close Relationships-Revised, ECR-R; Fraley, Waller, & Brennan, 2000).

3.2.3 Materials and measures

3.2.3.1 Tactile stimulation. Two skin areas (9 cm long x 4 cm wide) were marked on the participant's right forearm (i.e., stimulation sites). The partner administered the touch to the participant using a cosmetic make-up brush (Natural Hair blush brush, No 7, Boots, UK). The partner was trained to administer each touch condition by watching a 4-minute video and then practicing the touch on the second experimenter outside the testing room. In each touch condition, the stroking was administered in four 45-second mini-blocks in an elbow-to-wrist direction (Essick et al., 2010; Krahé et al., 2016) at slow (3 cm/s – 1 stroke) or fast (18 cm/s – 6 strokes) velocities. The velocity of the slow and fast touch was chosen given it has been shown to be optimal and non-optimal, respectively, for targeting CT afferents (Löken et al., 2009; Gentsch et al., 2015), with these same velocities having also been validated in our previous studies as showing statistically significant differences in their effects on social and physical pain (Krahé et al., 2016; von Mohr et al., 2017) and the communication of social support (Kirsch et al., 2017). The 3-second stroking was alternated with 3-second pauses. Stimulation sites were also alternated between trials to avoid CT habituation.

3.2.3.2 Nociceptive stimulation and subjective pain report. We used an infrared CO_2 laser stimulation device with a wavelength of 10.6 µm (SIFEC, Ferrières, Belgium) to deliver noxious radiant heat stimulation. The laser stimulus (80 ms duration, spot diameter of 6 mm) was applied to the dorsum of participant's left hand, changing the stimulation site between consecutive applications. This laser stimulates Aδ- fibers without co-activating lower-threshold Aβ-fibers (Churyukanov, Plaghki, Legrain, Mouraux, & El-Deredy, 2012). Using an ascending-descending-ascending staircase, we identified each participant's Aδ threshold for 'pinprick pain'(i.e., the lowest skin temperature that elicited a report of "pinprick sensation", which is linked to Aδ fibers, Lee et al. 2009). Beginning at 38°C, the laser temperature increased by steps of 4°C until the participant reported a clear pinprick sensation. Next, the temperature was decreased by steps of 2°C until the participant reported no pinprick sensation. Finally, the temperature was increased by steps of

1°C until the participant reported a pinprick sensation for three consecutive repetitions of the same temperature. The pain threshold (*M*=47.65 °C, *SD*=2.35) was used to set a mild-to-moderate (but always tolerable) sharp pinprick sensation (3°C above threshold, i.e., experimental trials) and no pinprick sensation (2°C below threshold, distractor trials). To ensure that participants were able to discriminate between these two laser intensities (i.e., 3°C above threshold, 2°C below threshold), they performed a forced-choice task in which they received a total of 20 randomised laser stimuli (10 stimuli set at the experimental intensity and 10 at the distractor stimuli intensity) and had to identify whether or not they felt the pinprick. If the percentage of correct trials was higher than 75%, we proceeded to the main experimental task. However, if participants scored less than 75% correct, their laser distractor intensity was decreased by 3°C (instead of 2°C) and we repeated the force-choice task (this was the case for two participants).

Each block consisted of 60 laser stimuli (40 experimental stimuli and 20 distractor stimuli), presented in pseudorandom order with an interstimulus interval of 10-15 s. The laser heated the skin to a specific temperature (rather than adding a fixed amount of heat) through the constant, online measurement of skin temperature at target laser stimulation, which was increased until it reached the predetermined temperature for the experimental (M= 50.65°C, *SD*=2.35) and distractor (M= 45.59°C, *SD*=2.38) trials. This allowed to control for potential confounders associated with changes in skin temperature throughout the experimental session. Participants were asked to keep their eyes on a white fixation cross on a computer screen in front of them and rate the intensity of each laser stimulus when the word 'rating' appeared on the screen (3 s after each laser stimulus). Participant's self-reported pain intensity was recorded using a numeric keyboard on an 11-point scale ranging from 0 (no pinprick sensation) to 10 (extremely painful pinprick sensation). Mean pain ratings for the experimental stimuli in each block (across the four mini-blocks for the touch conditions) were averaged and used as the measure of subjective pain report. The pain ratings of one participant were not recorded due to technical difficulties with the keyboard and are therefore not included in the statistical analyses (final sample n = 31 in pain ratings analyses).

3.2.3.3 EEG recording and LEP analyses. The study was carried out using a BioSemi ActiveTwo EEG system (http://www.biosemi.com; Biosemi, Amsterdam, The Netherlands) with a 64-electrode cap. A BioSemi analog input box (AIB) connected to the analog output of the laser stimulation device was used to record the online measurement of skin temperature at target laser stimulation site in register with the EEG recording across the experimental task. The electrooculography (EOG) was monitored with a total of four electrodes located at the outer canthi of both eyes as well as above and under the right eye. The sampling rate during recording was 1024Hz.

EEG data were processed and prepared for statistical analysis using EEGLAB/ERPLAB toolboxes for MATLAB (R2015b) (https://sccn.ucsd.edu/eeglab/index.php ; https://erpinfo.org/erplab/ ; see also Lopez-Calderon & Luck, 2014). Triggers for each experimental trial were set offline according to each participant's individual pinprick threshold by using the continuous skin temperature measurements recorded by the laser stimulation device. Data were then downsampled to 256Hz and digitally filtered (between .4 and 30 Hz) to reduce environmental noise. The EEG signal was then segmented into one-second event-related epochs (200 ms before and 800 ms after stimulus onset) and baseline-corrected. Visual inspection was used to remove noisy scalp channels and noisy eye channels, and trials with muscle and eye blink artifacts were rejected. Only averaged potentials for experimental trials were analyzed. We measured N1 and N2-P2 local peak amplitudes for individuals with at least 65% experimental trials following artifact rejection (as in Krahé et al., 2016). On average, participants had 91.7% (*SD*=7.58%), 89.85% (*SD*=6.48%) and 89.93% (*SD*=8.23%) experimental trials for the pain baseline (no touch), slow touch and fast touch conditions, respectively.

Average waveforms per condition were computed. For each waveform, the peak amplitude of the N1, N2 and P2 were measured as follows: The N1 was measured at the central electrode contralateral to the stimulated side (C6), referenced to Fz (Krahé et al., 2015, 2016). It was defined as the most negative deflection following stimulus onset and preceding the N2 wave (Lee et al., 2009). The N2 and P2 were measured at the vertex (Cz) referenced to the average of P9 and P10 (electrodes close to the mastoids, Luck 2014). The mastoids themselves were not used as an offline reference point for the N2 and P2 given technical difficulties associated with these channels during data collection, resulting in lack of signal from these channels in ~40% of participants. The N2 and P2 were defined as the most negative and positive deflection, respectively, after stimulus onset (Lee et al., 2009). In accordance with prior literature reporting that the earliest neural activity associated with laser stimulation occurs after 120 ms (Valentini et al., 2012), no deflection occurring before 120 ms after stimulus onset was selected as the peak (Krahé et al., 2015). One participant was excluded because she had fewer than 65% usable experimental trials, i.e., trials without artifacts. Further, two participants were excluded from the N1 and the N2-P2 analyses given that no plausible peak could be identified across any of the experimental conditions. For participants for whom we had average potentials available and had plausible potentials in at least one condition, we estimated the missing data using the maximum likelihood estimation command in the multilevel modelling analyses. The missing data from the N1, N2-P2 was not associated with any condition, rather indicating noise in the EEG and not a systematic bias. Overall, n = 29 participants were retained in N1 analyses and n = 29 in N2 and P2 analyses.

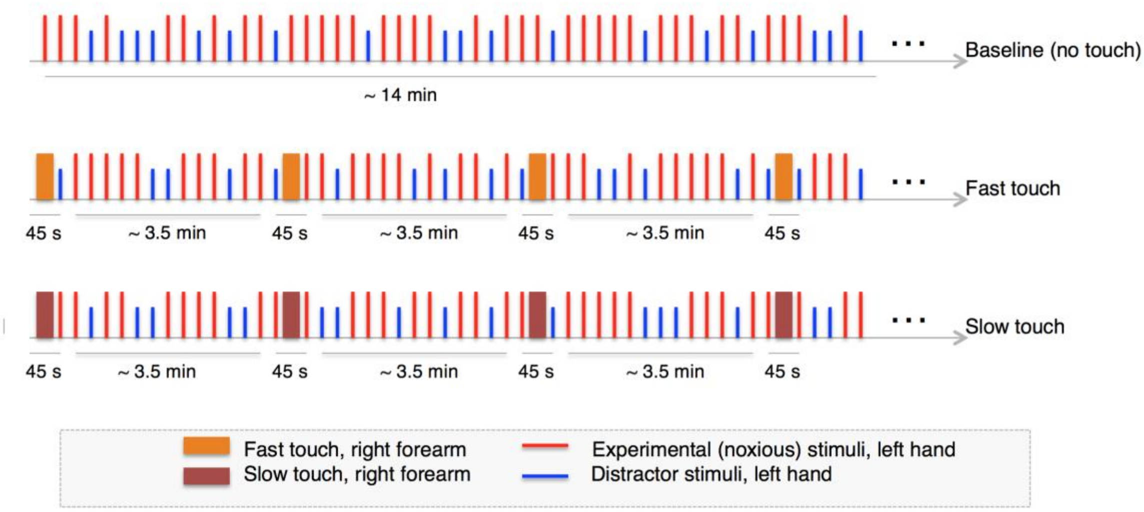
3.2.3.4 Adult attachment style. We employed the ECR-R (Fraley et al., 2000) to measure adult attachment style. This questionnaire is designed to measure individual differences with respect to the extent to which individuals are insecure about the responsiveness and availability of their romantic partners (i.e., attachment anxiety) and the extent to which individuals are uncomfortable with being close and depending on their romantic partners (i.e., attachment avoidance). The ECR-R consists of 36 items on a 7-point scale and yields continuous scores on attachment anxiety and attachment avoidance dimensions, with higher scores denoting greater attachment anxiety and avoidance, respectively. The ECR-R is a well-validated measure (Ravitz, Maunder, Hunter, Sthankiya, & Lancee, 2010). In the present sample, Cronbach's alpha was α= .86 for attachment anxiety and α=.89 for attachment avoidance.

3.2.4 Procedure

Upon obtaining written informed consent, each participant's pinprick pain threshold was determined, and the experimental and distractor laser intensities to be used in the main task were set based on this threshold. The experiment consisted of three laser blocks. Even though participants were told they would be receiving touch from their partners, they did not see or speak with their partners during any of the blocks, and they were prevented from seeing the stimulated skin areas through the use of a black box placed around the stimulated arms.

In the first block, we recorded participant's EEG while administering a baseline nociceptive stimulation block (no touch). In the two other blocks, participants received one of the two stroking velocity conditions (slow or fast touch) from their partner, followed by noxious stimuli (with the order of the stroking velocity conditions counterbalanced across participants). Each of these touch blocks was divided into four mini-blocks, alternating tactile stimulation with noxious stimulation (tactile and noxious stimulation were administered in spatial and temporal incongruence and asynchrony in order to avoid concurrent multisensory effects; see Figure 3.1 for a schematic of the experimental design). Between each block, there was a 7-minute break with Sudoku and/or crossword puzzle to minimize carryover effects; in the meantime, the partner was trained with the other touch velocity s/he was about to deliver to the participant. EEG was recorded throughout the periods of laser stimulation following slow and fast touch conditions. At the end of the study visit (approximately 120 minutes), participants were asked retrospectively to rate how comfortable they felt with the touch provided by their partner in each condition.

To avoid biasing the results of the main pain task, participants returned for a second visit, between 3 and 5 days after the first visit, in which they completed the adult attachment style questionnaire (ECR-R) and provided pleasantness ratings for slow and fast touch. Participants were paid £50 for their (and their partner's) time and



were fully debriefed at the end of the second visit.

Figure 3.1: Experimental design. Our experimental design for the main task included a baseline (no touch) nociceptive block followed by a fast touch or a slow touch

block. The order of the touch (fast or slow) blocks was counterbalanced across participants. The laser stimuli (experimental and distractor trials) were presented in pseudorandom order with an interstimulus interval of 10-15 s.

3.2.5 Plan of statistical analyses

All statistical analyses were conducted in STATA (Version 14). As repeated measures (Level 1) were nested within individuals (Level 2), multilevel modelling was implemented. For each outcome variable (pain ratings and N1, N2 and P2 local peak amplitude), we specified multilevel models with touch condition (slow touch/fast touch) as a dummy-coded categorical predictor, attachment avoidance and attachment anxiety as continuous predictors, and included all interaction terms. We controlled for pain baseline differences by including them as covariates (see also Supplementary Material Table S1 for analyses controlling for relationship quality in our models). All continuous predictors were mean-centred in order to avoid multicollinearity issues (Tabachnick & Fidell, 2007). Significant interactions were followed up by examining differences between conditions at low (−1 SD), moderate (mean) and high (+1 SD) continuous attachment style scores (see Aiken & West, 1991 for testing and interpreting interactions on continuous variables).

3.3 Results

3.3.1 Descriptive statistics and manipulation checks

Mean adult attachment scores were $M = 2.50$ ($SD= 0.75$) for attachment anxiety and $M = 2.55$ ($SD = .69$) for attachment avoidance (see Appendix 1 for comparisons with the general population). Attachment anxiety and avoidance dimensions were correlated at $r = .35$, $p<.05$. On average, participants reported good relationship quality/adjustment (M=25.84, SD=3.18) as measured by the seven-item Dyadic Adjustment Scale (Sharpley & Rogers, 1984). Relationship quality/adjustment did not correlate with attachment anxiety or avoidance dimensions (see Appendix 2). Table 3.1 presents descriptive statistics for pain ratings and associated neural responses (N1, N2 and P2 local peak amplitudes).

As expected, participants reported feeling more comfortable with slow touch (M=2.38, SD=1.16), as compared to fast touch (M=1.41, SD=1.74) from their partner, $t(31)=3.67$, p=001. Participants also reported higher pleasantness in response to slow touch (*M*=72.15, *SD*=13.48), as compared to fast touch (*M*=54.72, *SD*=14.16), *t(*31)=-5.89, *p*<001. Thus, our manipulations were successful in terms of perceived pleasantness and comfort of the touch.

Table 3.1
Mean (SD) for pain-related outcome measures**.**

	Baseline (no touch)	Slow touch	Fast touch
N1 local peak amplitude (μV)	-5.33 (3.27)	-3.50 (2.23)	-4.20 (2.60)
N2 local peak amplitude (μV)	-10.90 (7.09)	-5.92 (4.61)	-7.52 (5.08)
P2 local peak amplitude (μV)	16.02 (10.14)	9.65 (7.48)	11.81 (6.42)
Pain ratings	4.06 (1.73)	3.01 (1.84)	3.58 (1.82)

3.3.2 Do slow, affective touch and adult attachment style – alone and in interaction – modulate pain and associated neural responses?

3.3.2.1 Main effects. Full model results are presented in Table 3.2. Supporting our first hypothesis, a significant main effect of touch condition was found on the subjective pain ratings, N1, N2 and P2 local peak amplitudes. All our effects were in the same direction: Regarding the pain ratings, participants reported less pain in the slow touch (*M*=3.01, *SE*=.13) compared to the fast touch (*M*=3.58, *SE*=.13) condition (see Table 2). With respect to the neural responses associated with pain, the N1 local peak amplitude was significantly smaller in the slow touch (*M*=-3.48 μV, *SE*=.37) compared to the fast touch (*M*=-4.28 μV, *SE*=.39) condition; the N2 local peak amplitude was significantly smaller in the slow touch *(M*=-5.92 μV, SE=.59) compared to the fast touch (*M*=-7.65 μV, *SE*=.59) condition; and the P2 local peak amplitude was significantly smaller in the slow touch (*M*=9.65 μV, *SE*=.80) compared to the fast touch (*M*=12.11 μV, *SE*=.80) condition. No other main effects were significant (see Table 2). Together, these results suggest that pain report and associated neural responses were attenuated in response to slow, affective touch relative to fast, non-affective touch (see Figure 3.2 for N1, N2-P2 waveforms).

Table 3.2
Slow versus fast touch: multilevel modeling results for all outcome measures.

Effect	Dependent variable	b	*SE*	*p*-value	Confidence intervals	
					Lower	Upper
Slow touch vs. fast touch	**N1**	**-.97**	**.46**	**.036**	**-1.88**	**-.06**
	N2	**-2.06**	**.76**	**.007**	**-3.54**	**-.57**
	P2	**2.85**	**.89**	**.001**	**1.12**	**4.59**
	Pain ratings	**.62**	**.13**	**< .001**	**-.37**	**.86**
Attachment anxiety	N1	-.21	.54	.691	-1.28	.85
	N2	-1.35	.86	.116	-3.03	.33
	P2	1.61	1.18	.17	-.69	3.92
	Pain ratings	.01	.20	.97	-.39	.41
Attachment avoidance	N1	.05	.60	.939	-1.13	1.22
	N2	-.67	.96	.488	-2.56	1.22
	P2	-1.45	1.32	.270	-4.03	1.13
	Pain ratings	-.06	.22	.787	-.49	.37
Attachment anxiety * attachment	N1	-.77	.81	.343	-2.36	.82
	N2	**-2.70**	**1.22**	**.028**	**-5.11**	**-.29**

avoidance	P2	.97	1.68	.564	-2.33	4.27
	Pain ratings	-.02	.29	.945	-.59	.55
Touch condition *	N1	1.17	.64	.068	-.09	2.43
attachment anxiety	N2	1.26	1.04	.229	-.79	3.31
	P2	-2.01	1.23	.101	-4.41	.393
	Pain ratings	**-.41**	**.18**	**.023**	**-.76**	**-.05**
Touch condition *	N1	.28	.74	.709	-1.17	1.72
attachment	N2	2.19	1.17	.061	-.10	4.50
avoidance	P2	1.78	1.37	.195	-.91	4.48
	Pain ratings	-.15	.19	.442	-.22	.51
Touch condition *	N1	.19	1.05	.854	-1.87	2.26
attachment	N2	1.31	1.50	.384	-1.64	4.25
avoidance *	P2	-2.22	1.76	.207	-5.67	1.23
attachment anxiety	Pain ratings	-.26	.26	.305	-.76	.24

*Note. Significant main effects and interactions are highlighted in bold. Same pattern of results were observed when controlling for relationship quality (see Supplementary Table S1). While the interaction between attachment anxiety and attachment avoidance was statistically significant, follow-up tests were non-significant/trend level (see Appendix 3). Baseline pain as a covariate was statistically significant across all pain outcomes, $p<.05$

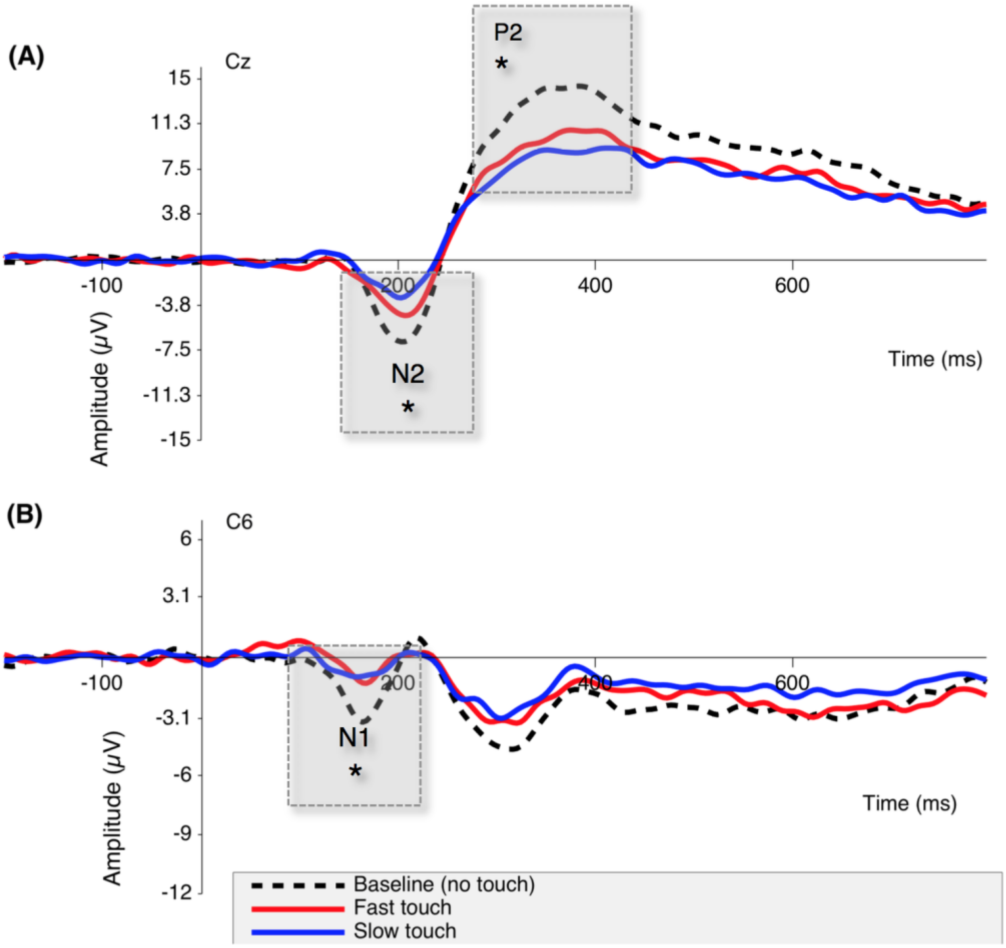


Figure 3.2: (A) Effect of touch condition on the N2-P2 waveform measured at the vertex (Cz) averaged across participants (B) Effect of touch condition on the N1 waveform measured at the contralateral side of stimulation averaged across participants (C6). N1, N2 and P2 local peak amplitude was significantly smaller in the slow touch compared to the fast touch condition, as denoted by asterisks. Baseline pain (no touch) as a covariate was statistically significant across the N1, N2 and P2 local peak amplitude.

3.3.2.2 Touch condition in interaction with attachment style.

Partially supporting our second hypothesis, we found a significant touch condition by attachment anxiety interaction on pain ratings, b = -.41, SE = .18, p = .023, but not on the neurophysiological outcome measures. Follow-up tests on the pain ratings showed that the difference between slow and fast touch conditions was significant for low (b = −.93, SE =.20, p <.001) and moderate attachment anxiety (b = −.62, SE =.13, p <.001), but not for high attachment anxiety (b = -.31, SE =.17, p = .074); see Figure 3.3. Thus, the higher the attachment anxiety, the smaller was the difference between slow and fast touch on pain ratings, i.e., at high levels of attachment anxiety, slow and fast touch did not differ in terms of their effects on pain ratings. There was no significant two-way interaction between attachment dimensions and no three-way interaction of touch condition, attachment anxiety and attachment avoidance on the pain ratings, indicating that these results were driven by the attachment anxiety dimension. Contrary to our second hypothesis, the interaction between touch condition and attachment avoidance was non-significant for all outcome measures.

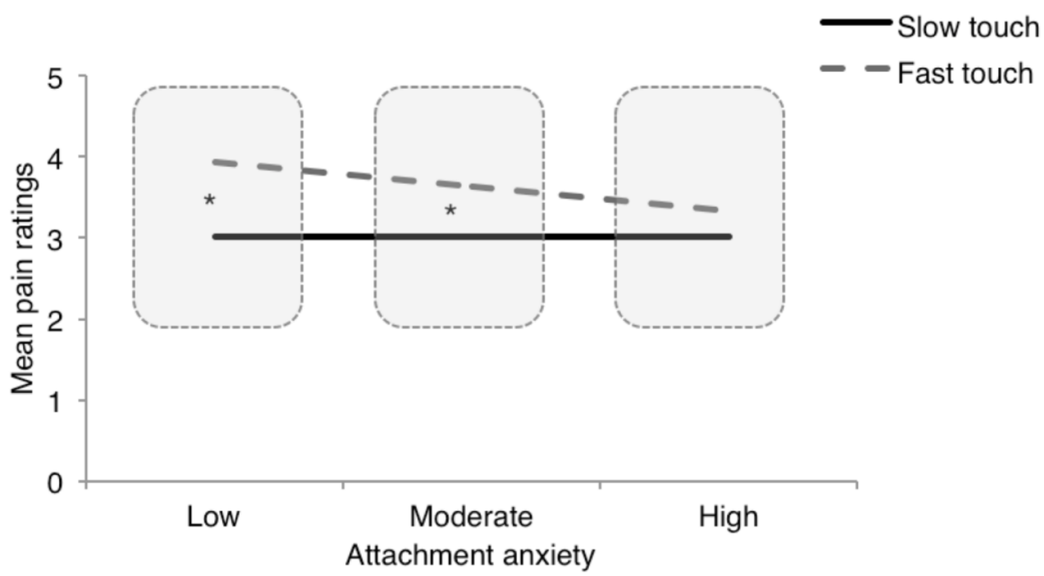


Figure 3.3: Touch condition by attachment anxiety effects for pain ratings. X-axis denotes attachment anxiety scores plotted at -1SD, mean, and +1SD. Y-axis denotes mean pain intensity ratings. Participant's self-reported pain intensity was recorded on an 11-point scale ranging from 0 (no pinprick sensation) to 10 (extremely painful pinprick sensation). Statistically significant differences are marked by asterisk, p<.05.

3.4 Discussion

While passive social support from one's romantic partner can have pain-attenuating effects and corresponding modulation of neural responses (Eisenberger et al., 2011; Goldstein et al., 2018; Krahé et al., 2015), little is known about the effects of active partner support on pain. Here, we investigated the effects of partner CT-optimal touch on pain, given the experimentally established role of this type of touch in the communication of positive emotions and social support (Kirsch et al., 2017; von Mohr et al., 2017). We found that slow, affective versus fast, non-affective touch from one's partner reduces subjective pain ratings and similarly attenuates laser evoked potentials (LEPs) both at earlier (N1) and later (N2-P2) stages of cortical processing. Contrary to our second hypothesis, adult attachment style did not affect laser-evoked potentials as in other social contexts (Krahé et al., 2016), but one facet of adult attachment style, namely attachment anxiety, had a moderating role on self-reported pain. These findings are discussed in more detail below.

Regarding our first hypothesis about the role of active, affective touch on pain reduction, we found such effects on pain report and LEPs reflecting both early and later stages of cortical nociceptive processing, namely the N1 and N2-P2 local peak amplitude. Our findings on the N2-P2 complex, which has been linked to activity in areas such as the anterior insula and anterior cingulate cortex (Garcia-Larrea et al., 2003) and to late, conscious aspects of noxious processing (Lee et al., 2009; Mouraux & Iannetti, 2009), are consistent with previous neuroimaging studies on passive social support (e.g., Eisenberger et al., 2011; Krahé et al., 2015) which found similar downregulation of brain areas supporting conscious aspects of noxious processing, such as the anterior insula and dorsal anterior cingulate cortex (Eisenberger et al., 2011). However, contrary to these studies, our N1 findings indicate that the effects of active, affective touch may begin at earlier stages of cortical nociceptive processing. Even though the N1 wave represents an early stage of sensory processing more directly related to ascending nociceptive input (Lee et al., 2009; Valentini et al., 2012), such cortical encoding is already 'late' in the grand scheme of noxious encoding. The N1 has been linked to activation in the operculoinsular and primary somatosensory cortex (Garcia-Larrea et al., 2003; Valentini et al., 2012), and such initial cortical coding of noxious afferent inputs is considered an essential, yet distinct stage of signal processing, different from later stages that are associated with the conscious aspects of pain and its affective regulation.

It is unlikely that the LEP downregulation we observed is based on potential interactions between nociceptive and CT pathways at the spinal cord level (Liljencrantz et al., 2017; Mancini et al., 2015), as the tactile and noxious stimulation in our study were delivered at different times and in different body locations. Instead, given that LEPs have been recently proposed to detect environmental threat to the body in response to sensory salient events (Legrain et al., 2011; Mouraux & Iannetti, 2009), we speculate that affective touch by one’s romantic partner when applied before noxious stimulation may reduce the sensory salience of impending noxious stimulation. Salience has various definitions. Here, we use the term to describe the importance of a stimulus (its weighting in relation to other factors) for indicating potential or actual threat to the body (Legrain et al., 2011) and for inducing related responses (Garcia-Larrea & Peyron, 2013). Conceptualizing the LEP-related brain activity as being part of a ‘salience network’ (Legrain et al., 2011), we have recently proposed that activity in this salience network is also modulated by information regarding contextual factors from the (social) environment (Krahé & Fotopoulou, 2018; Krahé et al., 2013; von Mohr & Fotopoulou, 2018; see also Atlas & Wager, 2012; Buchel, Geuter, Sprenger, & Eippert, 2014 for the role of expectations and active inference). Although the precise neurophysiological mechanisms of the effects of active, affective touch on pain will need to be studied in future studies, we discuss below four possible explanations of how the sensory salience of noxious stimulation may have been moderated in this study.

First, it is well known that pain can be modulated by distraction. While the current study controls various facets of social distraction better than previous studies (see section 3.1 Introduction), similarly to other pain modulation studies, we cannot exclude with absolute certainty that our two touch conditions did not have some difference in their general attentional demands. For example, non-affective touch delivered at fast speeds might have greater attentional demands than slow, affective touch (Davidovic, Starck, & Olausson, 2017). However, we think this is unlikely because if fast touch was, in fact, more attentional grabbing and thus distracting, we would expect fast versus slow touch to attenuate pain. Instead, our findings show the opposite pattern and as discussed below, it is possible that the mechanism by which affective touch can selectively modulate pain may relate to its salience.

Second, given the many factors that can influence pain when comparing across different socially supporting contexts, e.g. individual factors, habituation, distraction, mood, social presence, familiarity and many more, our aim was to compare directly between two specific and well controlled types of touch, slow and fast stroking on the forearm by the same, familiar person at different times and in different body locations than the noxious stimulation. To address this aim optimally, we have elected to use a within-subjects design, measuring individual pain measures before any manipulation and subsequently counterbalancing order between our two critical conditions. While this design is optimal for assessing whether pain responses are different between the two critical conditions, it does not allow us to disentangle between the potential general effects of touch on pain (beyond the critical manipulation of stroking speed) and the general effects of condition order on pain. In other terms, baseline always precedes the two touch conditions, and hence any general touch effects on pain could be due either to the touch or the fact that the touch conditions come always after the baseline condition and hence could be subject to habituation effects. However, we can say that there is an effect of slow, affective touch versus fast, non-affective touch on pain, as their order was counterbalanced across conditions and was found to have no effect on our main comparisons. It is still possible however that fast, non-affective touch may be increasing pain in comparison to slow touch rather than the other way around. As we said above we cannot disentangle the role of habituation from the role of general touch in our studies and hence it is possible that fast, non-affective touch led to less habituation than slow touch in our study. However, we also note that non-affective touch has long being known to reduce rather than increase pain in previous studies (e.g., see Mancini et al., 2015 for recent study) and future studies could thus include further speeds to account for the direction of the observed effects.

Third, given that CT firing correlates with perceived pleasantness in response to dynamic stroking (Löken et al., 2009; but see Chapter 1, section 1.3.2 more generally), with our own findings also suggesting increased perceived pleasantness in response to slow (versus fast) touch, it is possible that affective touch may reduce the sensory salience of impending noxious stimulation in a similar way as positive mood-related manipulations (e.g., positive/pleasant pictures, music and odours, see Chantal Villemure & Bushnell, 2002 for a review). Given the importance for quick and unbiased experimental succession between touch and pain, we did not collect mood ratings in this experiment. Instead, we merely examined, as an off-line manipulation check, the perceived sensory pleasantness of CT and non-CT touch. Interestingly, the perceived pleasantness of the touch did not relate to any of our pain measures, including individual subjective pain ratings and LEPs in our critical comparison between touch conditions (see Appendix 4). Thus, future studies should include specific online measures of mood to further explore this hypothesis.

Fourth, CT-optimal touch is a particularly effective form of communicating embodied (non-verbal) social support (see Chapter 1 and Chapter 2). Specifically, recent evidence on this very modality suggests that this particular kind of slow dynamic touch, but not the faster stroking touch also tested here as a control condition, conveys positive social intentions such as social support even in the absence of any other sensory or social cue (Kirsch et al., 2017). Thus, it is possible that this type of touch attenuates the saliency of impending noxious stimuli by signaling the presence of an active, socially supportive environment. This interpretation is consistent with recent theories on the importance of social interactions for the experience and regulation of emotions, and particularly homeostatic emotions such as pain (Atzil & Barrett, 2017; Fotopoulou & Tsakiris, 2017). According to such theories, the perception of the social environment of pain can affect inferential processes about the perception of these modalities, by influencing the weighting of prior expectations about certain sensory signals versus the signals themselves in given contexts (Decety & Fotopoulou, 2015; Krahé et al., 2013; von Mohr & Fotopoulou, 2018; similar to how non-social expectations influence pain, e.g., Atlas & Wager, 2012; Geuter, Boll, Eippert, & Büchel, 2017). Accordingly, affective touch prior to a noxious stimulus may modulate pain by changing beliefs about how threatening a noxious stimulus is in a supportive social context. Future studies should thus also take direct measure of perceived social support and examine whether the latter possibility or more general positive mood effects best explain the effects of CT-optimal touch on pain. In addition, future studies could elucidate whether the effects of slow, affective touch on pain are specific to the CT-system. For example, could slow touch on glabrous skin, that does not possess CT fibres (McGlone et al, 2014), lead to similar effects in romantic couples?

Turning now to our second study hypothesis about the potential moderating role of adult attachment style based on the observation of such effects in different social contexts (e.g. Krahé et al., 2016), we found such an effect only on subjective pain ratings and only in relation to adult attachment anxiety. Specifically, the higher the attachment anxiety, the smaller the effects of slow versus fast touch on self-reported pain. Given that anxious attachment is associated with craving closeness and reassurance from others (Hazan & Shaver, 1987b), we hypothesize that any kind of physical contact, in this case slow or faster touch from one's partner, is enough to ease attachment anxiety, signal closeness and hence attenuate self-reported pain. The fact that we did not observe any other attachment effects on our pain measures as in earlier work on affective touch between strangers (Krahé et al., 2016), may be explained by the fact that individual differences in attachment have less of a role to play when there is an existing degree of attachment security between partners. The latter can be assumed in the partners of the current study who were in a relationship for at least 12 months, had good relationship quality (see Appendix 1) and showed relatively secure attachment in relation to existing norms on the same measure and our previous study (see Appendix 2).

3.4.1 Limitations, strengths and future directions

To the best of our knowledge, our study was the first to investigate the effects of active, affective touch on pain in the context of a romantic relationship. While there are many ways to provide active support during pain (e.g., supportive text messages, verbal reassurance, social distraction; see also Chapter 1), the current findings are important given that the only variable manipulated was the velocity of the touch from the romantic partner. Thus, we demonstrate that a simple, yet specific embodied interaction can have pain-attenuating effects without the need for any explicit labelling by words or pictures. Moreover, in comparison to other types of embodied social support, such as for example hand-holding, the tactile interaction studied here was manipulated with a degree of experimental control, at a time different than the noxious stimulation and tested against control conditions that involve the same support provider. Therefore, the problematic comparison between partners and strangers or friends could be avoided and many confounding factors, such as social proximity, familiarity and social desirability can be excluded as potential explanations of our effect.

However, despite these methodological advantages, our study had several limitations. First, the experimental control of the study limits its ecological validity as typically couples will use a much richer embodied and verbal interaction to provide social support. Relatedly, in order to be able to assess the effects of touch on pain, including LEPs, as well as to avoid concurrent multisensory effects (if the touch had been given during the noxious stimulation), the touch was delivered in advance (indeed methodologically, LEPs had to be recorded following the touch manipulation), and repeated in mini-blocks, of ‘impending’ noxious stimuli. However, it is likely that romantic couples will also use this type of embodied social support as a soothing, consoling touch during or after pain and future studies could explore any differences based on such timescales. Second, while this study examined the pain-attenuating effects of touch delivered at velocities that activate the CT system optimally versus velocities of minimal known activation of this system (Löken et al., 2009), the functional role of this system and its particular, neurophysiological contribution to our effects remain to be specified by future studies. Third, we only tested pain in women, while their partners provided support by touch, to control for gender effects associated with the perception of touch (Gazzola et al., 2012; Suvilehto et al., 2015); however, future research is needed to examine whether the present results extend to men. Finally, the sources of the N1 and its functional implications remain debated: most notably, in relation to the precise contribution of the primary somatosensory cortex and operculoinsular cortex (Iannetti, Zambreanu, Cruccu, & Tracey, 2005; Tarkka & Treede, 1993; Valentini et al., 2012) as well as its implications for perceptual versus pre-perceptual pain processing at such early stages.

In sum, we found that active touch administered by the romantic partner at the optimal velocities of the CT system prior to noxious laser stimulation at a different body part attenuated subjective pain ratings and neurophysiological responses to pain, namely the N1, N2 and P2 local peak amplitudes more than touch administered at non-optimal CT velocities. Such effects were moderated only by one facet of adult attachment style (attachment anxiety) and only for subjective ratings of pain rather than the neurophysiological measures. Our effects indicate that the analgesic effects of active affective touch may begin at earlier stages of cortical nociceptive processing, as reflected by the N1 local peak amplitude, and expand to later, conscious aspects of noxious processing, as reflected by the N2-P2 complex and self-reported pain ratings. Given that LEPs have been recently proposed to detect environmental threat to the body in response to sensory salient events (Legrain et al., 2011), we propose that affective touch by one’s romantic partner (when applied before noxious stimulation) may reduce the sensory salience of impending noxious stimulation, due to either its perceived affective or pro-social effects.

Chapter 4

Affective Touch and the Perception of Peripersonal Space

4.1 Introduction

Chapter 2 and 3 investigated how affective touch attenuates social and physical pain, respectively. This chapter will examine whether affective touch can also modulate the perception of space around the body, i.e. the part of space where we approach or try to avoid interesting or threatening objects, respectively. Indeed, under conditions of bodily threat, such as pain, one's body may induce action to mobilize withdrawal or act upon the threatening stimuli. Thus, the effective piloting of the body to avoid or manipulate threatening stimuli requires an integrated neural representation of the body as well as the space surrounding the body (Holmes & Spence, 2004). Accumulating evidence (Maravita, Spence, & Driver, 2003; Maravita, Spence, Kennett, & Driver, 2002) suggests that multi-sensory representation of our body also includes the immediate space surrounding the body, known as PPS. In this sense, PPS represents the portion of space where physical interactions between our body and the environment occur. Supportive of this notion, neurophysiological studies on primates have described a specific population of multi-sensory neurons that respond to somatosensory stimuli on the body as well as visual and auditory external stimuli but only when they occur close and not far from the body (Rizzolatti et al., 1981). Neuroimaging (e.g., Blanke, Slater, & Serino, 2015; Bremmer, Duhamel, Ben Hamed, & Graf, 2002; Cléry, Guipponi, Wardak, & Ben Hamed, 2015), neuropsychological (e.g., di Pellegrino, Ladavas, & Farne', 1997; di Pellegrino & Làdavas, 2015; Làdavas, 2002) and psychophysiological (e.g., Maravita et al., 2003, 2002) studies have also provided evidence supporting the existence of a similar system in humans, whereby processing of tactile bodily stimuli is more strongly affected by external (mostly visual) stimuli presented close to the body.

Critically, as mentioned in Chapter 1, PPS representation is thought to be dynamic rather than static so that its boundaries shrink or expand in order to optimize the processing of self-relevant events depending on the requirements of the environment. This is important not only for grasping and manipulating objects, i.e., action-oriented purposes (e.g., Fogassi & Luppino, 2005; Graziano, 1999; Maravita et al., 2003; Rizzolatti et al., 1997, 1981), but also for detecting and acting upon threatening stimuli close to one’s body, i.e., defensive purposes (see de Vignemont & Iannetti, 2015 for a discussion about the distinct functions of PPS). For example, recent evidence has shown that PPS expands in the face of threatening stimuli (e.g., Anelli, Ranzini, Nicoletti, & Borghi, 2013; de Haan et al., 2016; Taffou & Viaud-Delmon, 2014; Vagnoni, Lourenco, & Longo, 2012), with such effects being most prominent when participants reported being fearful of the particular threatening stimuli (e.g., spiders or dogs, see de Haan et al., 2016; Taffou & Viaud-Delmon, 2014). Indeed, people need to respond to threat not only after but also before it actually happens and thus, it makes sense that they represent the space around their body in a protective way depending on the context, such as perceived threat.

However, the space around our body does not only represent the space where we implement goal-directed or defensive actions, but is also the space where proximal interactions with others occur and therefore, can be influenced by social context. Indeed, we live in a constantly ever-changing social environment, and our PPS expands or shrinks depending on other people around us. In particular, studies in sociology and anthropology suggest that personal space helps regulate contact in social situations, which may vary depending on the strength of the social relationship (from intimate to public) as well as culture (Hall, 1966; 1968). Moreover, such space is shaped by the acquaintance of the individuals and even the type of interaction between them (Sommer, 1969; Felipe & Summer, 2017). Advances in technology have propelled similar research in other fields, including social neuroscience. For instance, recent evidence suggests that the physical presence of another person, as well as the nature of the interaction, influences PPS (Heed, Habets, Sebanz, & Knoblich, 2010; Teneggi et al., 2013). Using an audio-tactile interaction paradigm to measure shifts in PPS, Teneggi et al. (2013) found that PPS boundaries shrink in the mere presence of another person, as compared to a mannequin. However, these socially-induced changes seem to be bidirectional. In a second experiment, Teneggi et al. (2013) employed an economic game finding that a positive interaction with another person (i.e., being treated fairly versus unfairly), led to an expansion of PPS. In another study, a similar expansion of PPS was observed when participants perceived the person facing them as moral, relative to when they perceived the other person as immoral (Pellencin et al., 2018). Maister and colleagues (2015), used the enfacement illusion to manipulate the degree of self-identification with another person via multisensory integration, and measured the PPS of the participants. The authors showed that participants remapped the other's PPS into their own PPS, only after a synchronous, and not after an asynchronous, interpersonal stimulation shared with the other. Indeed, the results showed a facilitation of reaction times not only when the sound was close to the participant's body but also when the sound was close to the other's body (Maister, Cardini, Zamariola, Serino, & Tsakiris, 2015). Together, these studies suggest that social context and social perception influence PPS. However, little is known about how socially supportive behaviors, and particularly active supportive behaviors (i.e., involving action from the support provider), influence PPS. Indeed, supportive actions from others play an important role not only in how we interact with the environment but also on how we anticipate and react to threat (e.g., see Coan et al., 2006 and Chapter 3 more generally).

Accordingly, the present Chapter aimed to examine whether active, social support modulates the perception of the space surrounding our body. Specifically, if we take PPS as a critical, spatial zone around our body that creates a margin of safety relative to approaching dangers (see Cléry & Ben Hamed, 2018 for a review), one would expect such critical zone to expand when socially supportive cues signal environmental safety – particularly when that person is around us. Indeed, as reviewed in the previous Chapters, active social support from others has been shown to attenuate bodily threat, such as pain. However, it remains unknown whether the effects of active, social supportive cues on bodily perception (e.g. pain) extend to the space around the body, i.e. the peripersonal space. Thus, here we employed slow, affective touch, that has been shown to be a particularly effective and salient embodied form of communicating active, social support (Kirsch et al., 2017; see also Chapter 1 for its neurophysiological specificity and affective valence), to investigate whether active social support modulates the segregation between peripersonal and extrapersonal space. Such effects were examined in both a social (i.e., the presence of another individual) and non-social (i.e., the absence of another individual) PPS context. In addition, given that the perception of social variables themselves depend on individual differences in attachment style (see Chapter 1) and have been shown to modulate bodily threat such as pain (see Chapter 3), we also examined whether key individual differences in attachment style moderated our effects.

In sum, using a virtual reality version of a well-validated multisensory interaction task to measure shifts in PPS (e.g., Pellencin et al., 2018; see also Teneggi et al., 2013), this study investigated whether slow affective touch, alone and in interaction with attachment style, modulated PPS in a social versus non-social PPS context. In particular, forty-eight participants received slow CT optimal touch versus very slow non-CT optimal touch, followed by the PPS task (half of the participants completed the social PPS task and the other half the non-social PPS task). For the PPS task we used a vibro-tactile detection task in which participants were asked to respond as fast as possible to a tactile stimulus, while looking at an approaching ball using augmented reality. We measured RTs across five different facilitation distances (from very far to very close) and using a linear function fitting the relationship between reaction time and the temporal delay of the tactile stimulation, we extracted the slope from these five distances as a measure of the differentiation between close and far space. Using these methods, we sought to test two main hypotheses. We first expected that PPS representation would differ when receiving slow touch (at 3 cm/s), that is thought of as being primarily mediated by the CT system and is typically perceived as pleasant and socially supportive (see Chapter 1), versus slower touch (at .3 cm/s), that is known to not activate CTs optimally and is typically judged to feel 'neutral'. In particular, we expected the PPS to extend under the slow, affective versus very slow, non-CT touch condition towards the body of another person, as reflected by less differentiation between close and far space in the social PPS task, consistent with the notion that this type of active support facilitates approaching behavior. Second, we expected that such effects would be moderated by individual differences in adult attachment style, in that affective touch should have the largest effect on an extended PPS in individuals with higher attachment anxiety (who fear of rejection and seek clear signals of support) and the smallest effect in individuals with higher attachment avoidance (who prefer to cope with threat alone).

4.2 Methods

4.2.1 Participants

Fourty-eight females were recruited via the University College London (UCL) Psychology Subject Pool and were compensated for their participation with £8 or 1 credit. Only females were recruited to control for gender effects related to touch (Gazzola et al., 2012; Suvilehto et al., 2016). Half of the participants completed the social version of PPS task (i.e., with a person sitting in front of them), whereas the other half completed the non-social version of the PPS task (i.e., without a person sitting in front of them). The mean age of participants was 28.87 (SD=3.29) and 23.52 (SD=3.78) for the social and non-social group, respectively, and there were no differences on age across the groups, *p*=.115.

4.2.2 Stimuli and apparatus

The PPS task was administered by the aid of a virtual reality headset (Oculus Rift DK2; 900 x 1090 per eye, ~105 FOV) and the ExpyVR software (https://lnco.epfl.ch/expyvr) a new augmented-reality technology developed at the EPFL (Laboratory of Cognitive Neuroscience at the Ecole Polytechnique Federale de Lausanne). This technology allowed us to present a looming ball (i.e., visual stimuli) on a transparent background. In addition, participants were asked to hold sensory electrodes (i.e., vibrotactile stimulator; custom-made at the EPFL) with their left hand fingertips, which delivered mild (non-painful) vibrations. Participant's right hand was placed on a keyboard, and participants were asked to respond to the tactile stimulation as fast as possible, by pressing the space bar and to ignore the stimuli presented on the head-mounted display (see section 2.3.2 for more details about the trials and stimuli). In the social PPS task, the experimenter was sitting in front of the participants (90 cm away) with the looming ball appearing at the level of the neck of the experimenter. In contrast, in the non-social PPS, there was no person sitting in front of the participant.

4.2.3 Experimental manipulations and outcome measures

4.2.3.1 Tactile manipulation. One skin area (9 cm long x 4 cm wide) was marked on the participant's left forearm (i.e., stimulation site). The experimenter administered the touch to the participant using a cosmetic make-up brush (Natural Hair blush brush, No 7, Boots, UK). In each touch condition, the stroking was administered in 10 one-minute mini-blocks in an elbow-to-wrist direction (Essick et al., 2010; Krahé et al., 2016) at slow (3 cm/s – 1 stroke, 3 second duration) or very slow (.3 cm/s – 1 stroke, 30 second duration) velocities. Before each maxi block (slow versus very slow) the touch was administered for 3 min as an 'induction' of the effect. The velocity of the slow and very touch was chosen given it has been shown to be optimal and non-optimal, respectively, for targeting CT afferents (Löken et al., 2009; Gentsch et al., 2015). The stroking was alternated with PPS mini-block trials (see Figure 4.1).

4.2.3.2 Peripersonal space measurement. In order to measure changes in PPS following stroking stimulation, the PPS task included three types of trials, namely bimodal visuo-tactile, unimodal tactile and catch trials. The critical bimodal visuo-tactile trials started with appearance of the ball on the center of the transparent screen, gradually approaching the participants for approximately 2600 msec. Together with the visual stimulus, a tactile stimulation (lasting 200 msec) was delivered to the participant's left hand by the vibrotactile stimulator. The tactile stimulator was given at 5 temporal delays from the appearance of the ball (after 433, 866, 1299, 1732, 2165 msec), with the first corresponding to Time 5 and the last to Time 1) and consequently, perceived by the participant when the virtual, visual object was placed at 5 different distances from her (from very close to the body, Distance 1, to very far, Distance 5). In this sense, the longer delay corresponds to a closer distance. In other words, 433 msec from the beginning of the movement of the ball (Time 5) would correspond to the farthest distance perceived by the participant, in this case D5 – and vice versa. In the second type of trial, namely unimodal tactile and unimodal visual/catch trials, participants received the tactile stimuli at the same time intervals but no ball was presented or the ball was presented without any tactile stimuli respectively. The visual unimodal trials are included as a manipulation check to make sure the participants are not giving any responses by pressing the space bar. In contrast, the unimodal tactile serve as baseline for how quick participants respond to the tactile stimuli without any visual stimuli, i.e., to control for the effect of temporal delay of tactile stimulation on the subject's response.

Each PPS block consisted of 180 trials: 30 unimodal visual trials, 50 unimodal tactile trials (10 for each distance), and 100 bimodal trials (20 trials for each distance), divided into 10 mini-blocks and presented in a pseudorandom order with an interstimulus interval of 0.9, 1.15, 1.4, 1.65 and 1.9 seconds. Tactile unimodal and visuo-tactile stimuli RTs were averaged separately across distance in each PPS block (across the 10 mini-blocks for the touch conditions) for each participant. Using a conservative approach, reaction times (RTs) from each distance were then baseline corrected by substracting the unimodal tactile responses (msec) from the visuo-tactile responses (msec) (e.g., as done in Pellencin et al., 2018; Teneggi et al., 2013). This delivered RTs (baseline corrected) across five distances for each participant per touch condition. The slope of the latter was extracted using a linear function (MatLab 2015b), which reflects the amount of segregation between the close (peripersonal) and the far (extrapersonal) space. The linear function was described by the following equation: $y(x)=y_o +k*x$, where x represents the timing of tactile delivery in ms (independent variable), y the reaction time (dependent variable), y_o the intercept at x=0 and k is the slope of the linear function (Pellencin et al., 2018). Thus, a 'PPS slope' was obtained for each participant per touch condition (slow vs. very slow touch) in both the social and non-social group. A steeper, or bigger, 'PPS slope' indicates more differentiation between close and far space. In contrast, a smaller 'PPS slope' indicates less differentiation between close and far space.

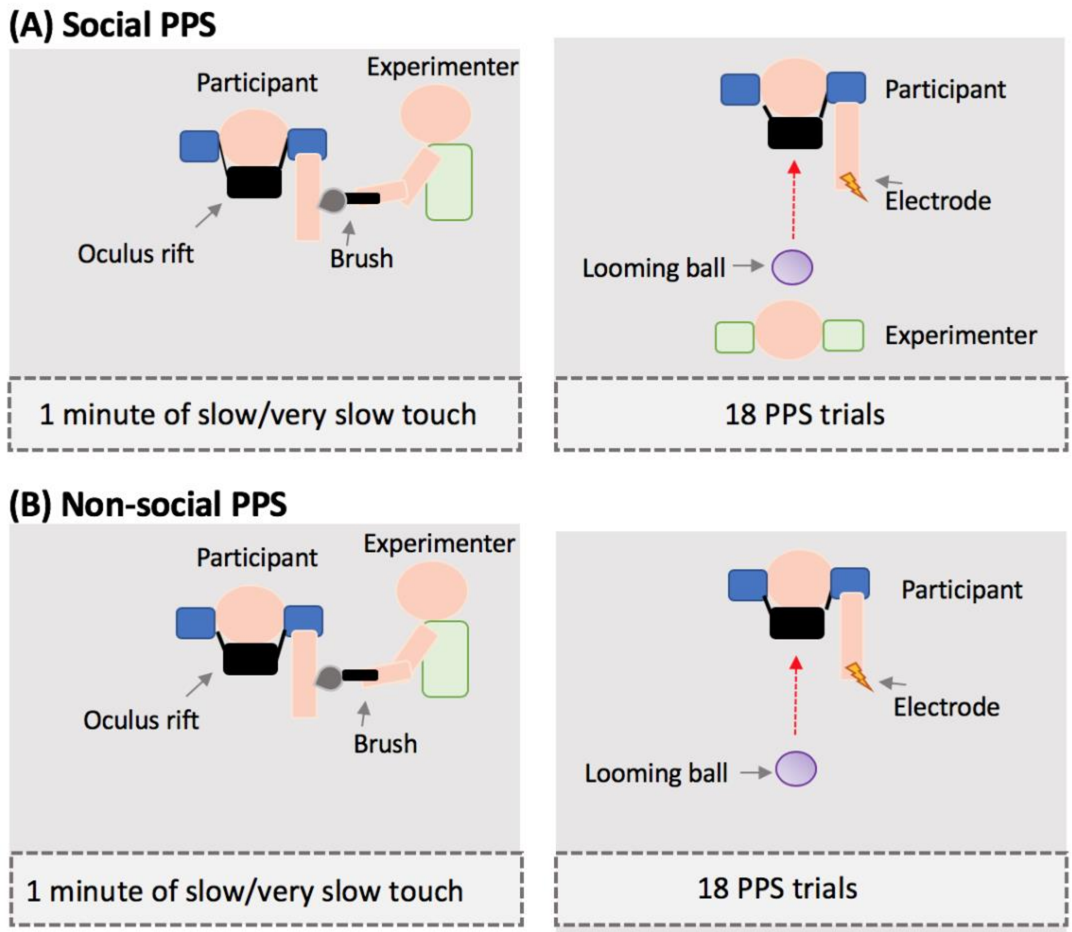


Figure 4.1. Example of one mini-block. In each mini-block, participants received slow or very fast touch (within-subjects manipulation), followed by 18 PPS trials, with the experimenter sitting either in front of them or not (depending on their assigned group, i.e., between-subjects manipulation: (A) social PPS or (B) non-social PPS). In the social PPS condition, the experimenter sat quietly across the participant (90 cm away, facing the participant), while the virtual ball appeared on the transparent screen (oculus rift) for the bimodal visuo-tactile and unimodal visual trials, gradually approaching the participant.

4.2.3.3 Adult attachment style. We employed the ECR-R (Fraley et al., 2000) questionnaire to measure adult attachment style. This is the same questionnaire that was used in Chapter 3. The ECR-R measures individual differences with respect to the extent to which individuals are insecure about the responsiveness and availability of close others (i.e., attachment anxiety) and the extent to which individuals are uncomfortable with being close and depending on close others (i.e., attachment avoidance). The ECR-R yields continuous scores on attachment anxiety and attachment avoidance dimensions, with higher scores denoting greater attachment anxiety and avoidance, respectively (see Chapter 3 for more details).

4.2.3.4 Tactile manipulation check. As a manipulation check, participants were administered with a 30 second duration stroke (at .3 cm/s) and a 3 second duration stroke (at 3 cm/s) and asked to rate how pleasant they perceive the slow and very slow touch (same speeds as used in the main task). These reports were given using a visual analogue scale (VAS) drawn on a paper. The scale had 2 anchors (0; not at all pleasant and 100; extremely pleasant) at each end of a 10 cm line and the participants had to rate how pleasant the touch was drawing a vertical line on it.

4.2.4 Procedure

Upon obtaining written informed consent, a skin area (9 cm long x 4 cm wide) was marked on the participant's left forearm (i.e., stimulation site). Participants were told that they would be receiving touch by the experimenter on their left forearm, followed by the PPS task in which they would observe a looming ball and receive some tactile vibrating stimuli by the electrode they were holding on their left hand. They were asked to respond to the tactile vibrating stimuli as fast as possible by pressing the space bar and to ignore the visual stimuli presented on the head-mounted display when responding.

The experiment consisted of two blocks. In each block, participants received one of the two stroking velocity conditions (slow or very slow touch) from the experimenter, while keeping their eyes closed, followed by the PPS trials (with the order of the stroking velocity conditions counterbalanced across participants). Each of these blocks was divided into ten mini-blocks, alternating tactile stimulation (1 minute duration) and the PPS trials (approximately 1 minute) (see Figure 4.2 for a schematic of the design). Before the first maxi block (slow vs very slow touch), participants received 3 minutes tactile stimulation as an induction of the effect. The beginning of each maxi-block was cued by a fixation cross appearing on the center of the transparent cross, wherein participants were further asked to tell the experimenter when they saw the fixation cross appear on the screen in order to make sure they were keeping their eyes open during the PPS trials (and begin the PPS mini-block). Between each block there was a 5-minute break to minimize carry-over effects from the touch, but also to avoid participants from becoming fatigued. Importantly, participants assigned to the social PPS group were able to observe a second experimenter seating in front of them while they completed the PPS trials, whereas participants assigned to the non-social PPS had no other person in sight while completing the PPS trials.

At the end of the study visit, participants provided pleasantness ratings for slow and very slow touch and completed the adult attachment style questionnaire (ECR-R).

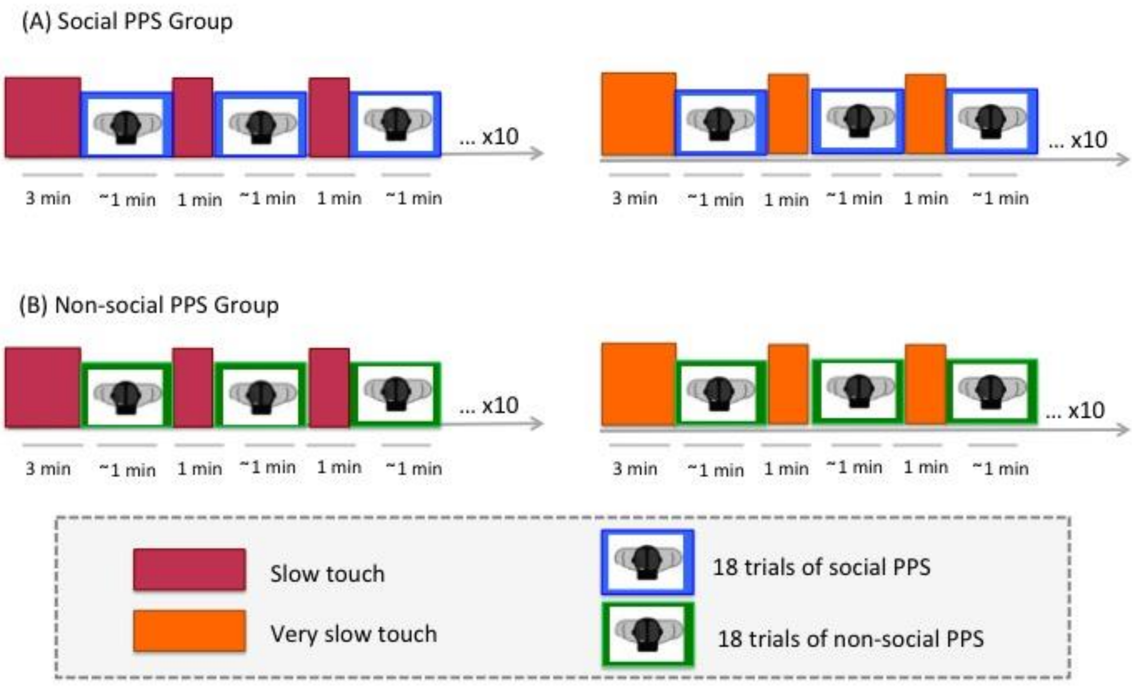


Figure 4.2: Experimental design. Our experimental design for the main task included a slow, 3 cm/s, and a very slow, .3 cm/s, touch condition (within-subjects manipulation; with the order counterbalanced across participants), followed by PPS trials, with the experimenter sitting either in front of them or not (depending on their assigned group, between-subjects manipulation: social or non-social PPS).

4.2.5 Plan of statistical analyses

All statistical analyses were conducted in STATA (Version 14). As repeated measures (Level 1) were nested within individuals (Level 2), multilevel modelling was implemented using the ‘mixed’ command. For our outcome variable (PPS slope, extracted using linear fitting) in each group, we specified multilevel models with touch condition (slow touch/very slow touch) and PPS group (social/non-social) as dummy-coded categorical predictors. To assess the role of attachment anxiety, we first specified attachment anxiety as a continuous predictor in our model, and included all interaction terms, while controlling for attachment avoidance. To assess the role of attachment avoidance, we then specified attachment avoidance as a continuous predictor in our model, and included all interaction terms, while controlling for attachment anxiety. All continuous predictors were mean-centred in order to avoid multicollinearity issues (Tabachnick & Fidell, 2007). Significant interactions were followed up by examining differences between conditions at low (−1 SD), moderate (mean) and high (+1 SD) continuous adult attachment style scores (Aiken & West, 1991).

4.3 Results

4.3.1 Descriptive statistics and manipulation checks

Mean adult attachment styles were $M = 3.51$ ($SD = 1.03$) for attachment anxiety and $M = 3.51$ ($SD = .75$) for attachment avoidance in the social PPS group, and $M = 3.41$ ($SD = 1.02$) for attachment anxiety and $M = 2.92$ ($SD = 1.31$) for attachment avoidance in the non-social PPS group. There were no significant differences in attachment anxiety, or attachment avoidance, between the social and non-social PPS group, t(46)=.338, p=.737, t(46)=1.929, p=.060, respectively (there were also no significant differences in attachment anxiety or avoidance between the current samples and the general population; see Appendix 5 for descriptive statistics and comparisons). Across the groups, attachment anxiety and attachment avoidance were not correlated, although a trend was observed, $r = .26$, $p=.059$.

Table 4.1 presents descriptive statistics for distance RTs and the extracted PPS slope. Analyses conducted across touch conditions on the RTs by distance (baseline corrected) suggested that the PPS task worked as expected in both groups. Across groups, there was a main effect of distance, $F(4,184)=5.72$, $p<.001$, $\eta^2_{partial}=.11$. Specifically, planned comparisons indicate faster RTs in D1, closest distance to the body, relative to D5, farthest distance away from the body, t(47)=3.11, p=.003. Even though group (social PPS, non-social PPS) did not interact with distance, $F(4,184)=.672$, $p=.612$, $\eta^2_{partial}=.01$, there was a trend for a main effect of group, $F(1,46)=3.89$, $p=.055$, $\eta^2_{partial}=.08$, indicating faster RTs in the non-social versus social PPS group. Given one would expect faster RTs in response to visuo-tactle stimuli on distances closer to the body, i.e., multisensory boosting effect (e.g., Noel et al., 2015), these results indicate that our PPS task was successful.

Analyses conducted on the pleasantness ratings scores of both type of touch suggested that slow and very slow touch was perceived as expected in both groups. Participants perceived slow touch (*M*=76.97, *SD*=20.65) as more pleasant than very slow touch (*M*=58.46, *SD*=19.54), $F(1,43)=30.28$, $p<.001$, $\eta^2_{partial}=.41$. Importantly, group did not interact with touch velocity, $F(1,43)=.44$, $p=.510$, $\eta^2_{partial}=.01$, indicating that slow touch was perceived as more pleasant than very slow touch, irrespective of the assigned (social and non-social) PPS group and hence our manipulations were successful in terms of perceived pleasantness of touch.

Table 4.1
Mean (SD) for RTs (msec; baseline corrected) at each distance and extracted PPS slope.

	D1	D2	D3	D4	D5	PPS slope
Social PPS						
Slow touch	-20.52 (4.51)	-25.85 (4.31)	-12.64 (2.86)	-17.08 (4.55)	-15.06 (4.25)	1.97 (4.57)
Very slow touch	-19.96 (4.17)	-27.97 (3.36)	-19.16 (5.19)	-9.28 (4.28)	-13.41 (4.44)	3.18 (5.14)
Non-social PPS						
Slow touch	-35.42 (5.09)	-25.98 (6.34)	-31.50 (6.70)	-17.86 (4.93)	-21.11 (4.99)	3.67 (7.68)
Very slow touch	-25.99 (5.05)	-34.61 (6.69)	-24.90 (4.86)	-22.52 (5.71)	-20.68 (4.35)	2.27 (2.27)

4.3.2 Multilevel modeling results

Full model results are presented in Table 4.2 and 4.3. There was no main effect of PPS group or attachment style for PPS slopes. Similarly, the main effect of touch condition was not significant, and there was no interaction between touch condition and PPS group. Similarly, the touch condition by attachment anxiety (see Table 2), or touch condition by attachment avoidance, two-way interactions (see Table 3) were not significant. Further, there was no three-way interaction between any attachment dimension, touch condition and PPS group. Together, these results suggest that the segregation between close and far space, is not modulated by slow touch – alone or in interaction with attachment style and/or social versus non-social PPS conditions.

However, unexpectedly, there was a significant attachment anxiety by PPS group interaction on PPS slopes, b = 3.75, SE = 1.77, p = .034; see Table 4.2. Follow-up tests on PPS slopes showed that the difference between social and non-social PPS conditions was significant for low (b = 3.96, SE =1.77, p=.026) and high attachment anxiety (b = -4.76, SE =1.77, p = .007), but not for moderate attachment anxiety (b = −.40, SE =1.20, p=.739); see Figure 4.3. Thus, at lower levels of attachment anxiety, i.e., higher degree of attachment security, the bigger the PPS slopes on the social versus non-social PPS condition. In other words, at low levels of attachment anxiety, there is a steeper differentiation between close and far space when there is someone siting in front of the participant. Conversely, at higher levels of attachment anxiety, the smaller the PPS slopes on the social versus non-social PPS condition, indicating less, shallower, differentiation between close and far space when someone is sitting in front of the participant. The interaction between attachment avoidance and PPS group was non-significant for PPS slopes (see Table 4.3).

In sum, these results do not support our first nor second hypotheses, given that affective touch, alone and in interaction with attachment style, did not modulate the segregation between close and far space. In addition, such effects were not moderated by the social context, i.e, social versus non-social PPS group. However, these multilevel results indicate that attachment anxiety (but not attachment avoidance) affects the segregation between close and far space depending on the PPS group, irrespective of the touch.

Table 4.2
Slow versus very slow touch: multilevel results for PPS slopes, controlling for attachment avoidance

Effect	b	*SE*	*p*-value	Confidence intervals Lower	Upper
Slow versus very slow touch	1.21	1.69	.474	-2.11	4.52
Social vs. non-social PPS group	1.70	1.69	.314	-1.61	5.02
Touch condition * PPS group	-2.61	2.39	.275	-7.30	2.07
Attachment anxiety	-1.62	1.19	.174	-3.96	.72
Touch condition * attachment anxiety	.12	1.68	.942	-3.18	3.42
PPS group* attachment anxiety	**3.75**	**1.77**	**.034**	**.29**	**7.22**
Touch condition *PPS group * attachment anxiety	1.16	2.39	.626	-3.53	5.86
c. Attachment avoidance	-.45	.65	.485	-1.73	.82

Table 4.3
Slow versus very slow touch: multilevel results for PPS slopes, controlling for attachment anxiety

Effect	b	*SE*	*p*-value	Confidence intervals Lower	Upper
Slow versus very slow touch	1.21	1.78	.499	-2.29	4.72
Social vs. non-social PPS group	1.71	1.79	.340	-1.8	5.21
Touch condition * PPS group	-2.61	2.53	.302	-7.57	2.35
Attachment avoidance	.22	1.201.73	.900	-3.18	3.61
Touch condition * attachment avoidance	-.11	2.44	.965	-4.89	4.58

PPS group * attachment avoidance	-.09	2.03	.964	-4.07	3.89
Touch condition *PPS group * attachment avoidance	.85	2.81	.762	-4.66	6.36
c. Attachment anxiety	.30	.69	.665	-1.05	1.64

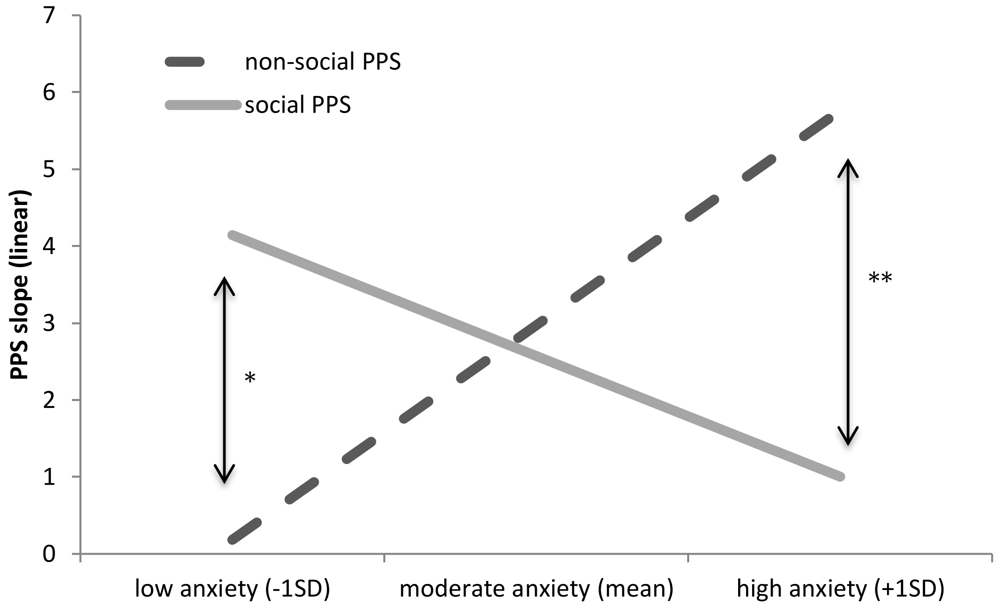


Figure 4.3: Effects of attachment style on PPS slopes. Effects plotted at low (-1 SD), moderate (mean) and high (+1SD) attachment anxiety scores on social and non-social PPS groups. A steeper PPS slope indicates more differentiation between close and far space. In contrast, a smaller PPS slope indicates less differentiation between close and far space. One and two asterisks indicate p<.05 and p<.01, respectively.

4.4 Discussion

Using a visuo-tactile interaction task to measure shifts in PPS, this Chapter investigated for the first time whether embodied active support, namely affective (slow velocity, low pressure, dynamic) touch –alone and in interaction with attachment style– modulated the differentiation between peripersonal and extrapersonal space in a social and non-social context. Specifically, we measured PPS slopes extracted from five different facilitation distances (from close to far away), which reflect the extent to which there is more or less differentiation between close and far away space from one's body. Our results do not support the hypothesis that slow affective touch, thought to be primarily mediated by the CT system and is typically perceived as pleasant and socially supportive, versus slower touch, that does not optimally activate the CT system and is typically perceived as 'neutral', may modulate the segregation between close and far space. Moreover, although we did not find reliable evidence to suggest that such effects were moderated by individual differences in attachment anxiety nor attachment avoidance, we found that attachment anxiety (but not attachment avoidance) affects the segregation between close and far space depending on the social context. Specifically, we found that the higher attachment anxiety, the less differentiation between close and far space when there is someone versus no one sitting across from the participant. Opposite pattern of results are found in lower scores of attachment anxiety, which reflects scores closer to 'attachment-security'. These findings, and consideration of their limitations and directions for future research, are discussed in more detail below.

The fact that we did not observe differences in the segregation between close and far space following the slow CT touch, versus very slow non-CT touch, was unexpected. Previous literature on the social modulation of PPS (e.g., Maister et al., 2015; Tennegi et al., 2013; Pellencin, et al., 2017) led us to hypothesize that active socially supportive behaviors would lead to less differentiation between close and far space, particularly in the social PPS task, thereby reflecting an expansion of PPS. In fact, slow affective touch has been shown to attenuate bodily threat, such as pain (e.g., Coan et al., 2006, Eisenberger et al., 2011, see also Chapter 3), and one would expect such effects of touch to influence the immediate space surrounding the body, particularly as PPS is a critical space for triggering approaching and defensive behaviors (Holmes & Spence, 2004). Thus, this null finding suggests that at least in terms of the segregation between close and far space, there is not reliable evidence to suggest that affective touch can influence PPS, even when there is someone sitting across from the participant. However, future research is needed before drawing firm conclusions. Below, we propose a few candidate explanations that may have led to such a lack of findings. First, it is possible that alternating between the touch and the PPS task between mini-blocks may have attenuated the effects of the touch, particularly as the PPS task involves high level cognitive resources to detect and respond to the vibro-tactile stimuli as soon as possible. In this sense, participants may have been more focused on this reaction time task and consequently, the tactile manipulation may not have been powerful enough to surpass distraction effects. However, such design was employed in order to avoid multisensory integration effects, or distraction effects associated with the touch, if the affective touch had been administered concurrently with the PPS task. Second, given that the social role of affective touch has been predominantly examined in the context of pain (e.g., Krahé et al., 2016; Liljenctrantz et al., 2017; see also previous chapters), it is possible that its effects may be context specific. The current study employed a ball as a stimuli, and although it consisted of an 'approaching' stimuli and may pose some threat to a certain degree, individuals may not perceive it as precisely threatening. Thus, future research is needed to examine whether affective touch modulates PPS when using explicitly threatening objects instead (e.g., approaching spider), with significant findings here being in line with a function-specific PPS representation, i.e., body protection in this case, rather than a single cortical map representing the PPS, i.e., both object grasping and body protection (de Vignemont & Iannetti, 2015).

Similarly, we did not find an interaction between attachment style (anxious or avoidant) and affective touch in the PPS slopes, suggesting that we cannot discard the possibility that individual differences in attachment styles do not moderate the effects of touch on the segregation between close and far space. This was surprising given the growing evidence suggesting that attachment style moderates the effects of social support on bodily threat (see Krahé et al., 2013 for a review). One potential explanation about the lack of findings here is related to the fact that affective touch itself does not seem to have an effect on the segregation between close and far space. In this sense, individual differences in attachment style that may influence the perception of touch itself may not play a critical role in moderating such effects. Indeed, as it will be discussed in section 4.4.1, it is possible that the very slow, control touch could have been perceived as equally supportive as the slow, affective touch, i.e., our main manipulation of touch did not work (note that manipulation checks were only collected for the perceived pleasantness of the touch). Thus, if this were the case, one would not necessarily expect an attachment style by touch condition interaction in the PPS slopes. As an alternative explanation, however, it is also possible that the stimuli employed (i.e., looming ball) did not trigger any attachment phenomenon in relation to the touch. Indeed, social support (in this case slow, CT-optimal touch) is more likely to trigger the attachment phenomenon in contexts of threat (Krahé et al., 2013; Ravitz et al., 2010), and as mentioned above, the employed stimuli, i.e., looming ball, may not have been perceived as particularly threatening by the participants. Thus, future research is needed to examine whether such null effects remain in the face of explicitly threatening objects (e.g., approaching spider or snake).

However, we found that the lower the attachment anxiety, the steeper the PPS slope in the social versus non-social PPS task, irrespective of the touch. Critically, lower scores in attachment dimensions reflect higher attachment security (Fraley et al., 2000), which is associated with individuals expecting availability and reliable responsiveness from others, i.e., there is no worry about abandonment/rejection nor persistent checking of reassuring signals from others (Ravitz et al., 2010). Thus, these results point to a larger differentiation between close and far space in the mere presence of another person when there is a higher degree of attachment security. Such findings are consistent with prior evidence suggesting that PPS boundaries shrink when the subjects face another individual (Teneggi et al., 2013). In contrast, however, our findings also suggest that the higher the attachment anxiety, the smaller the PPS slopes in the social versus non-social PPS task, indicating less differentiation between close and far space in the presence of another person at higher degrees of anxiety. These findings are consistent with prior research suggesting that PPS expands by anxiety (Sambo & Iannetti, 2009) yet show that this effect is present only in social contexts. Such effects are likely due to our measure (ECR-R) tapping into individual differences on anxiety in the context of social relationships.

Given that higher attachment anxiety is characterized by hyperactivation of attachment behavior, involving worrying about rejection/abandonment and persistent checking of signals of support from others (Ravitz et al., 2010), we speculate that the merging between close (self) and far (other) space might serve such coping mechanism. In other terms, based on prior experiences, these individuals have the belief that others are unreliable, and consequently, a lesser distinction between close and far space in the presence of others may not only underpin their need of closeness but also facilitate their persistent checking of others as others are seen as ‘untrustworthy’. Interestingly, our other dimension of attachment style, namely attachment avoidance, did not modulate the PPS slopes. This null finding suggests that explicit representations about the unavailability of others and a preference to cope with threat on their own, which characterize avoidantly-attached individuals (Ravitz et al., 2010), may not determine the segregation between close and far space in social and non-social contexts.

4.4.1 Limitations, strengths and future directions

To the best of our knowledge, our study was the first to investigate the effects of affective touch and attachment style on PPS. However, the present findings should be considered in light of study limitations and directions for future research. First, a mixed design was employed, with a between-subjects manipulation of social versus non-social PPS, which may thus entail potential individual variability confounds. Nevertheless, such mixed design was deemed necessary given the duration and nature of the study, which could have led to participant's psychological fatigue if a within-subjects design was employed. However, our only finding consisted of an interaction between attachment anxiety and the PPS group, which therefore makes this design slightly problematic, i.e., other differences intrinsic to each group cannot be excluded. Thus, future studies employing the social versus non-social PPS condition as a within-subjects factor are needed to fully examine the role of attachment style on PPS.

Second, although our study is the first to show that individual differences in attachment style influence PPS, these findings should be taken with caution. Although there was no main effect of touch condition, we cannot exclude with certainty that being touched did not have an effect in our findings regarding attachment anxiety. Instead, we can only say that attachment anxiety modulated the segregation between close and far space differently in social and non-social contexts, irrespective of the touch. Thus, this finding needs to be replicated without any prior administration of tactile stimuli.

Third, although our tactile manipulation of social support has several strengths, e.g., good experimental control as the only variable manipulated here was the velocity of the touch, i.e., confounders such as different support providers, familiarity and social desirability effects were minimized, it also possesses some limitations worth considering before drawing firm conclusions about the null findings reported in this study. First, when using tactile stimulation in the form of stroking there is always a compromise between the frequency of tactile stimulation and the duration of the stroking. Therefore, although we controlled for the duration of the stroking by keeping the stimulation site constant (i.e., 9 cm), there is always the potential confound of the frequency of tactile stimulation.

Relatedly, it is worth noticing that in contrast to the previous Chapters, our control condition consisted of non-CT optimal very slow (.3 cm/s) touch, instead of non-CT optimal fast touch (18 cm/s). This very slow touch was selected as, like the faster 18 cm/s touch, it has been shown to not activate the CT system optimally and is typically judged as less pleasant than the 3 cm/s touch (Löken et al., 2009; Gentsch et al., 2015; see also Chapter 5), with our manipulation checks supporting this notion. Yet, in contrast to the fast touch, this very slow touch allowed us to keep a more similar frequency rate between the affective and non-affective touch (i.e., 20 and 2 instead of 20 and 120 strokes per minute). This was considered important as the PPS task further involves vibro-tactile stimulation and we opted to keep this confounder to a minimum. However, we therefore cannot discard that the lack of findings here could be due to this control touch condition, especially as this type of very slow, control touch could be potentially perceived as equally supportive than the slow, affective touch.

In sum, we did not find conclusive evidence for the hypothesis that slow, affective touch, as compared to very slow, non-affective touch, modulates PPS, a critical space for triggering approaching and defensive behaviours. However, the current findings demonstrate for the first time that attachment style, and particularly attachment anxiety, influences the segregation between close and far space differently in social and non-social contexts. Specifically, the higher the attachment anxiety, the smaller the PPS slopes on the social versus non-social PPS condition, indicating less differentiation between close and far space when someone versus no one is sitting across the participant. Given that a craving for closeness and persistent checking of signals of support and reassurance characterizes these individuals, we have interpreted this finding as a lesser differentiation between self and other's space to facilitate their persistent checking of others. Future work is needed to examine the role of attachment style on PPS depending on the social context, without the touch manipulation.

Chapter 5

Sensitivity to Affective Touch Depends on Adult Attachment Style

5.1 Introduction

In the previous Chapters we saw that not only affective touch but also attachment style plays an important role in how we perceive bodily threat. It still remains unknown, however, if affective touch itself is influenced by individual differences in attachment style. As mentioned in Chapter 1, evidence suggests that the perception of social support itself is influenced by attachment style, and attachment style may be particularly relevant for our perception of affective touch. Affective touch perception does not only depend on bottom-up signaling (primarily mediated by CT afferents) but also depends on top-down factors, such as the psychological state of the individual or socio-contextual factors (e.g., touch provider and their intentions; Ellingsen, 2015, see also Chapter 1 section 1.3.2). As pre-existing affective-cognitive models of social relating, individual differences in attachment style could thus determine the top-down influences on the perception of affective touch. Therefore, this Chapter aimed to investigate whether attachment style influences the perception of affective touch. Although previous reports have examined the relationship between social touch and attachment style, particularly in the context of parental aversion to touch and infant's security (e.g., Main, 1990), to the best of my knowledge, this is the first study to investigate the relationship between individual differences in attachment style and CT-optimal touch, i.e. tactile stimuli delivered according to physical properties have been found to elicit the strongest responses in CT fibers (Löken et al., 2009).

Although attachment theory has been covered in Chapter 1, it is worth highlighting that its key tenet is that infants have an innate drive to form a close bond with their primary caregivers (usually the mother) to ensure their survival and well-being in times of threat. In the past decades, the emphasis in attachment research has been influenced by the additional, cognitive hypothesis that differences in the responsiveness and availability of mothers to the infant's attachment needs lead to the development of internal working models of social relating and associated affect regulation strategies (Main et al., 1985). These working models are described as affective-cognitive schemas, termed ‘attachment representations’ or most generally referred to as attachment styles. As close others begin to serve similar functions and satisfy the same needs for which parents are primary responsible, then at some point attachment will be transferred to close others, such as in romantic relationships (Hazan & Shaver, 1987). Importantly, attachment patterns remain relatively stable across the life span (Waters et al., 2000).

However, the emphasis on these working models has somewhat shifted attention away from Bowlby’s original attention to physical ‘proximity seeking’ as the primary behavioural strategy for coping with threat (in a wider sense; Bowlby, 1969; Bowlby, 1977). Crucially, a central aspect of proximal caregiving during threat is touch. Touch sets the stage for one of the earliest maternal interactions, including automatic engagement in tactile stimulation of their abdomen to passively stimulate the fetus which in turn reaches out to touch the uterus wall (Marx & Nagy, 2015; 2017), as well as being a necessary part of caregiving interactions (Field, 2010; Stack, 2007). In non-human mammals, it has long being established that touch between conspecifics has evolved to promote not only caregiving but also stress regulation and affiliative bonding (Dunbar, 2010), with well-studied neurophysiological, genetic and epigenetic mechanisms (Harlow & Harlow, 1962; Nelson & Panksepp, 1998b; Weaver et al., 2004). Interestingly, idiosyncratic differences in maternal tactile behaviours lead to individual differences in rats’ behavioural and neuroendocrinal responses to stress during adulthood (Zhang, Chretien, Meaney, & Gratton, 2005).

There is also increasing understanding in humans about the role of touch in promoting affiliative bonds, affect regulation and healthy development (e.g., Brauer et al., 2016; Field, 2010), while early social and tactile deprivation have corresponding detrimental effects (e.g., Beckett et al., 2006; Carlson & Earls, 1997). Specifically, following on the animal literature, research has explored the impact of maternal touch on human infants’ emotion regulation and particularly on stress responses (e.g., Feldman, Singer, & Zagoory, 2010) such as decreasing cortisol levels and crying. Moreover, the effects of touch on cognitive and affective development extend to self-awareness (e.g., Filippetti, Orioli, Johnson, & Farroni, 2015; Fotopoulou & Tsakiris, 2017) and social learning. For instance, touch is a particularly effective way of directing infant attention (Cascio, 2010; Stack & Muir, 1992) and a particularly effective cue for increasing infants' appropriate eye-contact behaviours (Peláez-Nogueras et al., 1996). Finally, the effects of touch on brain development have been investigated recently. Evidence suggests that there is an association between the frequency of maternal touch during mother-infant interactions and functional connectivity in various nodes of the infants' default mode network, thought to support self-awareness and social cognition (Brauer et al., 2016).

Despite this progress in infant research, however, less is known about any lasting effects of such early tactile interactions, and particularly the relationship between individuals' life-long attachment style and their reactivity to social touch. The primary aim of the present study was the investigation of this relationship, and particularly the investigation of how individual differences in adult attachment style can affect the perception of a neurophysiologically specific type of touch that has been shown to be highly relevant in close relationships, namely affective touch. Specifically, in adults, slow gentle, CT-optimal, stroking touch, as compared with faster gentle non-CT optimal, stroking touch, has been shown to specifically communicate social intimacy and support (Kirsch et al., 2017), to reduce experimentally-induced feelings of social rejection (see Chapter 2) and subjective and neural responses to noxious stimulation (Krahé, et al., 2016; see also Chapter 3), as well as to contribute uniquely to embodied facets of self-awareness (e.g., Crucianelli et al., 2013; Panagiotopoulou, Filippetti, Tsakiris, & Fotopoulou, 2017). Critically, as reviewed in Chapter 1, CT afferents are thought to respond optimally to this type of touch, being found most active in response to low pressure stroking, and are velocity and temperature tuned. Specifically, CTs mean firing rate is higher in response to relatively slow velocity tactile stimulation (1-10cm/s^{-1}) and lower in response to velocities above or below this range, suggesting that stroking within the 1-10 cm/s range optimally activates CT afferents. The activation of CTs (i.e., their mean firing frequency) is strongly correlated with perceived pleasantness (Löken, et al., 2009), suggesting a relationship between positive hedonic sensation and CT fibres activation (see Chapter 1 for more details). Moreover, neuropsychological (Kirsch et al., 2017; Olausson et al., 2002; Håkan Olausson et al., 2008), neuroimaging (Bjornsdotter, Loken, Olausson, Vallbo, & Wessberg, 2009; Case et al., 2016; Lindgren et al., 2012; Mcglone et al., 2012) and neuromodulation (Case et al., 2017) studies on the perception of affective touch have shown selective involvement of brain networks that have been associated with the processing of interoceptive signals, that is, signals regarding the physiological condition of the body.

Accordingly, it has been hypothesized that CT-fibers are the peripheral end of a dedicated interoceptive tactile system supporting the affective and affiliative functions of touch (e.g., Craig, 2002; Morrison et al., 2010; Olausson, Johansson, Morrison, McGlone & Vallbo, 2010). Nevertheless, the relationship between CT-optimal stimulation, autonomic regulation, and interoception remains unclear in adults, as CT-optimal touch is specifically associated with reductions in cardiac reactivity and skin conductance responses (Pawling et al., 2017), but not other measures of autonomic reactivity, such as cortisol variability (Triscoli, Croy, Steudte-Schmiedgen, Olausson, & Sailer, 2017), or interoceptive awareness such as heartbeat counting (Crucianelli et al., 2017). One possible explanation for the lack of relationship between interoceptive measures such as cardiac awareness and affective touch perception is that such measures do not typically account for top-down factors (cognitive beliefs, styles and expectations). Indeed, to our knowledge, the relationship between the perception of this tactile modality, as well as other interoceptive modalities such as cardiac awareness, and attachment style remains unexplored.

Therefore, the present study aimed to characterize individual differences in affective touch and cardiac awareness in terms of differences in pre-existing models of social interactions, namely attachment styles. Specifically, if affective touch is an interoceptive modality particularly relevant to social affiliation and affect regulation, one can presume that the perception of this specific type of touch in adulthood can further depend on individual differences in attachment. As pre-existing affective-cognitive models of social relating, individual differences in attachment style could determine the top-down influences on the perception of affective touch. Indeed, the relationship between the tactile stimuli (in this case delivered according to physical properties have been found to elicit the strongest responses in CT fibers), and the conscious perception of affective touch is highly variable, likely influenced by top-down factors such as social context, e.g., the person providing the touch and our inferences about that person and their intentions (Ellingsen et al., 2015) that are in turn influenced by prior beliefs about interpersonal relating. Such findings exist in other interoceptive modalities such as hunger (Alexander & Siegel, 2013) and pain (see Chapter 1), the latter being an interoceptive modality with opposite hedonic (positive vs. negative valence) and social (care vs. harm) characteristics to affective touch (see von Mohr & Fotopoulou, 2018 for discussion). Studies have also shown that the effects of social support on subjective, physiological and neural responses to pain, including support conveyed by CT-optimal touch (see Krahé et al., 2016; see also Chapter 3), depend on individual differences in attachment style (see Chapter 1).

However, to our knowledge, the relationship between attachment style and sensitivity to affective touch has not yet been studied. Here, we extend previous literature to examine how attachment style relates to the perception of affective touch, as well as to a different non-social modality of interoception, namely cardiac accuracy. Specifically, acknowledging the different research traditions in measuring attachment (see Ravitz et al., 2010 for a review), we examined attachment using two different measures. First we administered the gold standard Adult Attachment Interview (AAI; George, Kaplan, & Main, 1996). Taking a categorical approach, this semi-structured interview yields secure vs. insecure attachment classifications (as well as further sub-classifications of attachment characteristics) on the basis of questions relating to childhood experiences with caregivers. In addition, we used a well-validated self-report questionnaire (ECR; Fraley, Waller, & Brennan, 2000). This questionnaire pertains to adult romantic relationships and takes a dimensional rather than categorical approach, yielding continuous scores of attachment anxiety and avoidance. Attachment anxiety is characterized by a need for emotional closeness, worries of rejection and abandonment, over-dependence on others, negative views of self, positive views of others, and high emotional reactivity. Attachment avoidance is characterized by a need for emotional distance, resistance to trusting and depending on others, positive views of self, negative views of others, and suppression of emotion.

Given their history in seeking comfort through proximity, we expected that securely attached individuals, based on a categorical AAI classification, would find affective, CT-optimal touch (i.e., delivered at CT-optimal speeds, 1-10 cm/s) more pleasant than non-CT optimal touch (delivered at non-CT-optimal speeds, below and above 1-10 cm/s). By contrast, yet in line with previous findings on tactile exposure (Sailer & Ackerley, 2018), we expected that insecurely attached individuals (associated with reduced proximity-seeking in the case of dismissive attachment, or truly obtaining comfort through proximity, including touch, in the case of preoccupied attachment) would be less sensitive to affective, CT-targeted touch, that is, they would show reduced perceived pleasantness discrimination between the two types of touch. Exploring such differences further using a continuous measure of adult attachment style, we expected that this reduced sensitivity to the hedonic effects of CT-optimal and non-CT-optimal touch would be especially pronounced in individuals scoring higher in anxious and avoidant attachment dimensions, given their typical negative feelings and beliefs about seeking, or receiving social support (Mikulincer et al., 2003).

In addition, to investigate whether the relationship between insecure attachment and affective touch sensitivity is specific to this modality, or whether it relates to all interoceptive domains, we also employed a widely-used task of heartbeat counting as a measure of 'interoceptive accuracy', a particular facet of interoceptive awareness (see Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). Given previous findings about the dissociation between cardiac accuracy and affective touch (Crucianelli et al., 2017), we expected that attachment style, as measured by both categorical and continuous measures, would not relate to cardiac accuracy as measured by the standard heartbeat perception task, confirming the specificity of CT-optimal, affective touch to social bonding and attachment.

5.2 Methods

5.2.1 Participants

Participants were *N* = 44 right-handed women aged 18 – 31 years old (*M* = 23.87, *SD* = 3.77), recruited from King's College London and University College London. Participants did not currently suffer from and/or have a history of psychiatric disorders, neurological or medical conditions, and did not have wounds, scars, tattoos or skin irritation/diseases on their forearms. Participants were invited to take part in a study on bodily self-awareness consisting of two separate parts: one part involved rating the pleasantness of touch administered by the experimenter at different velocities (the touch paradigm; see below) and an interoceptive accuracy (heartbeat perception) task. The other part comprised the adult attachment interview, and participants also completed the Experiences in Close Relationships Revised questionnaire (ECR-R; Fraley et al., 2000) a self-report measure of adult attachment style. Participants' numerical IDs were used to match data from the different parts of the study and written informed consent was obtained from all participants. The Chair of the Research Department of Clinical, Educational and Health Psychology, University College London (UCL), approved this study and the experiment was conducted in accordance with the Declaration of Helsinki.

5.2.2 Touch paradigm

A trained experimenter unknown to participants manually stroked participants' left forearm using a cosmetic make-up brush (Natural hair Blush Brush, No 7, The Boots Company). Participants were seated comfortably at a computer, with their left forearm rested at an approximate 45° angle in front of them (their palm facing upwards) but separated from their view by means of a curtain. Two 9cm long by 4cm wide areas were marked continuously along participants' left volar forearm between wrist and elbow. To ensure a constant pressure, the brush splayed no wider than the 4cm window. Touch was administered to the underside of participants' left forearm in an elbow-to-wrist direction (Essick et al., 2010; Löken et al., 2011) at four different velocities, administered in a pseudo-randomized order and alternating between skin areas to avoid habituation: two CT-optimal speeds i.e., 3cms^{-1} and 9cms^{-1} and two non-CT-optimal speeds i.e., 0.3cms^{-1} and 27cms^{-1}. Each velocity was administered for 9s, followed by a 30-second interval during which participants rated the pleasantness of the touch on visual analogue scale from -100 (very unpleasant) to 100 (very pleasant) on a computer. Each velocity was administered three times and a mean rating was calculated for each velocity.

5.2.3 Interoceptive accuracy

We measured interoceptive accuracy using the heartbeat perception task (Schandry, 1981). Participants' heart rate was recorded using MP150 Data Acquisition Hardware (BIOPAC Systems Inc). A heartbeat monitor was attached to the tip of the left index finger and checked for tightness so that participants could not feel a pulse at this site. During a short training session participants were instructed to report the number of perceived heartbeats within a 15 seconds time interval. They were explicitly told to only count and report the number of actually perceived (and not estimated) heartbeats. The experiment started with a 10 second resting period. Participants closed their eyes and then silently counted their heartbeat (keeping their hand still and without feeling their pulse) for three trials lasting 25 seconds, 35 seconds and 45 seconds; the order was pseudo-randomised and participants were not informed of the duration of each trial. The beginning and end of each counting interval was signaled via tones. There was a 20 second pause after each trial during which participants verbally indicated their count for each trial. Interoceptive accuracy was computed using the mean score of the three heartbeat counting trials, using the transformation detailed in (Schandry, 1981) (see formula also below).

$$(1 \div 3) \times \sum_{i=0}^{3} [1 - ((recorded\ items - counted\ items) \div recorded\ items)]$$

This yields a score between zero and one, with one denoting greater correspondence between actual and perceived number of heartbeats i.e., higher interoceptive accuracy.

5.2.4 Adult attachment interview

The AAI (George et al., 1996) is a semi-structured interview, including 20 questions and lasting up to circa one hour. Meta-analyses and psychometric testing indicate stability, and discriminant and predictive validity in both clinical and non-clinical populations (Bakermans-Kranenburg & Van IJzendoorn, 1993; Hesse, 2008; Ravitz et al., 2010; van Ijzendoorn & Bakermans-Kranenburg, 2008). Participants were asked to reflect about their childhood experiences and early relationships with parents/caregivers. Questions included whether participants had experienced loss, separation or rejection, how their caregiver typically responded in particular situations e.g., when the participant was upset, and the kinds of implications these experiences had for the participant's adult life (see Hesse, 2008) for a detailed introduction to the AAI). All interviews were audio recorded and transcribed verbatim (including pauses). A trained coder coded all interview transcripts and classified participants as secure, dismissive, preoccupied, or unresolved, which allowed us to categorize participants as either securely or insecurely (dismissive, preoccupied, unresolved) attached i.e., our main two categories of interest. A second trained coder independently coded 25% of interviews. Agreement between the two coders was perfect (Cohen's kappa = 1) for the secure vs. insecure classification. Six participants did not attend the AAI session; hence, n = 38 participants were included in these analyses.

5.2.5 Self-report measure of adult attachment style (ECR-R)

The ECR-R (Fraley et al., 2000) comprises 36 items rated on a 7-point scale (1 = strongly disagree and 7 = strongly agree) regarding the general experience of intimate adult relationships; 18 items pertain to attachment anxiety (e.g., “I'm afraid that I will lose my partner's love.”) and 18 to attachment avoidance (e.g., “I don't feel comfortable opening up to romantic partners.”). Item responses are averaged (after reverse-scoring appropriate items) separately for each subscale to produce a mean score for attachment anxiety and attachment avoidance, with higher scores denoting greater attachment insecurity. This dimensional scoring is in line with research indicating that adult attachment styles are best conceptualised as dimensional constructs (Fraley, Hudson, Heffernan, & Segal, 2015). The ECR-R is well-validated (Ravitz et al., 2010; Sibley, Fischer, & Liu, 2005) and demonstrates excellent internal consistency: Cronbach’s $\alpha = .91$ for attachment anxiety and $\alpha = .90$ for attachment avoidance in the present sample.

5.3 Results

5.3.1 Descriptive statistics and preliminary analyses

5.3.1.1 CT and non-CT optimal touch perception. Pleasantness ratings showed an inverted U-shaped pattern commonly observed for these velocities (see e.g., Löken et al., 2009) : ratings were lowest for velocities at either end of the velocity spectrum i.e., the 0.3cm/s^{-1} and 27cm/s^{-1} velocities, and highest for the intermediate velocities i.e., 3cm/s^{-1} and 9cm/s^{-1} (see Figure 5.1). Velocity was associated with pleasantness ratings, $F(3, 129) = 59.46$, $p < 0.001$, with Sidak-corrected pairwise comparisons indicating that velocities differed significantly from each other ($p < .001$) except for the two CT optimal velocities (3cm/s^{-1} vs. 9cm/s^{-1}, $p = .999$) and the two non-CT-optimal velocities (0.3cm/s^{-1} vs. 27cm/s^{-1}, $p = .807$). Therefore, we computed mean ratings for CT-optimal vs. non-CT-optimal velocities by calculating the average of ratings for 3cms^{-1} and 9cms^{-1} speeds, and 0.3cms^{-1} and 27cms^{-1} speeds, respectively. CT-optimal vs. non-CT-optimal velocities differed as expected, paired samples $t(43) = 11.41$, $p < .001$, with CT-optimal velocities perceived as more pleasant ($M = 48.43$, $SE = 3.34$) than non-CT-optimal velocities ($M = 3.55$, $SE = 3.74$).

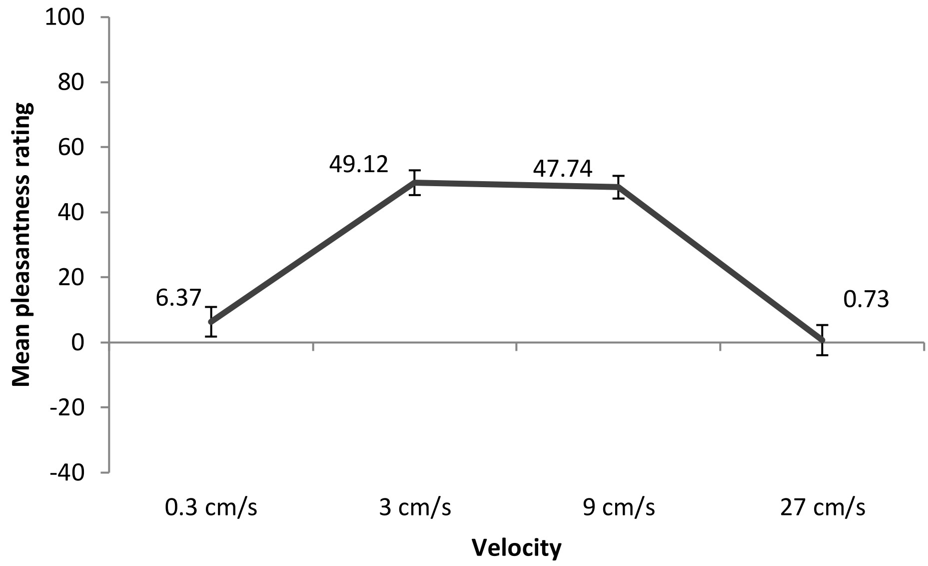


Figure 5.1: Pleasantness ratings for the four touch velocities: 2 CT-optimal (3 cm/s and 9 cm/s) and 2 non-CT optimal (0.3 cm/s and 27 cm/s). Pleasantness scale range: -100 to 100. Error bars denote ±SEM.

5.3.1.2 Interoceptive (cardiac) accuracy. Mean (*SD*) interoceptive accuracy was .42 (.25). The obtained mean score was slightly lower than mean scores in previous studies using this paradigm (e.g., Crucianelli et al., 2017; Garfinkel et al., 2015).

5.3.1.3 Relationship between CT-optimal vs. non-CT optimal touch discrimination and interoceptive (cardiac) accuracy. Affective-neutral touch discrimination (operationalised as a difference score of CT-optimal velocities minus non-CT-optimal velocities, i.e., greater scores denoting higher pleasantness ratings for CT-optimal vs. non-CT-optimal touch) was not significantly correlated with interoceptive (cardiac) accuracy, $r = .21$, $p > .05$.

5.3.1.4 Attachment classifications and dimensions. Based on the AAI, our sample ($n = 38$) showed the following classification frequencies: $n = 30$ participants (79%) were classified as securely attached and $n = 8$ (21%) as insecurely attached, of which $n = 1$ (3%) was preoccupied, $n = 5$ (13%) were dismissing, and $n = 2$ (5%) were unresolved. Despite an overrepresentation of securely attached individuals, our sample is in line with the general population AAI norms for non-clinical adult mothers (van Ijzendoorn & Bakermans-Kranenburg, 2008) as well as non-clinical adolescents/students (Bakermans-Kranenburg & van IJzendoorn, 2009), also suggesting a larger proportion of dismissive vs. preoccupied individuals. Mean (*SD*) ECR-R dimensional anxiety scores = 2.99 (0.98) and avoidance scores = 3.03 (0.93); in relation to general population norms for women, our sample fell below the mean for anxiety (population norm *M* = 3.56, *SD* = 1.13) and above the mean for avoidance (population norm *M* = 2.92, *SD* = 1.21; see information by Fraley, 2012: http://internal.psychology.illinois.edu/~rcfraley/measures/ecrr.htm). ECR-R dimensions were moderately correlated with each other, *r* = .49, *p* < .001, and were mean centered in statistical analyses to minimize multicollinearity issues (Aiken & West, 1991).

5.3.1.4 The relationship between categorical and dimensional measures of attachment style. A MANOVA with ECR-R anxiety and ECR-R avoidance scores as outcome variables and AAI classification (secure vs. insecure) as the independent variable showed that ECR-R scores did not differ by AAI classification, *F*(2, 36) = 1.74, *p* = .191, Wilk's lamda = .910. In other words, it was not the case that ECR-R anxiety scores were significantly lower in the secure vs. insecure group (Secure: *M* = 2.87, *SD* = 0.98; Insecure: *M* = 3.37, *SD* = 0.78), or that ECR-R avoidance scores were significantly lower for securely vs. insecurely attached participants (Secure: *M* = 3.05, *SD* = 1.00; Insecure: *M* = 2.90, *SD* = 0.71). This result supports the choice of two separate measures for this multi-dimensional construct.

5.3.1.5 The relationship between measures of attachment and interoceptive accuracy. AAI classification was not associated with interoceptive accuracy, *F*(1,35) = 0.45, *p* = .505. In addition, neither ECR-R anxiety (*r* = -.05, *p* > .05) nor ECR-R avoidance scores (*r* = .13, *p* > .05), were significantly correlated with interoceptive accuracy, as predicted.

5.3.2 Main analyses

5.3.2.1 Association between interview-assessed attachment style (AAI classification) and the perception of CT optimal touch. To examine whether attachment classification as measured by the AAI was associated with the perception of affective touch, we specified a multilevel regression model with mean pleasantness rating as the outcome variable and velocity (CT-optimal vs. non-CT-optimal), AAI (security vs. insecurity), and their interaction as predictor variables, and controlled for interoceptive accuracy. A random effect was included to account for the repeated assessment of the outcome variable within individuals.

AAI classification predicted pleasantness ratings across velocities: insecurely attached participants rated touch as more pleasant (*M* = 34.52, *SE* = 7.46) than did securely attached participants (*M* = 23.21, *SE* = 3.59). More critically, the hypothesised velocity by AAI interaction was significant (see Table 5.1 for full model results). Follow-up tests showed that the difference between CT-optimal and non-CT-optimal velocities was significant for securely attached participants (b = 49.01, *SE* = 4.08, $p < .001$), and insecurely attached participants (b = 28.19, *SE* = 8.44, $p = .001$). However, the difference in pleasantness ratings for CT-optimal and non-CT-optimal velocities was smaller for insecurely vs. securely attached participants (see adjusted mean difference above and Figure 5.2, top panel): an independent samples t-test on the CT-nonCT touch difference score (see above for how this was computed) confirmed that the difference was smaller in the insecure group (*M* = 28.81, *SD* = 14.13) than the secure group (*M* = 49.01, *SD* = 4.85), $t(36) = 2.06$, $p = .047$. Therefore, although both groups were able to discriminate between the two forms of touch, attachment insecurity was associated with lower sensitivity to CT-optimal versus non-CT-optimal touch, in line with our hypothesis.

5.3.2.2 Association between questionnaire-assessed attachment style (ECR-R) and the perception of affective touch. To test whether attachment style dimensions as measured by the ECR-R questionnaire were associated with the perception of pleasant touch, we specified a multilevel regression model with mean pleasantness rating as the outcome variable, and velocity (CT-optimal vs. non-CT-optimal), ECR-R attachment anxiety, ECR-R attachment avoidance, as well as all interaction terms, as predictor variables, and again controlled for interoceptive accuracy. As above, a random effect was included to account for the repeated assessment of the outcome variable within individuals.

Neither attachment anxiety nor attachment avoidance, nor the interaction between the two dimensions were associated with pleasantness ratings across velocities, indicating that pleasantness of touch in general was not influenced by continuous attachment style scores. However, importantly, the hypothesised velocity by attachment anxiety interaction was significant (see Table 5.1 for full model results). Follow-up analyses revealed that the difference between CT-optimal and non-CT-optimal velocities was significant at lower (i.e., -1SD; b = -53.06, *SE* = 5.12, $p < .001$), moderate (i.e., mean; b = -44.32, *SE* = 3.52, $p < .001$) and higher (i.e., +1SD; b = -35.58, *SE* = 5.24, $p < .001$) levels of attachment anxiety. Similar to the

AAI results, the difference in pleasantness ratings between CT-optimal and non-CT-optimal velocities was smallest at higher levels of attachment anxiety (see adjusted mean difference above and Figure 5.2, bottom panel). This finding indicates that higher attachment anxiety was associated with lower sensitivity to CT-optimal versus non-CT-optimal touch. The velocity by attachment avoidance interaction was non-significant, as was the three-way velocity by attachment anxiety by attachment avoidance interaction. Thus, attachment avoidance was not associated with the perception of affective touch, either alone or interaction with attachment anxiety. In sum, partially supporting our hypothesis, higher attachment anxiety but not attachment avoidance was associated with reduced sensitivity to affective touch.

Table 5.1
Model results for effects of attachment on the perception of affective touch.

		b	*SE*	*p* value	95% CI lower	95% CI higher
AAI	Velocity (CT-optimal vs. Non-CT-optimal)	49.01	4.08	< **0.001**	41.12	57.00
	AAI (security vs. insecurity)	21.72	9.53	**0.023**	3.05	40.40
	Velocity by AAI	-20.82	9.37	**0.026**	-39.19	-2.45
ECR-R	Velocity (CT-optimal vs. Non-CT-optimal)	44.30	3.53	< **0.001**	37.39	51.21
	ECR-R anxiety	5.04	3.95	0.202	-2.71	12.78
	ECR-R avoidance	-3.92	4.21	0.352	-12.16	4.33
	Velocity by ECR-R anxiety	-8.93	3.90	**0.022**	-16.58	-1.28
	Velocity by ECR-R avoidance	-2.09	4.14	0.614	-10.20	6.02
	ECR-R anxiety by ECR-R avoidance	-0.25	2.88	0.932	-5.89	5.40
	Velocity by ECR-R anxiety by ECR-R avoidance	1.27	2.86	0.656	-4.33	6.88

Note. AAI = Adult Attachment Interview; ECR-R = Experiences in Close Relationships – Revised questionnaire.

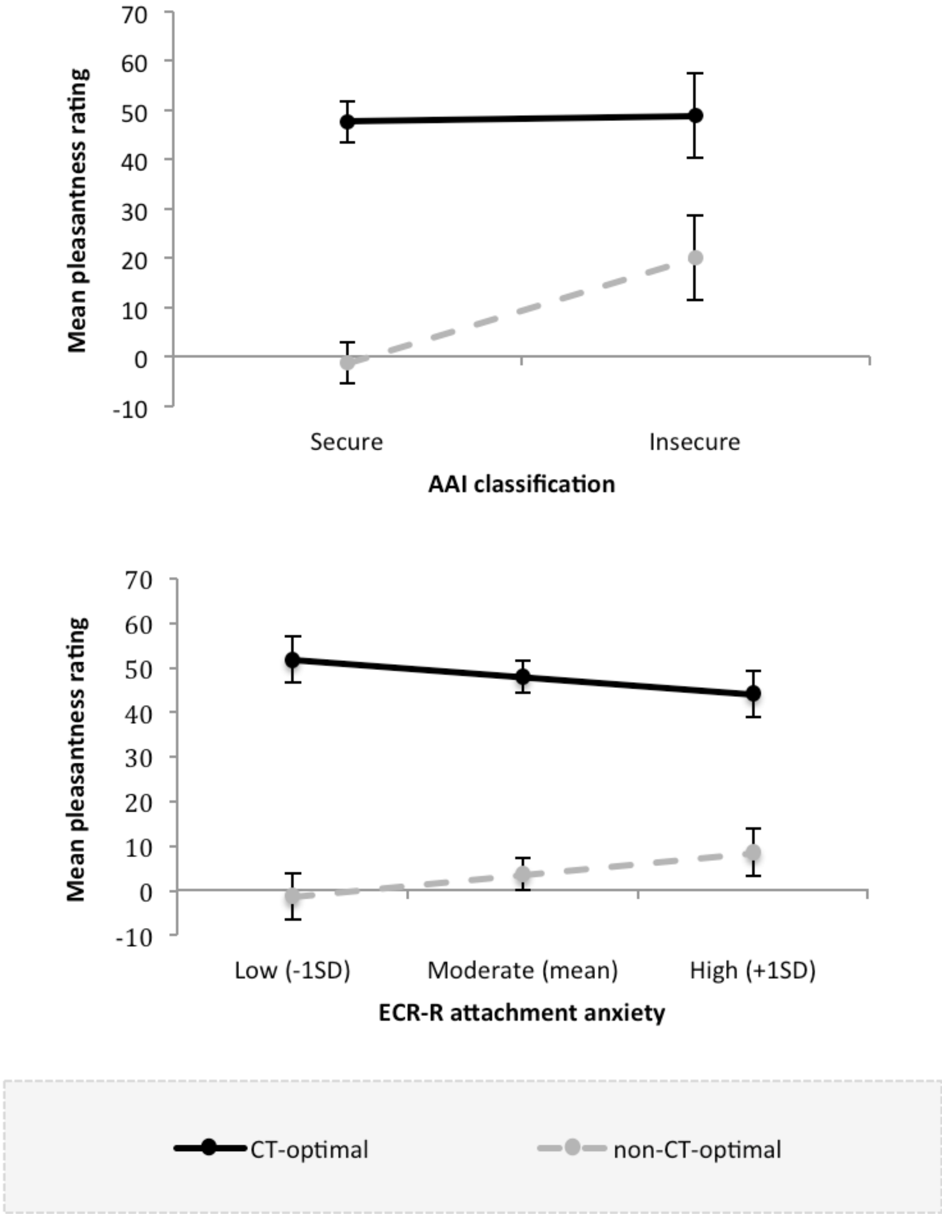


Figure 5.2: Interactions between velocity (CT-optimal vs. non-CT-optimal) and attachment classification on the Adult Attachment Interview (AAI) on the pleasantness ratings (top panel); and velocity and attachment anxiety measured using the Experiences in Close Relationships – Revised questionnaire (ECR-R) on the pleasantness ratings (bottom panel). Effects are plotted as secure versus insecure AAI classification for the former and at -1SD, mean, +1SD attachment anxiety for the latter. Error bars represent standard error of the mean.

5.4 Discussion

This chapter investigated the association between attachment styles and affective touch in adulthood. Under the assumption that affective touch supports affiliative bonds and social cognition and is influenced by top-down factors such as social context, we assessed how affective-cognitive models of social relating (i.e., attachment) influence the perception of affective touch. Using the gold standard assessment of adult attachment (the Adult Attachment Interview; AAI), we found that insecure attachment was associated with lower sensitivity to CT vs. non-CT touch. This semi-structured interview yields categorical attachment classifications in an implicit way, relating to representations of childhood experiences with caregivers. Acknowledging the different traditions in measuring attachment and the multi-dimensionality of this construct, we also used a well-validated self-report questionnaire that pertains to explicit evaluations of close relationships and takes a dimensional rather than categorical approach. This measure showed that higher attachment anxiety, though not higher attachment avoidance, was associated with lower sensitivity to affective (CT optimal) vs. non-affective (non-CT optimal) touch. Attachment style as assessed by both measures was not related to cardiac perception accuracy, suggesting that attachment is not relevant to all interoceptive modalities in the same way. These results will be discussed in turn below.

We found that both secure and insecure attachment groups (assessed by the AAI) were able to discriminate between affective vs. non-affective touch. However, the insecure attachment group was significantly worse in this discrimination than the secure group, suggesting that differences in pre-existing models of social interaction and related top-down expectations contribute to individual differences in affective touch perception. This finding provides further support to theoretical proposals regarding an association between the perceived affectivity of touch and social affiliation (see Chapter 1). Attachment representations are thought to originate in early caregiving experiences, in which touch plays a central part (Field, 2010; Stack, 2007). There is also evidence that childhood patterns of social relationships are reinforced across the lifespan (Waters et al., 2000) and it thus appears that affective responses to touch are also carried into adulthood. In fact, recent evidence suggests that individuals who experience low exposure to touch in everyday life are worse at discriminating CT-targeted touch, and the reasons behind experiencing less tactile exposure seem to relate to a lack of tactile, enjoyable experiences with close, familiar others (Sailer & Ackerley, 2018), which may be related to attachment. Nevertheless, other epigenetic effects should be considered. For example, increased licking and grooming (LG) in rat mothers (homologue to affective touch) alters the epigenome at a glucocorticoid receptor gene promoter in the hippocampus. In turn, offspring of mothers that showed higher vs. lower levels of LG were found to have differences in DNA methylation (Weaver et al., 2004), as well as differences in behavioural and HPA responses to stress (Liu et al., 1997; see also Meaney, 2001).

Differences in attachment (as measured by the AAI) were not related to cardiac accuracy. To date, there is no evidence to suggest that cardiac accuracy is an interoceptive modality relevant to social affiliation and thus pre-existing models of social relating, such as attachment classifications, were not predicted to influence this interoceptive modality. This finding also speaks to the more general relationship between interoceptive modalities. Other studies have shown that the perception of affective touch and cardiac perception accuracy are unrelated (Crucianelli et al., 2017), even though heart rate decreases have been associated with affective touch (Pawling et al., 2017). The current findings confirm this and further suggest that differences in attachment relate to the perception of affective touch but not cardiac perception accuracy. However, before drawing any firm conclusions, it’s worth mentioning that these type of cardiac accuracy measures have been recently criticised, as they are subject to several confounds, such as time estimation and heart rate activity (Zamariola et al., 2018).

Turning to our second two-dimensional measure of attachment style, we found that higher scores in attachment anxiety were related to poorer discrimination between affective and non-affective touch. This finding suggests that anxious attachment style as assessed by an explicit measure of adult close relationships relates to the perceived affectivity of touch in a similar way to insecure attachment as assessed by the AAI. In insecure attachment, others are perceived as unreliable and inattentive, and particularly in anxious insecure attachment this might generate anxiety (Nolte, Guiney, Fonagy, Mayes, & Luyten, 2011). These kinds of social expectations might thus affect the way in which affective touch is perceived and enjoyed. Consistent with recent research suggesting that infants as old as two months old show selective sensitivity to CT-targeted touch (Jönsson et al., 2018; Tuulari et al., 2017), we hypothesized that any difference in this discrimination in adulthood based on attachment styles would relate to top-down effects. Indeed, we also observed that insecure attachment style was related to the overall perceived pleasantness of our tactile stimuli, irrespective of whether or not they were in the CT-optimal range.

The fact that we did not observe differences in discrimination in our questionnaire dimension of attachment avoidance was unexpected, particularly as these individuals are characterized by a need for emotional distance and reduced proximity-seeking, including touch (Bartholomew & Horowitz, 1991; Brennan, Clark, & Shaver, 1998; Ravitz et al., 2010). This null finding thus suggests that at least at an explicit level, current top-down representations of close relationships in these individuals may not determine the perceived affectivity of touch. However, future research is needed before drawing firm conclusions. Here, we propose a few candidate explanations that may have led to such a lack of findings. First, although measurements of attachment style can possess benefits at a theoretical and statistical level, self-reported questionnaires have been largely criticized for being passive, i.e., not detecting attachment phenomena that need to be activated to be manifested (Ravitz et al., 2010). As such, this could have contributed to the current lack of findings. Also, as self-report measures, they are subject to social desirability effects, which are likely to be more pronounced in more avoidantly-attached individuals.

Finally, as with our other implicit measure of attachment, we found that individual differences in attachment style (as measured by the questionnaire dimensions) were not related to cardiac accuracy, suggesting that cognitive models of current close social relationships and related top-down expectations do not contribute to individual differences in cardiac interoceptive perception. Given that individual differences in attachment style were related to the perceived affectivity of the touch and not cardiac accuracy, this finding provides further support to the specificity of the relationship between affective touch and attachment style.

5.4.1 Limitations, strengths and future directions

Our findings should be considered in light of their limitations and directions for future research. First, it should be noted that there were no differences in the attachment anxiety or avoidance questionnaire scores between the secure and insecure AAI groups. This finding, together with prior research suggesting a trivial to small relation between self-report measures of attachment and the AAI (Roisman et al., 2007), speaks to the different aspects captured by each of these measures and consequently supports the choice of two separate measures for this multi-dimensional construct.

Second, on the AAI, small numbers in the insecure attachment group meant we were unable to further compare preoccupied vs. dismissing individuals. Future studies could aim to recruit larger groups of preoccupied and dismissing individuals to examine whether results on the insecure group may have been driven by preoccupied or dismissive individuals (although interestingly, the largest subgroup in the insecure AAI classification was dismissive; in line with the general population AAI norms (Bakermans-Kranenburg & van IJzendoorn, 2009; van Ijzendoorn & Bakermans-Kranenburg, 2008).

Third, pleasantness ratings for the CT-optimal velocities overall fell in the middle of the positive side of the response scale; it is likely that touch by an attachment figure, such as the romantic partner, may feel even more pleasant to participants than touch by an experimenter. It is clear that many social, environmental factors, including the relationship with the touch provider, can influence the perception of CT-optimal, affective touch (see Chapter 1). For instance, although the effects on perceived pleasantness between a person versus a robot delivering the touch seem to be comparable (Triscoli et al., 2013), evidence suggests that at least in romantic partners, the perception of pleasantness depends on the quality of their relationship (Triscoli, Croy, Olausson, & Sailer, 2017), thereby highlighting the importance of the quality of interpersonal interactions in touch perception. Similarly, the current effects on affective vs. non-affective touch discrimination may be subject to social context, in which for instance, touch by an attachment figure could activate attachment behaviors that are not at display when strangers are involved (see Ravitz et al., 2010). Thus, future research could incorporate partner-administered touch.

Fourth, we only tested women in order to control for gender effects associated with the perception of touch (e.g., Bendas, Georgiandis, Olausson, Weidner, & Croy, 2017; Croy, D'Angelo, & Olausson, 2014; Essick et al., 2010; Gazzola et al., 2012; Suvilehto, Glerean, Dunbar, Hari, & Nummenmaa, 2015; but also see, Rochelle Ackerley, Carlsson, Wester, Olausson, & Backlund Wasling, 2014; Jönsson et al., 2015; Sehlstedt et al., 2016). However, future research is needed to examine whether the present results extend to men. In particular, given that men tend to show higher attachment avoidance and lower anxiety than women (see del Giudice, 2011 for a meta-analysis), one could speculate potential gender effects when looking at CT-targeted touch sensitivity in relation to attachment style. Whether or not these exist, and may thus account for the mixed findings in the literature regarding general gender effects in touch perception, needs to be examined by future research.

Finally, in contrast to the previous Chapters, here we employed multiple velocities (i.e., 2 at CT-optimal speeds and 2 at non-CT optimal speeds, one below and one above the CT range), as well as a higher number of touch trials per velocity, which allowed us to examine the relationship between attachment style and affective touch in a more reliable manner. In fact, post-hoc analyses conducted on the data of the previous Chapters, suggest that (at least in relation to our continuous self-reported measure of attachment, i.e., the ECR-R), there is no relationship between affective touch sensitivity and attachment anxiety (nor avoidance) dimensions, as measured in each of these studies (see Appendix 6 and 7 for exploratory multilevel regression results). However, this discrepancy between the previous chapters and the current one could be due to several confounds, including differences in touch giver, differences in the number of touch trials and velocities examined, sample size, and carry-over effects associated with the main task (e.g., in previous chapters, as the relationship between attachment style and affective touch perception was not our aim, all pleasantness ratings were collected only as manipulation checks at the end of the main experiment which examined other variables). The implications of these findings in our theoretical model will be discussed in more detail in Chapter 7.

In sum, the present study corroborates and extends previous literature on the affectivity of touch and its relation with affiliative bonds and social cognition. Given that attachment style (in both measures) was not related to perceived cardiac accuracy, these findings point to the specificity of the relationship between affective, CT-optimal touch and attachment style. Future work is needed to examine the role of social context and whether the present results extend to men.

Chapter 6

Affective Touch Dimensions: From Sensitivity to Awareness

6.1 Introduction

The role of affective touch on pain, as well as individual differences in attachment style that influence such effects, has been examined in previous chapters. Importantly, one key characteristic of affective touch is that touch administered on hairy skin at CT-optimal speeds leads to increased feelings of pleasantness. Nevertheless, the perceived pleasantness resulting from CT-optimal touch has been mostly assessed by ratings (as also done in previous chapters). However, as discussed in Chapter 1, ratings may not be optimal for assessing the perceived pleasantness of CT-targeted touch. Specifically, despite neuroimaging evidence suggesting differential brain activations for touch administered at CT-optimal speeds on CT versus non-CT skin, evidence using pleasantness ratings suggests a similar pattern of results when assessing the perceived pleasantness of the touch in non-CT skin versus CT skin (see Chapter 1). For example, one study reported that while slow CT-optimal touch was associated with increased activity in the posterior insular cortex and mid-anterior orbitofrontal cortex or in the somatosensory cortex depending on the stimulation skin site (i.e., CT versus non-CT skin), there was no difference in perceived pleasantness between these skin sites as measured by pleasantness ratings (McGlone et al., 2012). Moreover, people prefer to be touched at a speed within the CT-optimal range, as well as engage brain regions involved in reward-related processes, when stroked both on CT and non-CT skin (Perini, Morrison, & Olausson, 2015). As such, it is thought that the perceived pleasantness in non-CT skin is the result of secondary reinforcement. In other terms, such effects in non-CT skin can be a result of top-down effects, i.e., learned expectations of pleasantness linked to touch at CT-optimal speeds that lead to a similar experience, even when the stimulation site does not contain CTs. Thus, novel ways to measure affective touch that take into account bottom-up and top-down processes in response to stroking at CT-optimal speeds are needed.

It is well known that tactile sensitivity varies across the body, which, among other things, depends on the neurophysiology of the skin (e.g., sensory afferent type and density). Human skin can be divided into two main categories, with different sensory afferent properties: glabrous skin (e.g., palm) and hairy skin (e.g., forearm). On the one hand, glabrous skin contains different types of myelinated mechanoreceptive afferents, which given their fast conduction velocity (60 m/s) provide the brain sensory information about the touch with high temporal-accuracy, i.e., tactile sensitivity and discrimination, including duration, texture, force, velocity and vibration (Johansson & Vallbo, 1979; Vallbo & Johansson, 1984). On the other hand, although with lower density (Provitera et al., 2007), hairy skin also possesses myelinated mechanoreceptive afferents, yet importantly, also contains unmyelinated, slow conducting CT afferents (Vallbo et al., 1999; Vallbo, Olausson, Wessberg, & Norrsell, 1993). As reviewed in Chapter 1, CTs have been implicated in the emotional processing of touch. Specifically, studies on unmyelinated CT afferents suggest that CT afferents preferentially encode low force, relatively slow stroking touch. Namely, CTs activation follow an inverted U-shape relationship between the mean CT firing mean frequency rate and the stroking velocity; that is, CTs activation is higher in response to relatively slow velocity tactile stimulation (1-10cm/s^{-1}) and lower in response to velocities above or below this range, suggesting that stroking within the 1-10 cm/s range optimally activates CT afferents. Moreover, such CT activation is strongly correlated with perceived pleasantness (Löken et al., 2009). No such relationship exists between the mean firing frequencies of myelinated afferents and stroking velocity. Instead, the response of myelinated afferents increases with faster velocities, and shows no relationship with perceived pleasantness (Löken et al., 2009).

Subsequently, a large body of research has focused on quantifying the sensory and emotional aspects of touch, including hairy and glabrous skin (Ackerley et al., 2014, 2014; Essick et al., 1999; Guest et al., 2011; McGlone et al., 2012). For example, Guest et al. (2011) developed and validated a descriptive scale for touch perception, namely the TPT, consisting of sensory and emotional descriptors. Using the TPT, it has been found that stroking the forearm (hairy, CT-skin) led to higher ratings of emotional descriptors, whereas stroking the palm (glabrous, non-CT skin) led to higher sensory descriptors (McGlone et al., 2012). Similarly, using different materials (i.e., soft brush, fur, sandpaper) has been shown to lead to higher emotional content on the forearm versus the palm and cheek (Ackerley, 2014). Nevertheless, the TPT has not been used to assess the emotional attributes of touch at different speeds, which as aforementioned, play an important role in both CTs firing rate and perceived pleasantness; perhaps because it would be difficult to use verbal descriptors when the only changing variable is the velocity of the touch. Instead, research on the field has mostly focused on the use of ratings, such as visual analogue scales on a continuous pleasantness dimension (e.g., ranging from not pleasant at all to extremely pleasant; see Chapter 1), and more recently evaluative conditioning (Pawling et al., 2017).

Employing pleasantness ratings, numerous studies have shown that when stroking the forearm, individuals perceive gentle stroking touch within the CT-range, i.e., 1-10 cm/s, as more pleasant than gentle stroking touch outside the CT-range (e.g., Ackerley et al., 2014; Morrison, Bjornsdotter & Olausson, 2011; Ellingsen et al., 2014; Sehlstedt et al., 2016), showing a similar inverted U-shape relationship between stroking velocity and perceived pleasantness as reported by Loken et al (2009). However, the use of ratings in general has been subject to several criticisms, including individual differences in the use of the scale. Moreover, within the CT literature, the use of pleasantness ratings has not been able to provide a clear distinction between CT and non-CT skin. Indeed, given that no CTs have been found on glabrous skin, one would not expect an inverted U-shape relation between stroking velocities and perceived pleasantness on glabrous skin such as the palm. However, several studies report that stroking within a CT-optimal range also leads to similar increase in ratings of pleasantness in both forearm and palm (Ackerley et al., 2014; Gentsch et al., 2015; McGlone et al., 2012; Löken, Evert, & Wessberg, 2011; c.f., Löken et al., 2009; Essick, James, & McGlone, 2009). Thus, it is thought that the effects of perceived pleasantness observed on the palm are likely due to secondary reinforcement, wherein top-down processes associated with expectations of pleasantness linked to relatively slow stroking can also lead to increased perception of pleasantness even when delivered to non-CT skin (McGlone et al., 2014). In this sense, pleasantness ratings may not be sufficient to discriminate between bottom-up sensory mechanisms (CT afferent signalling in response to touch at CT optimal speeds in CT skin) and top-down higher cognitive mechanisms (learned expectations linked to touch at CT optimal speeds) that may lead to the experience of pleasantness on the skin.

One way to tap into the sensory and cognitive domains that underpin the emotional aspects of touch is asking subjects to make forced decisions about the tactile stimuli, and assess the accuracy on their discrimination as well as their 'attitudinal predisposition'. This way of assessing sensory and cognitive domains, based on 'Signal Detection Theory' (SDT), has been applied to both exteroceptive (e.g., vision, audition, e.g., see; Cameron, Tai, Eckstein, & Carrasco, 2004; Hillyard, Squires, Bauer, & Lindsay, 1971; Verghese, 2001) and interoceptive modalities (e.g., heart beat activity, pain, e.g., see, Garfinkel et al., 2015; Mancini, Nash, Iannetti, & Haggard, 2014; Rollman, 1977) as a measure of exteroceptive or interoceptive sensitivity, respectively. Specifically, SDT provides a means by which one can measure an individual performance in detecting, or discriminating between, ambiguous stimuli by a known process (i.e., signal) or by chance (i.e., noise), providing two main outcomes: sensitivity (d') and response bias (C), which mainly tap into the sensory and cognitive domain, respectively (Heeger, 2017; Macmillan, 2002; Rollman, 1977). Sensitivity (d') indicates the strength of the signal (relative to the noise). Response bias (C) indicates the cognitive strategy or attitudinal tendency of the participant. These two parameters are extracted by calculating the proportion of trials in which the participant accurately detected the signal (i.e., hit rate) and the proportion of trials in which the participant said it was signal but it was in fact noise (false alarm rate) (see Abdi, 2007 for their respective formulas). Thus, the current Chapter aimed to go beyond prior investigations by combining for the first time CT stimulation with signal detection theory (SDT). In particular, consistent with the CT literature (Loken et al., 2009; McGone et al., 2014), we predetermined the tactile stimuli administered at CT-optimal speeds (1-10 cm/s range) as more likely to generate 'high pleasantness' judgements (i.e., signal) and the stimuli administered at non-CT optimal speeds (slower than 1 cm/s and faster than 10 cm/s) as more likely to generate 'low pleasantness' responses (i.e., noise). Participants' ability to accurately discriminate the touch in terms of pleasantness (high versus low), as well as their potential negative or positive bias (i.e., tendency to perceive the low-pleasant stimuli as high-pleasant or vice versa), was thus assessed using a forced-choice task on two different skin sites: forearm (CT-skin) and palm (non-CT skin) (type 1 task).

In addition, this Chapter measured the participant's own ability to recognize their trial-by-trial successful detection of pleasant stimuli (as high or low pleasant depending on CT versus non-CT optimal speeds, respectively) on forearm and palm.

Specifically, this study employed a receiver operating characteristic (ROC) analysis (type 2 task) as a measure of metacognitive sensitivity (Fleming & Lau, 2014). This measure of metacognitive sensitivity has been applied to exteroceptive and interoceptive modalities (e.g., Fitzgerald, Arvaneh, & Dockree, 2017; Garfinkel et al., 2013, 2015; Palser, Fotopoulou, & Kilner, 2018) as an index of how participant's confidence relates to their accuracy (type 2 hit) and inaccuracy (type 2 false alarm) on detecting a signal, while being 'bias free'. For example, one may think that when one is confident, one is more likely to be correct. However, this is not always the case; one can have high overall confidence (e.g., a bias to provide high confidence ratings) that does not relate to correct responses, and vice-versa. Critically, although metacognitive measures have been applied to several modalities, with recent research arguing for the supramodality of metacognition, i.e., finding a correlation between visual, auditory, and tactile metacognitive efficiency (Faivre, Filevich, Solovey, Kühn, & Blanke, 2017), it still remains unknown whether these supramodal confidence findings extend to interoceptive signals. In this study, one could speculate differences in metacognitive sensitivity on a skin site that possesses CT afferents versus one that does not. In particular, if one takes confidence as an individual's subjective probability of their decision being correct and consequently, one of many forms of uncertainty, one would expect higher confidence in a skin area in which pleasantness detection is not only based on top-down effects, but also possesses the necessary sensory inputs, i.e., CT-afferents, such as the forearm. Whether or not higher confidence predicts pleasantness judgment's accuracy better on the forearm versus the palm was therefore investigated in this study.

In sum, in two experimental studies, the present Chapter aimed to test three major hypotheses. First, given that CTs are located on the forearm but not the palm, we hypothesized higher pleasantness sensitivity (d') on the forearm versus palm, consistent with the specificity of bottom-up CT-based signaling. This should lead to a measure of *affective touch sensitivity*. Second, we hypothesized more negative response bias (C) on the palm versus forearm, suggesting a tendency to judge the touch as high-pleasant on this non-CT skin area, in line with potential top-down effects of pleasantness on the palm explaining the increased feelings of perceived pleasantness on the palm (where no CTs have been found) reported by the literature. Third, we hypothesized higher confidence to predict the accuracy of detected pleasantness (as measured by the ROC analyses) better on the forearm versus the palm, given that reduced uncertainty is likely observed in a skin area where both bottom-up and top-down processes linked with touch at CT-optimal speeds occur. This metacognitive measure can be considered as a measure of *affective touch awareness.*

6.2 Experiment 1

6.2.1 Methods

6.2.1.1 Participants. Based on an initial pilot using the exact same method outlined below, with a separate sample size of 21 participants, with an effect size of Cohen's d= .27 and .30 for sensitivity d' and response bias, respectively, power calculations indicated we would require at least ninety subjects to achieve a power of .80 (G*power 3.1). Thus, ninety-four participants (M_{age}=22.97, SD_{age}=5.56) were recruited via the University College London (UCL) Psychology Subject Pool for this study and received £10 or 1 credit in compensation for their time. Both females and males (Fourty-nine females, fourty-five males) were recruited. Even though the experimenter delivering the touch was always female, there were no gender effects across any of our outcome measures (see Appendix 8). The UCL ethics committee approved this study and the experiment was conducted in accordance with the Declaration of Helsinki.

6.2.1.2 Procedure. Signal Detection Preparation and Familiarisation Phase: Upon obtaining written informed consent, participants were informed that they would receive soft tactile stimuli on their arm and two adjacent stroking areas (each measuring 9 cm long) were marked on the participant's forearm and palm (same arm). As an example of the kinds of touch they were about to receive in the main task, participants received one repetition of four randomised types of touch with a soft cosmetic brush (Natural hair Blush Brush, No. 7, The Boots Company; 1 stroke at 2 CT speeds: 3 cm/s and 9 cm/s; and 2 non-CT speeds: .5 cm/s and 18 cm/s). The velocity of the touch or their expected effects of felt pleasantness (i.e., high versus low) were not disclosed to participants. It's worthwhile mentioning that we decided to not disclose the expected effects of pleasantness in the familiarisation phase because the expected effects could have driven the participants to base their judgements on this memory element and thus answer the main task based on these example velocities, irrespective of their actual perceived pleasantness.

Signal Detection Main Task: Participants were told they would receive similar kinds of touch on their forearm and palm, and they would have to focus on the sensation arising from the touch and categorise the touch into two categories of felt pleasantness: 'high' or 'low'. In each trial, following the participant's pleasantness judgement, they were also asked to provide confidence ratings on their judgment using a scale ranging from -4 'not at all confident' to 4 'extremely confident'. Next, using the same soft cosmetic brush (Natural hair Blush Brush, No. 7, The Boots Company), the first half of the participants received 48 randomised touch trials of 4 CT-optimal speeds (1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s) and 4 non-CT optimal speeds (0.3 cm/s, 0.5 cm/s, 18 cm/s, 30 cm/s; i.e., two velocities that were slower and two that were faster than the CT optimal range) on their forearm (CT-skin; 24 trials) and palm (non-CT skin; 24 trials). Interim analyses were conducted following this first half of the sample on our main outcome measures, i.e., sensitivity d' and response bias (revealing the same pattern of results as those reported below with the total sample size; see Appendix 9). As there is a reasonably high chance to observe a significant effect after collecting only half of the participants suggested by a priori power analyses (Lakens, 2014), we continued testing for the planned total sample size but results below were interpreted under a lower alpha level set at .025 (i.e., alpha/2 given the two analyses: one interim and one after all the data was collected) to control for type 1 error as a result of performing interim analyses (see Lakens, 2014). Nevertheless, for the second half of the participants, we increased the number of touch trials to 64 randomised trials (i.e, 4 trials per velocity instead of 3), in order to increase reliability and approach a more normal distribution of what we predetermined as the signal and noise. This was accounted for in our calculation of d' and C by adjusting the number of signal and noise trials (see below for d' and C calculations). Moreover, independent sample t-tests conducted between the first and second half of the sample indicated no significant differences in any of our outcome measures, all *p*'s > .05, confirming that there were no differences on d', C and aROC between the first and second half of our sample.

Manipulation check (pleasantness ratings): Following the main Signal Detection task, we collected pleasantness ratings of CT optimal (1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s) and non-CT optimal (0.3 cm/s, 0.5 cm/s, 18 cm/s, 30 cm/s) speeds in order to make sure that participants were in fact perceiving touch at CT-optimal speeds as more pleasant than non-CT optimal speeds (this is important for SDT analyses given we are considering CT-optimal speeds as the signal). One trial per velocity was delivered at each skin site (with the order randomised across skin site). We used the same soft brush to administer the randomized 16 trials. After each trial, participants were instructed to rate verbally the pleasantness of the touch using a scale ranging from 0 ‘not at all pleasant’ to 100 ‘extremely pleasant.

Tactile acuity: Following the control task, general tactile sensitivity to punctuate touch was also tested using Von Frey monofilaments in a force detection paradigm (only on the second half of the sample, i.e., n=47, consistent with prior studies employing a similar sample size (e.g., Ackerley et al., 2014), finding significant results when comparing tactile acuity on forearm versus palm). As determined in pre-tests, five calibrated monofilaments with sufficient range of forces were chosen: 0.4 mN, 0.7 mN, 1.6 mN, 3.9 mN, 9.8 mN, 19.6 mN, 39.2 mN. Using an increasing/decreasing detection difficulty task (Bell-Krotoski et al., 1993), we established a threshold monofilament for each skin site (i.e., forearm and palm; the order of skin site was counterbalanced across participants). Each monofilament was pressed five times (for 1s with a 1s gap) and after the five presses, the participant was asked to say how many presses they felt.

6.2.1.3 Data analyses. Signal detection (sensitivity d’ and response bias C): In order to implement signal detection analysis, and consistent with prior literature on CT stimulation and perceived pleasantness (Löken, et al., 2009), the stimuli administered at CT-optimal speeds (1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s) were considered as more likely to generate ‘high pleasantness’ judgements, i.e., signal, whereas the stimuli administered at non-CT optimal speeds were considered as more likely to generate ‘low pleasantness’ responses, i.e., noise (see Figure 6.1). We thus calculated normalised hit rates (P[‘‘high’’/CT-optimal speed], i.e. the proportion of hit trials to which subject responded ‘‘high’’ and the stimulus was administered at CT-optimal speeds), and false alarm rates (P[‘‘high’’/non-CT optimal speeds], i.e. the proportion of trials in which the touch was administered at non-CT optimal speeds but the participant responded ‘‘high’’) for the forearm (CT skin) and palm (non-CT skin) separately. These were used to obtain the perceptual sensitivity (d’), a measure of discriminability in detecting the high-pleasure target, and the response bias (C), which measures the tendency to report stimuli as ‘‘high’’. The *affective touch sensitivity* (d’) was quantified as: d’ = z(hit rate)- z(false alarm rate). The response bias (C) can be expressed as: C = (z[hit rate] + z[false alarm rate]) * 0.05. Data from one participant was not included given that the number of ‘high’ responses to low-pleasant stimuli was equivalent to the maximum (i.e., 16 ‘high pleasant’ responses we given to the 16 stimuli pretermined to generate ‘low pleasantness’ responses, i.e., noise), and thus d’ and C could not be computed. This yielded a total sample size of 93 participants for these analyses. We conducted paired t-tests between forearm and palm separately on sensitivity (d’) and response bias (C), to examine whether there was any difference in sensitivity (d’) and response bias (C) between CT and non-CT skin sites.

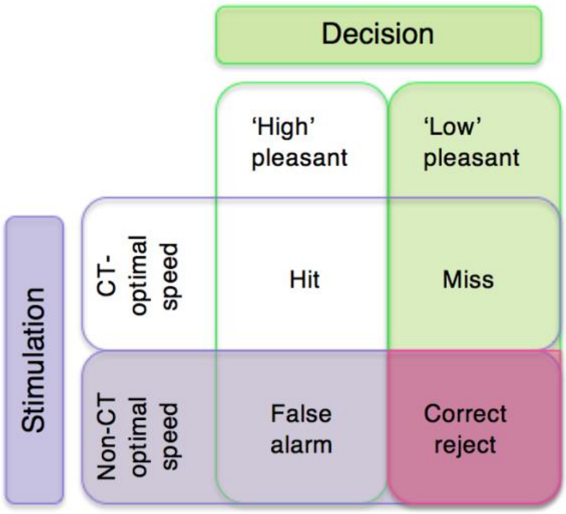


Figure 6.1: A schematic representation of the SDT model applied to affective touch. CT-optimal speeds include 1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s, which were considered as the high-pleasant stimuli. Non-CT optimal speeds include 0.3 cm/s, 0.5 cm/s, 18 cm/s, 30 cm/s; i.e., two velocities that were slower and two that were faster than the CT optimal range) and were considered as the low-pleasant stimuli. Normalised hit rates were calculated as (P[‘‘high’’/CT-optimal speed], i.e. the proportion of hit trials to which subject responded ‘‘high’’ and the stimulus was administered at CT-optimal speeds), and false alarm rates were calculated as (P[‘‘high’’/non-CT optimal speeds], i.e. the proportion of trials in which the touch was administered at non-CT optimal speeds but the participant responded ‘‘high’’).

Metacognitive sensitivity: To investigate the extent to which confidence predicts perceptual accuracy, i.e., correct and incorrect responses about the categorization of the tactile stimuli in terms of pleasantness and speed (i.e., type 1, high/low-pleasant, see above), a type 2 receiver operating characteristic (ROC) analysis was conducted. ROC examines the extent to which a signal (here confidence) is an effective detector of some binary variable *i*. For each confidence rating threshold (in this case 10), one computes the hit rate (i.e., proportion of trials correctly detected, e.g., proportion of i=1 trials detected as *i*=1; simply put, proportion of correct trials in which confidence was 'high') and the false alarm (proportion of trials incorrectly detected; e.g., i=0 trials detected as *i*=1; simply put, proportion of incorrect trials for which the confidence was 'high'). The ROC curve plots the hit rate versus the false alarm rate over all the possible detection thresholds. To measure how confidence is predictive of accuracy one typically computes the area under the ROC curve (aROC). The aROC provides a measure of the extent to which the detector is correct for a given level of confidence (Massoni, Gajdos, & Vergnaud, 2014) and therefore can be used as a measure of metacognitive sensitivity. Higher aROC indicates higher metacognitive sensitivity (Fleming & Lau, 2014). Data from thirty-six participants was not included in this analysis, given that there was not enough variance in the confidence ratings between the binary variable *i* for these participants and thus an aROC could not be computed (yielding a sample of 58 participants for this analysis). We conducted paired t-tests between forearm and palm separately on aROC scores, to examine whether higher confidence predicts accuracy better on CT versus non-CT skin.

Manipulation check (pleasantness ratings): CT optimal (1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s) and non-CT optimal (0.3 cm/s, 0.5 cm/s, 18 cm/s, 30 cm/s) touch ratings were averaged separately per skin area (forearm, palm) for each participant, creating CT-optimal touch palm, CT-optimal touch forearm, non-CT optimal palm and non-CT optimal forearm pleasantness averaged rating scores for each participant (see supplementary materials for group level analyses on pleasantness scores). To further validate our signal detection model in the main task, correlations were conducted between the sensitivity (d') scores of our participants and their difference scores on the averaged subjective pleasantness ratings (CT-optimal speed minus CT non-optimal speed) separately on forearm and palm.

Tactile Acuity: The threshold level for each participant (per skin site) was defined as the monofilament at which the participant could feel at least four (out of five) presses in both the increasing and decreasing detection difficulty aspects of the task. Von Frey filaments were then dummy coded from 1 to 7, from lower to higher filament force (i.e., 0.4 mN=1, 0.7 mN=2, 1.6 mN=3, 3.9 mN=4, 9.8 mN=5, 19.6 mN=6, 39.2 mN=7) for the purpose of this analyses. Data from 2 participants were removed as they reported more than five presses on either the ascending or descending order, yielding a total sample size of 45 participants for this analysis. In order to make sure participant's ability to discriminate pleasantness better between skin sites did not depend merely on general tactile sensitivity, we conducted correlations, *r*, between d' and the threshold level on both skin sites. We also conducted paired t-tests on the threshold level between forearm and palm to assess whether there was more tactile sensitivity on palm versus forearm. On a scale from 1-7, lower scores would indicate greater tactile sensitivity.

6.2.2 Results

6.2.2.1 Affective Touch Sensitivity (d') and Response bias (C). As expected, significantly higher sensitivity (d') was found on the forearm (*M*=1.43, *SD*=.91), as compared to the palm (*M*=1.19, *SD*=.94), *t*(92)=2.80, *p*=.006 (see Figure 6.2; top panel), even at an alpha level set at .025 (see section 6.2.1.2). However, contrary to our predictions, we found more negative response bias (C) on the forearm (M= -.32, SD=.47) as compared to the palm, (M= -.14, SD=.56), t(92)=2.76, *p*=.007 (see Figure 6.2; bottom panel), even at an alpha level set at .025 (see section 6.2.1.2). Thus, these results suggest that participants are better at discriminating high-pleasure target stimuli on the forearm vs. palm, with a tendency to also report low-pleasant stimuli as high pleasant on this same skin site.

6.2.2.2 Does confidence predict accuracy? Our aROC analysis measured the extent to which confidence was predictive of the success in correctly categorizing the touch as high or low pleasant (hit) than in inaccurate responses (false alarm), as a measure of metacognitive sensitivity, separately on the forearm and the palm. We found greater metacognitive sensitivity on the forearm as compared to the palm, i.e., greater area under the ROC curve was found on the forearm (M=.71, SD=.12), relative to the palm (M=.67, SD=.11), t(57) =2.12, *p* = .038; see Figure 6.3.

6.2.2.3 Manipulation check (pleasantness ratings). Analyses conducted on the pleasantness ratings scores suggested that CT-optimal touch (at CT speeds; 1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s) was perceived as more pleasant than non-CT optimal touch (at non-CT optimal speeds; 0.3 cm/s, 0.5 cm/s, 18 cm/s, 30 cm/s) at the group level (see Appendix 10). Further validating our signal detection model in the main task, we report a positive correlation between sensitivity d' and the pleasantness rating difference scores (CT-optimal speed – non-CT optimal speed) on the forearm, r=.45, p<.001, and palm, r=.46, p<.001 (see Figure 6.4). Thus, the bigger the difference on pleasantness ratings between CT and non-CT speeds, the higher their d' scores, on both forearm and palm.

6.2.2.4 Tactile acuity. As expected, tactile acuity sensitivity as measured by the von Frey filaments differed across skin sites, t(44) =11.89, $p<.001$. Specifically, higher tactile sensitivity was observed on the palm (M=2.33, SD=1.00) versus the forearm (M=4.44, SD=1.03). Moreover, tactile sensitivity did not correlate with d' sensitivity on the palm, r= -.06, p=.694, nor forearm, p= -.15, p=.330, indicating that participant's ability to discriminate pleasantness better between skin sites did not depend merely on general tactile, acuity sensitivity.

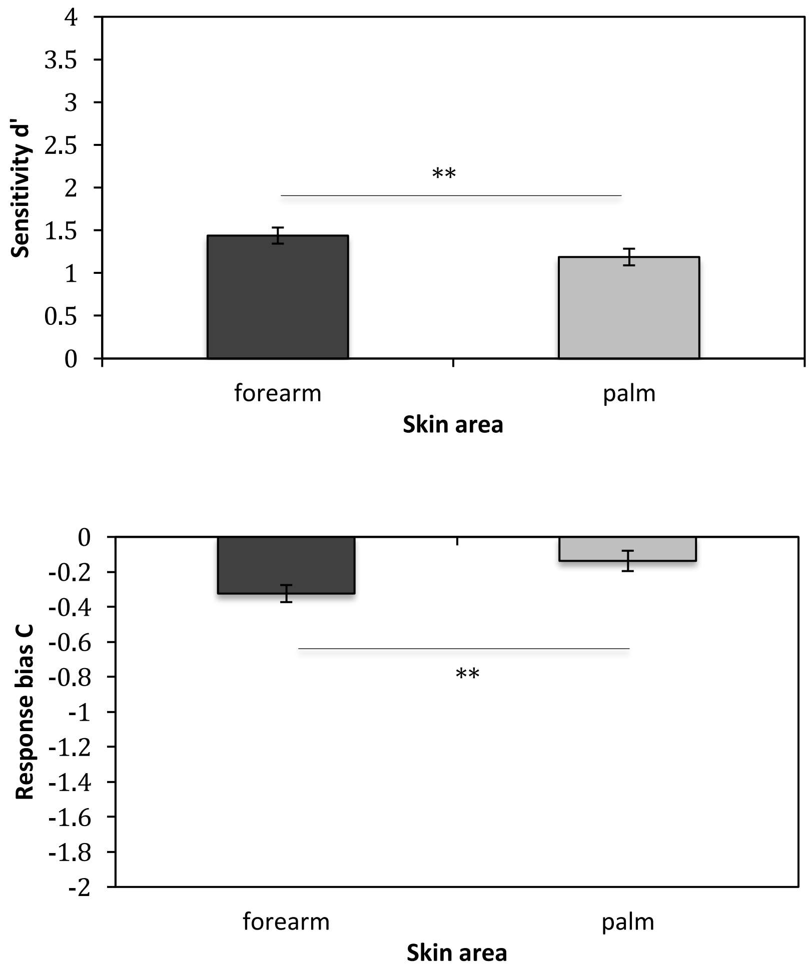


Figure 6.2: Sensitivity (d') for forearm (CT skin) and palm (non-CT skin); top panel. Response bias (C) for forearm (CT skin) and palm (non-CT skin); bottom panel. Error bars denote ± standard error of the mean for illustration purposes. ** indicate statistical significance, p<.01

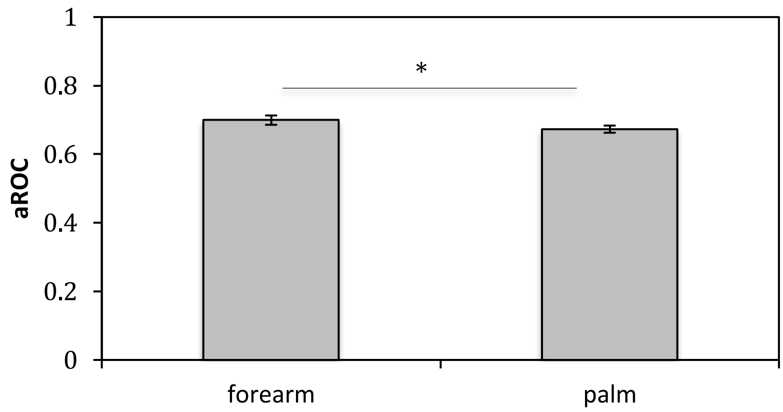


Figure 6.3: aROC for forearm and palm. Error bars denote ± standard error of the mean for illustration purposes. * indicate statistical significance, $p<.05$.

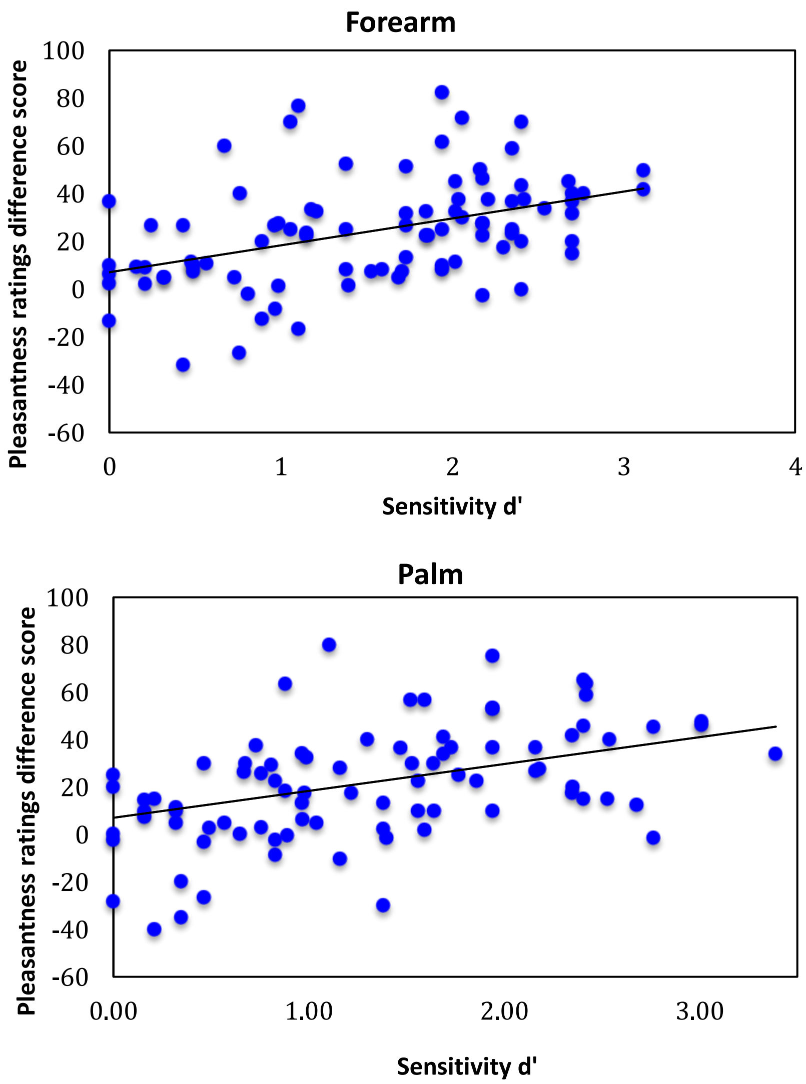


Figure 6.4: Top panel: Correlation between sensitivity d' (x-axis) and pleasantness ratings difference score (CT-optimal – non-CT optimal speed; y-axis) on the forearm. Bottom panel: Correlation between sensitivity d' (x-axis) and pleasantness ratings difference score (CT-optimal – non-CT optimal speed; y-axis) on the palm.

6.2.2.5 Summary of results for Experiment 1. In sum, consistent with our predictions, these results showed higher pleasantness (d') sensitivity on the forearm (CT skin) versus the palm (non-CT skin), even though higher tactile acuity as measured by the von Frey filaments was observed on the palm versus the forearm. In other terms, the touch delivered at CT-optimal speeds was judged as 'high-pleasant stimuli' (i.e., hits) more frequently than touch delivered at non-CT optimal speeds (i.e., less false alarms) in a skin area that contains CT afferents, i.e. the forearm, in comparison with a skin area that does not contain CT fibers, i.e the palm. By contrast, as a measure of tactile acuity, participants were able to detect to a better extent the von Frey stimuli (i.e., static, brief tactile stimuli) on a skin site that does not possess CT afferents, i.e. the palm, relative to the forearm. Similarly, higher confidence was more predictive of accurately detecting pleasantness on the forearm versus the palm, suggesting better metacognitive sensitivity (i.e., higher confidence in accurate [hit] relative to inaccurate responses [false alarm]) on CT-skin relative to non-CT skin. However, contrary to our predictions, we also observed more negative response bias (i.e., more hits and false alarms) on the forearm versus the palm, indicating a bigger tendency or 'attitudinal predisposition' to generally judge tactile stimuli as high-pleasant when administered on CT skin, irrespective of their speed. Finally, as a manipulation check, we collected pleasantness ratings from each stroking velocity on both forearm and palm. Positive correlations between pleasantness ratings difference score (the average of CT speeds minus the average non-CT speeds, termed hereafter 'CT ratings differential') and pleasantness (d') sensitivity indicated a moderate-to-strong positive relationship between d' and CT ratings differential on both forearm and palm. This relationship further validates our signal detection model in the main task by indicating that pleasantness (d') sensitivity, which is based on a binary, discriminatory response of high versus low pleasantness captures pleasantness perception in a similar way as widely-used, pleasantness ratings scales.

Nevertheless, there is the possibility that some of these results can be explained by order effects of skin site associated with the perception of pleasantness following tactile stimulation on a skin site that contains CT-afferents. In particular, recent evidence suggests that the perception of pleasantness for palm stimulation is influenced by preceding forearm stimulation, in that not only there is a general increase in perceived pleasantness following tactile stimulation on the forearm (which contains CT afferents) but also increased pleasantness is observed in response to touch at CT-optimal versus non CT-optimal speeds on this non-CT skin area (Löken et al., 2011). Thus, one may speculate that in a skin area where there are more top-down biases about CT-optimal velocities, such as the palm, the felt pleasantness following touch in the forearm may 'spill over' to this non-CT innervated skin area (and even to speeds outside the CT range). Indeed, as it will be further discussed in section 6.4, results from this experiment further suggest there is also a negative response bias in the palm (and not just the forearm), reflecting a tendency to judge the touch as 'high-pleasant'. Accordingly, a block design was employed to measure signal detection separately on each skin site in Experiment 2.

6.3 Experiment 2

6.3.1 Methods

6.3.1.1 Participants. Based on the initial pilot (see section 6.2.1.1), and given Experiment 1 (also revealing similar effect sizes, i.e., Cohen's d =.26 and .34), suggesting that at least ninety subjects are needed to obtain a power of .80, a similar sample size was selected for this experiment. Specifically, one hundred participants (M_{age}=21.9, SD_{age}=3.34) were recruited via the University College London (UCL) Psychology Subject Pool. The study was conducted in accordance with the Declaration of Helsinki and was approved by the University's ethics committee and participants received £10 or 1 credit in compensation for their time. Distinct to Experiment 1, in this experiment a block design was employed to measure signal detection separately on each skin site (i.e., the touch trials from the main SDT task were delivered first on the palm and then on the forearm, with the order counterbalanced across participants). Specifically, forty-nine participants were assigned to group A, in which they first completed the Signal Detection task on their forearm (block 1), and then completed the Signal Detection task on their palm (block 2). Conversely, fifty-one participants were assigned to group B, in which they first completed the Signal Detection only on their palm (block 1), and then completed the Signal Detection task on their forearm (block 2). Females and males were recruited (fifty-three females: twenty-five assigned to group A and twenty-eight to group B; forty-seven males: twenty-four assigned to group A and twenty-three to group B). Similar to Experiment 1, even though the experimenter delivering the touch was female, there were no gender effects across any of our outcome measures (see Appendix 11).

6.3.1.2 Procedure. Upon obtaining written informed consent, participants were informed that they would receive soft tactile stimuli on their arm and two adjacent stroking areas (each measuring 9 cm long) were marked on the participant's forearm and palm (same arm). As mentioned above, participants completed both the Signal Detection Task separately on their forearm and palm, with the order counterbalanced across participants (i.e., group A or B). For example, on the Signal Detection task – forearm block, participants were given the same instructions as described in Experiment 1 (see 'signal detection preparation and familiarization phase'). This was followed by the Main Signal Detection task – Forearm, where participants received 32 touch trials (4 trials per velocity, same velocities described in Experiment 1) but only on their forearm and asked to categorise the touch into two categories of felt pleasantness: 'high' or 'low', followed by confidence ratings on their judgment using a scale ranging from -4 'not at all confident' to 4 'extremely confident' (as in Experiment 1). On the Signal Detection task – palm block, participants were then given the same instructions but were told they would be receiving the touch only on their palm (including 'signal detection preparation and familiarization phase' described on experiment 1). As before, they received 32 touch trials (4 trials per velocity, same velocities described in Experiment 1) but only on their palm and asked to categorise the touch into two categories of felt pleasantness: 'high' or 'low', followed by confidence ratings on their judgment using a scale ranging from -4 'not at all confident' to 4 'extremely confident' (as in Experiment 1).

Following the completion of these two blocks, participants completed the same manipulation check (i.e., pleasantness ratings were collected for each of the eight velocities; 4 CT and 4 non-CT) described in Experiment 1. The order of skin site in this last control task resembled the order of blocks to which each participant had been assigned.

6.3.1.3 Data analyses. Signal detection (sensitivity d' and response bias C): Sensitivity d' and C for the forearm and palm was calculated in the same way as in Experiment 1 (see section 6.2.1.3 for details). Here, data from six participants were not included given that the number of 'high' responses to low-pleasant stimuli was equivalent to the maximum on either their forearm or palm (i.e., 16 'high pleasant' responses were given to the 16 stimuli predetermined to generate 'low pleasantness' responses, i.e., noise), and thus d' and C could not be computed. This yielded a total sample size of 94 participants for these analyses. We conducted a 2x2 mixed ANOVA, specifying order (first forearm, first palm) as between-group factor, separately on sensitivity (d') and response bias (C), to examine whether there was any difference in sensitivity (d') and response bias (C) between CT and non-CT skin sites, while examining potential order effects. Follow-up analysis used paired or independent t-tests with Bonferroni correction when applicable.

Metacognitive sensitivity: The aROC for the forearm and palm was calculated in the same way as in Experiment 1 (see section 6.2.1.3). Data from twenty-six participants was not included in this analysis, given that there was not enough variance in the confidence ratings between the binary variable *i* for these participants and thus an aROC could not be computed (yielding a sample of 74 participants for this analysis). We conducted a 2 (skin site: forearm, palm) x 2 (order: firs palm, first forearm) mixed ANOVA on aROC scores to examine whether high confidence predicts accuracy (hits) versus inaccuracy (false alarms) better on CT versus non-CT skin and whether such effects depend on the order of the block.

Manipulation check (pleasantness ratings): We analysed pleasantness ratings from our control task as described in Experiment 1 (see section 6.2.1.3 for analyses details).

6.3.2 Results

6.3.2.1 Affective Touch Sensitivity (d') and Response bias (C). Similar to Experiment 1, we found higher d' on the forearm (M=1.74, SD=.99) than on the palm (M=1.38, SD=1.01), $F(1,93)=10.93$, $p=.001$, $\eta^2_{partial}=.11$. There was no main effect of order $F(1,93)=.39$, $p=.573$, $\eta^2_{partial}=.00$, and order did not interact with skin area, $F(1,93)=.16$, $p=.693$, $\eta^2_{partial}=.00$ (see Figure 6.5; top panel). Thus, these results suggest that participants are better at discriminating high-pleasure target stimuli on the forearm vs. palm, irrespective of the order of the blocks.

With respect to response bias (C), there was no main effect of skin area, $F(1,93)=2.16$, $p=.145$, $\eta^2_{partial}=.02$, or order, $F(1,93)=.08$, $p=.794$, $\eta^2_{partial}=.00$. However, skin area interacted with order, $F(1,93)=27.28$, $p=<.001$, $\eta^2_{partial}=.23$. Post-hoc tests, using Bonferroni adjusted alpha level of .0125 per test (.05/4), showed that if participants completed the palm block first, then there was more negative response bias on the second block, i.e., forearm, $t(47)=4.28$, $p<.001$. Similarly, if they completed the forearm block first, then there was more negative response bias on the second block, i.e., palm, $t(46)=3.04$, $p=.004$. However, between-subjects analyses showed that when the palm versus the forearm goes first, there was more negative response bias on the forearm, $t(93)=2.60$, $p=.011$, but not the palm, $t(97)=1.94$, $p=.055$ (see Figure 6.5; bottom panel). Thus, these results suggest that exposure to touch may be associated with a general tendency to judge the touch as ‘high pleasant’, irrespective of skin area (although between-subjects effects suggest that such effects are more prominent if the palm is stimulated first), as reflected by more negative bias on the second block.

6.3.2.2 Does confidence predict accuracy? Similar to Experiment 1, although only at trend level, we found that high confidence was more predictive of accurately detecting pleasantness on the forearm versus the palm, i.e., greater area under the ROC curve was found on the forearm (M=.74, SD=.14) relative to the palm (M=.71, SD=.16), $F(1,72)=3.19$, $p=.145$, $\eta^2_{partial}=.04$, thus hinting to greater metacognitive sensitivity on CT-skin. There was no main effect of order, $F(1,72)=.09$, $p=.764$, $\eta^2_{partial}=.00$, and order did not interact with skin area, $F(1,72)=.17$, $p=.680$, $\eta^2_{partial}=.00$ (see Figure 6.6).

6.3.2.3 Manipulation check (pleasantness ratings). Similar to Experiment 1, analyses conducted on the pleasantness ratings scores suggested that CT-optimal touch (at CT speeds; 1 cm/s, 3 cm/s, 6 cm/s, 9 cm/s) was perceived as more pleasant than non-CT optimal touch (at non-CT optimal speeds; 0.3 cm/s, 0.5 cm/s, 18 cm/s, 30 cm/s) at the group level (see Appendix 12). Further validating our signal detection model in the main task, we report a positive correlation between sensitivity d’ and the pleasantness rating difference scores (CT-optimal speed – non-CT optimal speed) on the forearm, r=.44, p<.001, and palm, r=.59, p<.001 (see Figure 6.7). Thus, the bigger the difference on pleasantness ratings between CT and non-CT speeds, the higher the d’ scores, on both forearm and palm.

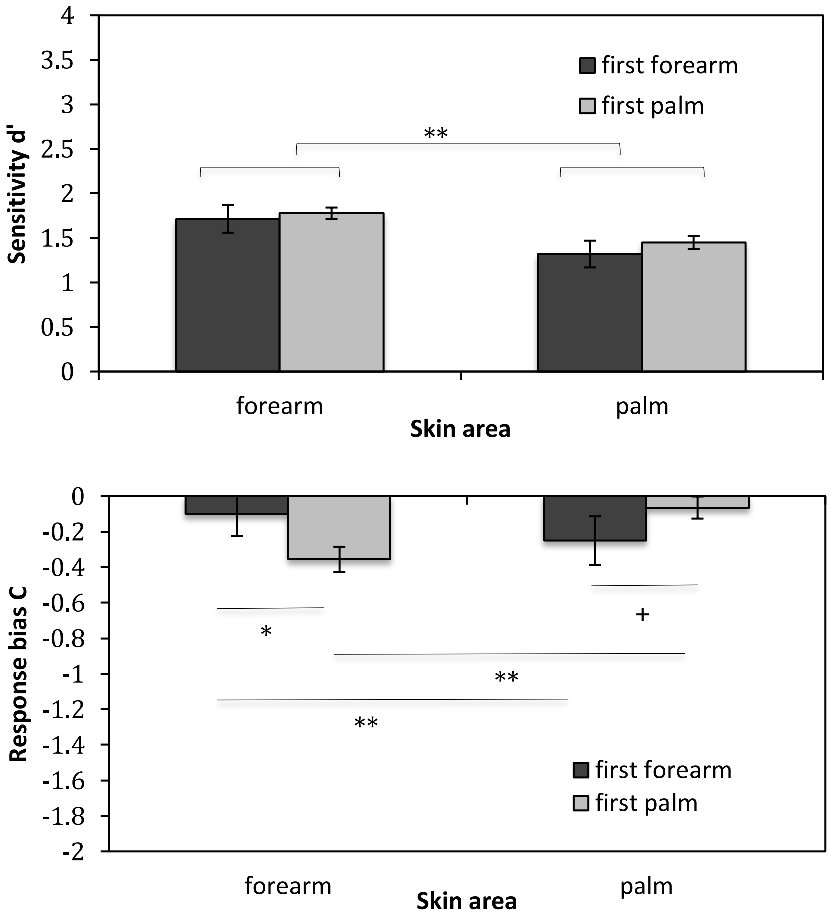


Figure 6.5: Sensitivity (d') for the forearm (CT skin) and palm (non-CT skin) by order of the blocks; top panel. Response bias (C) for the forearm (CT skin) and palm (non-CT skin) by order of the blocks; bottom panel. Error bars denote ± standard error of the mean for illustration purposes. * and ** indicate statistical significance at, p<.05 and p<.01, respectively. + indicates significance at a trend level.

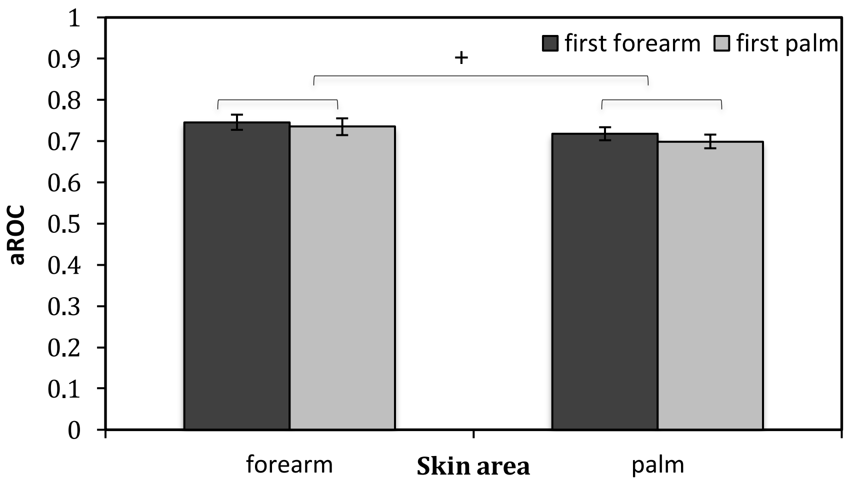


Figure 6.6: aROC computed for forearm and palm by order of the blocks. Error bars denote ± standard error of the mean for illustration purposes. + indicates a tendency towards significance

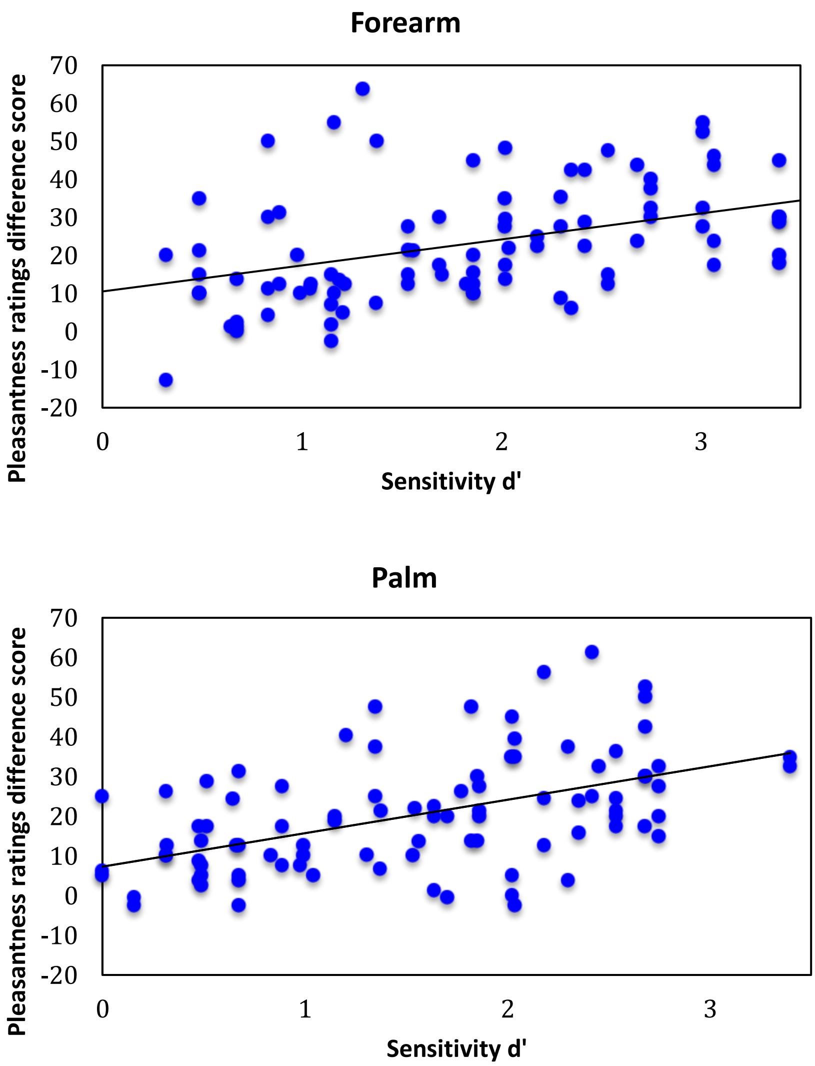


Figure 6.7: Top panel: Correlation between sensitivity d' (x-axis) and pleasantness ratings difference score (CT-optimal – non-CT optimal speed; y-axis) on the forearm. Bottom panel: Correlation between sensitivity d' (x-axis) and pleasantness ratings difference score (CT-optimal – non-CT optimal speed; y-axis) on the palm.

6.3.2.4 Summary of results for Experiment 2. In sum, consistent with Experiment 1, results from Experiment 2 showed higher d' sensitivity on the forearm (CT skin) versus the palm (non-CT skin), irrespective of order effects. Our effects on criterion C, suggest that the tendency to judge the touch as high-pleasant stimuli depends on the order of the block, with more exposure to touch being associated with a bigger tendency to report the stimuli as high pleasant, irrespective of skin area. Our aROC analyses show a similar pattern for metacognitive sensitivity as reported in Experiment 1, although such effects are only present at trend level in Experiment 2. Finally, analyses conducted on the pleasantness ratings further validated our signal detection model in the main task by indicating a moderate-to-strong positive relationship between d' and pleasantness ratings differential on both forearm and palm (as also seen in Experiment 1).

6.4 Discussion

Previous research on touch has mostly relied on asking subjects to rate the perceived pleasantness of tactile stimuli using measures such as visual analogue scales or Likert-type scales that are subject to individual response tendencies and biases, such as individual differences in the interpretation and use of the scale. Here we used a forced-choice task that asks for a binary response, i.e., to judge the touch as high- or low-pleasant, with an analysis approach that can take into account individual response tendencies. Specifically, by combining for the first time CT stimulation with a signal detection task (SDT), we extracted different parameters, such as sensitivity d', response bias, and metacognitive sensitivity (aROC), to provide an index of affective touch sensitivity and awareness. In Experiment 1 we implemented SDT with the touch trials randomized across CT and non-CT skin sites, i.e., forearm and palm, respectively. In Experiment 2, we implemented SDT using a block design (first forearm and then palm and vice versa). Supporting our first hypothesis, in both experiments, we found higher sensitivity d' on the forearm versus the palm, indicating that people are better at discriminating high-pleasure target stimuli (i.e., touch at CT-optimal speeds) on a skin site that contains CT afferents. Contrary to our second hypothesis, however, we found more negative response bias (C) on the forearm versus the palm, indicating a tendency to report the stimuli as 'high-pleasant' on CT-skin, irrespective of the touch velocity (i.e., CT-optimal and non-CT-optimal speeds) (Experiment 1). However, in a follow-up experiment we assessed a potential explanation for this finding, namely that such effects could be driven by order effects, and indeed we found that there is more negative bias following touch exposure, but irrespective of skin site (Experiment 2). Supporting our third hypothesis, we found that there was more metacognitive sensitivity on the forearm than the palm, i.e., high confidence was more predictive of perceived (pleasantness) accuracy on the forearm versus the palm (although such effects were found only at trend level in Experiment 2). Further validating our SDT model, we found a moderate-to-strong relationship between d' and pleasantness ratings differential (obtained from the manipulation check) on both forearm and palm in both experiments. These findings and their limitations are discussed in more detail below.

Microneurography studies have shown that the firing frequency of CTs, which have been found on hairy but not glabrous skin, and the stroking velocity follow an inverted U-shape relationship – with firing frequency of CTs being also highly correlated with pleasantness ratings (Loken et al., 2009). Such finding thereby suggests that there is a relationship between perceived pleasantness and coding at a peripheral level, hence perceived pleasantness on hairy skin is, at least partly, mediated by bottom-up CT afferent signalling. The present findings on sensitivity d' lend support to this finding by showing better discrimination to CT-optimal speeds (i.e., stimuli predetermined as 'signal'), i.e., affective touch sensitivity, on the forearm versus the palm, even though there was better tactile acuity on the palm versus the forearm as measured by the von Frey filaments. The latter finding was expected given that glabrous skin in the hand is known to contain dense myelinated tactile afferents (Vallbo & Johansson, 1984) that send fast, temporally-accurate information about the touch to the brain, explaining the high tactile acuity. Similar findings on tactile acuity on glabrous versus hairy skin, including skin areas such as the palm and the forearm, have been shown by Ackerley et al. (2014). In fact, it has been proposed that the distribution of afferents on these skin sites reflects the usage of these skin surfaces, with for example the palm of the hands being key in exploring our environment (where a larger distribution of Aβ myelinated afferents exists) and skin sites such as the forearm or face being key for interpersonal interactions (where a lower distribution of Aβ myelinated afferents exists yet these skin sites also contain unmyelinated CT afferents) (see Ackerley, 2014; also see Vallbo & Johansson, 1984; Johansson et al., 1988; Vallbo et al., 1995).

Returning to our findings on sensitivity d', it is worth noticing that the sensitivity d' found in both forearm and palm is above chance. In fact, when it comes to sensitivity d', zero values indicate no discrimination, but values above this range indicate at least some discrimination between these the stimuli predetermined as noise and signal – with the larger the d' value, the better the discrimination. In practice, d' of 4 or more indicates nearly perfect performance, and particularly in our study, given the number of signal and noise trials, d' of 3.725 indicates nearly perfect performance. Thus, participants in the present study were also accurately determining, to a certain degree, CT-optimal speeds on the palm (i.e., stimuli predetermined as 'signal') as 'high-pleasant' stimuli, and stroking velocities outside the CT range (i.e., stimuli predetermined as ‘noise’) as ‘low-pleasant’ stimuli (where no CTs have been found). On the one hand, these findings also raise the possibility that the CT system is not the only afferent system contributing to tactile pleasantness and further work is needed to establish its role in tactile perception, as well as the role of other fibres, spinal and brain mechanisms to perceived pleasantness. On the other hand, it is possible that such discrimination on the palm is a result of carry-over effects from preceding tactile stimulation from the forearm (CT skin). Indeed, previous research has shown that the perception of pleasantness on the palm is affected by stimulation on the forearm (Löken et al., 2011). However, we think this is unlikely because, as shown in Experiment 2, the order of the blocks (e.g., completing the SDT task first on the forearm and then on the palm) had no effects on sensitivity d’. Instead, our findings on sensitivity d’ suggest that this non-CT skin sensitivity is not affected by short, previous stimulation on CT-skin. We therefore speculate that such effects on the palm are due to learned associations between stroking velocity and pleasantness, which have been well reinforced throughout the lifespan. The precise role of CTs in such learning process still needs to be examined.

Turning to our second hypothesis, we found that there is more negative response bias (C) on the forearm versus the palm (resulting in more ‘hits’ and ‘false alarms’ in the former), indicating a bias to report the stimuli as ‘high-pleasant’ on CT-skin, irrespective of the touch velocity (Experiment 1). Such finding is consistent with previous research suggesting that CT skin, such as the forearm, is typically perceived as more pleasant than non-CT skin, such as the palm (e.g., Löken et al., 2011; Ackerley et al., 2014, except for speeds at 30 cm/s; see also Appendix 10 and 12 for pleasantness ratings manipulation checks). Critically, however, a negative response bias as reflected by negative values ($C<0$) was found on both the forearm and palm, indicating a tendency to report the stimuli as ‘high-pleasant’ irrespective of touch velocity in both CT and non-CT skin sites. Thus, although our hypothesis on criterion C was not fully confirmed, these results suggest that there are top-down effects of perceived pleasantness on both forearm and palm – though to a larger extent on the forearm. In line with the social touch hypothesis (Morrison et al., 2010), we speculate that the tendency to judge the touch as high versus low pleasant is associated with the exposure to touch, which may be greater in skin areas that are key for social interactions such as the forearm. In fact, recent evidence suggests that people with less touch exposure show a general tendency to rate gentle, stroking touch as less pleasant (Sailer & Ackerley, 2017). Supportive of this notion, our findings in Experiment 2 further suggest that the observed tendency to judge the tactile stimuli as high-pleasant stimuli depends on the order of the block, with more exposure to touch being associated with a larger tendency to report the stimuli as high pleasant, irrespective of skin area. Future work is needed to investigate if this is the case. As alternative explanations, it is also possible that (1) participants may be reluctant to categorise the touch as 'low-pleasant', which indeed has been a focus of recent debate regarding binary, similar 'yes-no' tasks as participants show substantial criterion effects (see Ruby, Giles, & Lau, preprint for a discussion) and thus, two-alternative-forced choice paradigm might be more optimal; and (2) the fact that there is actually a person touching participants gently with a soft brush, irrespective of the speed.

Regarding our third hypothesis, our aROC findings suggest that higher confidence was more predictive of accurately detecting high-pleasant target stimuli on the forearm versus the palm, indicating higher metacognitive sensitivity, i.e., affective touch awareness, on CT skin. Higher confidence, i.e., reduced uncertainty (Fleming & Daw, 2017), was expected in a skin area where not only top-down but also bottom-up CT signaling occurs. In this sense, one can speculate that the fact that there is some kind of reliable signaling on the forearm, in this case CT afferents that have been shown to signal pleasantness from the periphery, lead to reduced uncertainty on one's ability to correctly discriminate high-pleasant CT-targeted stimuli, i.e., bottom-up modality based theory of metacognition, in a way arguing against the supramodality of metacognition. Nevertheless, more work is needed before drawing any firm conclusions, particularly given that only one modality was tested here and thus we cannot conclude with certainty that these effects are necessarily bottom-up modality driven (other analyses such as meta d' would also be recommended, see Fleming & Lau, 2014). Thus, taken together, our findings suggest that there is not only increased affective touch sensitivity on the forearm versus the palm (as reflected by sensitivity d'; type 1 task), but also, higher confidence judgments regarding subject's performance on this task seem to better predict the accuracy on detecting the high-pleasant target stimuli on the forearm versus the palm (as reflected by the aROC analyses; type 2 task). Future studies should examine other drivers of confidence in participant's task performance, aside from the sensory certainty effects mentioned here. For example, could these effects be associated with response requirements, as in previous research suggesting that it is the precision rather than confidence that describes uncertainty of perceptual experience (Denison, 2017)? And could these post-assessments of decision quality be also guiding subject's accuracy in detecting CT-optimal targeted stimuli as the task develops?

6.4.1 Limitations, strengths and future directions

To the best of our knowledge, this is the first study to combine affective touch with signal detection paradigms. However, the present findings should be considered in light of their limitations and directions for future research. First, our SDT design employed two predetermined thresholds, whereas SDT research typically involves only one predefined threshold. For example, in experimentally induced pain, participants are asked to identify pinprick pain as 'high' or 'low' based on a predetermined pain threshold (i.e., the moment participant's begin to feel sharp pinprick pain, e.g., Borhani, Làdavas, Fotopoulou, & Haggard, 2017) In contrast, our SDT design employed two thresholds: below and above the CT range. This was done because of two main reasons. First, in pain for example, an increase in noxious stimulation leads to a linear increase in pain perception, while an increase in tactile velocity does not lead to an increase in perceived pleasantness, but rather to an increase in tactile acuity. Second, this was done in order to ensure that participant's pleasantness discrimination was not merely based on the increasing velocity of the touch. In fact, if this had been the case, we would have observed d' values very close to 0. Thus, although the two noise distributions (i.e., touch velocities below and above the CT ranged) were grouped together in order to analyze the data according to the SDT principles (with the same number of trials for noise and signal), future research should examine whether these results hold when setting only one threshold. For example, one could predetermine the threshold at 1 cm/s and examine the discrimination between speeds within the CT range (e.g., at 3 cm/s and 6 cm/s) and below the CT range (e.g., .3 cm/s and .5 cm/s), or the other way around. This was not further explored in the current data given the low number of trials (i.e., doing this would result in only 8 noise and 8 signal trials per skin area).

Second, we predetermined the tactile stimuli administered at CT-optimal speeds (1-10 cm/s range) as more likely to generate 'high pleasantness' judgements (i.e., signal) under the assumption that these speeds are perceived as more pleasant than those above and below the CT range. Such notion was further confirmed with our manipulation checks at a group level (see appendix 10 and 12), suggesting that touch delivered within the CT range (same speeds as in the main SDT task) was rated as significantly more pleasant than those below and above the CT range (in both forearm and palm). However, there could be individual differences in the CT threshold that could have influenced the SDT task. We therefore tried to minimize this issue by having a large sample size of participants in each experiment. Moreover, our correlations between d' and pleasantness ratings differential (obtained from the manipulation check) on both forearm and palm further validate our SDT model. Nevertheless, for the purpose of precision, future research should aim to first obtain an individual threshold for each participant (e.g., use a threshold detection procedure to assess the speeds at which participants begin to perceive the touch as more pleasant and then as less) and then apply the SDT paradigm (adapting the touch velocities to the respective threshold).

Third, the power to detect an effect is also influenced by the number of trials. While, clearly, our two experiments were sufficiently powered to determine affective touch sensitivity, this was partly due to the large sample size of this studies. Indeed, the number of trials for the SDT task is in the low side for measuring sensitivity d' and response bias C, and even more for the assessment of metacognition (Green & Swets, 1966). In particular, this could have posed problems for our aROC analyses, predominantly as many participants were not included in these analyses given the lack of variance in the confidence ratings. However, we chose to not increase the number of trials for the main SDT task as participants were already beginning to show psychological fatigue as it was. Future research should ensure adequate power when determining affective touch sensitivity and awareness.

Fourth, a trained experimenter always delivered the touch in this study, but this could have led to some human error, particularly given the eight different velocities administered in these two experiments. In order to optimise precision, future research may want to deliver the touch by means of a robotic device, particularly as no differences in perceived pleasantness have been reported when the touch is delivered by a robot versus a person (Triscoli et al., 2013). This was not done for the current experiment, given that pilot data (n=12) using an in house device versus an experimenter to collect pleasantness ratings at eight different touch velocities (same as in the current experiments) indicated that participants perceived the touch at CT-optimal speeds on the forearm as more pleasant than non-CT optimal speeds only when it was delivered by a person, $p<.001$, but not the robot, $p=.53$

(similar pattern of results was found when stroking the palm). We attributed these striking findings to the home-made robot used in this pilot (especially as it was showing a degree of undesirable vibration at one CT velocity, namely 9 cm/s) and thus, replication of the present study using a well-tested robot to deliver the touch is needed.

Finally, the experimenter providing the touch was always female, whereas the touch receivers were both females and males. In contrast to previous research suggesting gender effects associated with the perception of touch (e.g., Bendas et al., 2017; Ilona Croy et al., 2014; Essick et al., 2010; Gazzola et al., 2012) there were no gender effects found across any of our outcome measures, including our manipulation checks on pleasantness ratings (see Appendix 8 and 11). Future research is needed to investigate this issue in a full factorial design, i.e., manipulating the gender of the touch receiver as well as the gender of the touch provider.

In sum, the present study corroborates and extends previous literature on affective touch by showing that people are better at discriminating high-pleasure target stimuli (i.e., touch at CT-optimal speeds) on a skin site that contains CT afferents. Strikingly, however, the current findings also suggest a bias to report the stimuli as high pleasant on CT and CT non-innervated skin, irrespective of the stroking speed – although to a larger extent on CT innervated skin. Given that such bias seems to depend on the order of the block, with more exposure to touch being associated with a larger tendency to report the stimuli as high pleasant (irrespective of skin area), we have interpreted these findings in relation to presumed larger daily life exposure to this type of stroking touch in a skin area critical for social interactions. Finally, the current study suggests that higher confidence was more predictive of accurately detecting high-pleasant target stimuli on CT innervated skin. Given that CT afferents that have been shown to signal pleasantness from the periphery, we speculate that CT signaling reduces uncertainty on one's ability to correctly discriminate high-pleasant CT-targeted stimuli.

Chapter 7

General Discussion

7.1 Introduction

The main aim of this thesis was to examine the role of affective touch on the social buffering of threat, including the perception of physical (i.e., somatic) and social pain, as well as of peripersonal space (PPS, a critical zone for defensive reactions). In addition, this thesis took into account individual differences in attachment style that do not only modulate such effects but also impact the perception of affective touch alone. In particular, the first three experimental Chapters (Chapters 2-4) investigated the role of affective touch on social pain, physical pain and PPS, respectively. In addition, given that the relationship between social support and pain seems to depend on prior beliefs about interpersonal relating, the moderating role of attachment style was assessed in Chapter 3 and 4. Relatedly, Chapter 5 investigated whether the perception of affective touch itself depends on attachment style. Finally, the above studies and parallel developments in the literature on affective touch revealed the need to develop new measures to quantify the perception of affective touch beyond simple, subjective ratings and also to examine the relationship between perceptual and metacognitive sensitivity on this modality. Accordingly, Chapter 6 presented a novel way to assess how individual's differentiated between affective and non-affective tactile stimuli and how they evaluated their accuracy on this differentiation. Overall, these studies revealed that affective touch, i.e., dynamic, low-pressure touch delivered at a speed that optimally activates CT afferents, reduced physical and social pain but did not modulate PPS perception. Furthermore, the effects of affective touch on somatic pain were shaped, to a certain degree, by individual differences on adult attachment style. Critically, individual differences on adult attachment style further shaped the sensitivity to affective touch alone. In particular, one dimension of adult attachment style, namely (higher) attachment anxiety, seemed to lead to less sensitivity to affective versus non-affective touch and to smaller effects of affective versus non-affective touch on self-reported pain.

In this concluding chapter, the findings of the experimental studies will be reviewed collectively and discussed within a recent, Bayesian predictive coding of brain function, namely the Free Energy Principle, that allows one to put forward a unifying model of bottom-up and top-down determinants of pain and affective touch, while emphasizing the interdependence of perception, action and relevance of social factors. Subsequently, methodological issues arising from this thesis will be discussed. The thesis ends with a section on clinical implications and directions for future research.

7.2 Discussion of the findings arising from this thesis

Pain and affective touch have been recently re-classified as interoceptive modalities, even though their stimulation site lies outside the body (Craig, 2002, 2003, see also Chapter 1). The perception of these interoceptive modalities is highly influenced by top-down factors such as social context (see Chapter 1) and may specifically relate to social attachment (see also Chapter 5). Indeed, the phenomena in question needs a consideration of both bottom-up and top-down effects, as for example suggested by most recent pain theories (Baliki & Apkarian, 2015; Krahé et al., 2013). For instance, the long-observed fact that pain is modulated by social context has received experimental support in recent years, and such findings have been recently put forward under a more 'active' view of pain (Krahé et al., 2013). Specifically, it has been proposed that the perception of the social environment can affect inferential processes about the perception of these modalities, as well as related active tendencies, by influencing the certainty or precision (i.e., inverse variance or uncertainty) of an individual's predictions about an impending stimulus. In turn, the perception of the social environment depends on an individual's prior beliefs about interpersonal relating and associated behaviors, such as attachment style (Krahé et al., 2013). Similar observations have also been made regarding the modulation of CT-optimal affective touch by social context in the last decade (e.g., see Ellingsen et al., 2016).

More generally, the above notion is consistent with recent theoretical postulations (Fotopoulou & Tsakiris, 2017) suggesting that others are developmentally important on how we learn to perceive the world, and particularly so in early infancy, when we cannot move and thus rely on others to learn about interoception, e.g., bring or take away the stimuli from us in order to regulate our physiological state (see section 7.3.3 for more details). As both affective touch and pain can be caused by another person, one may presume that they can act as social contexts for each other, and one can further speculate that attachment styles, which develop on the basis of early social experiences (Krahé et al., 2013), can influence this relationship. The current thesis did not examine how pain can influence affective touch, but rather how affective touch can influence pain and whether attachment styles shape this relationship. Thus, the following sections will discuss the findings arising from Chapters 2-5 while taking a more integrative approach. First, the findings regarding the effects of affective touch on physical and social pain, as well as on PPS will be reviewed, focusing on how affective touch may work as an important active, socially variable signaling safety of the environment. Second, the role attachment style, as a moderator of such effects will be reviewed. Finally, the role of attachment style on affective touch alone, and how this may have further shaped the aforementioned effects, will be discussed.

7.2.1 What are the effects of affective touch on pain?

The modulation of pain by social support has generally been found to have pain-attenuating effects. Such effects have been interpreted in light of predictive coding frameworks, such as the free energy principle, elsewhere (Krahé et al., 2013). In this thesis, we used CT-optimal affective touch as a form of active, social support (see section 7.4.1 for full consideration of methodological issues surrounding affective touch as an active, embodied form of social support) to investigate its effects on different forms of pain, including physical and social, as well as on PPS, i.e., the immediate ‘protective’ space surrounding the body. Specifically, given that this interoceptive modality has been shown to effectively communicate social support (Kirsch et al., 2017), it is possible that it may modulate pain by signaling the presence of an active, socially supportive environment. In line with recent proposals on the social modulation of pain (Krahé et al., 2013) and particularly affective touch as a potent homeostatic regulator (Fotopoulou & Tsakiris, 2017), our findings suggest that affective touch attenuated physical (Chapter 3) and social (Chapter 2) pain. However, findings of this thesis were unable to provide evidence that affective touch can modulate the perception of PPS (Chapter 4), which is critical for defensive reactions in the face of threat, such as bodily pain. These findings are discussed in more detail below.

Chapter 3 examined the effects of affective touch by a romantic partner on physical pain, including behavioural and neural responses. Specifically, participants received slow, CT-optimal touch by their partners versus faster, CT non-optimal touch, followed by laser-evoked noxious stimulation, without any other communication between partners. As predicted, slow CT-optimal touch reduced both subjective and neural pain-related outcomes, namely laser-evoked potentials (LEPs). However, contrary to other neuroimaging studies on passive forms of social support between couples (e.g. Coan et al., 2006; Eisenberger et al., 2011; Krahé et al., 2015) our neural effects indicated that the effects of active support by one's romantic partner begin at earlier stages of cortical nociceptive processing, as reflected by changes in the N1 local peak amplitude (see Chapter 3 for a full discussion on the effects as well as limitations of other types of social support by partner). The N1 component is thought to reflect pre-perceptual sensory response (outside of conscious awareness), with activation in the operculoinsular and primary somatosensory cortex (Garcia- Larrea, Frot, & Valeriani, 2003; Valentini et al., 2012). Given that LEPs have been recently proposed to detect environmental threat to the body in response to sensory salient events (Legrain et al., 2011), we speculate that affective touch by one's romantic partner seems to reduce the sensory salience of impending noxious stimulation.

In particular, given recent evidence suggesting that affective touch conveys positive social intentions such as social support even in the absence of any other sensory or social cue (Kirsch et al., 2017), it is possible that this type of touch attenuates the saliency of impending noxious stimuli by signaling the presence of an active, socially supportive environment. This interpretation is consistent with recent theories on the importance of social tactile interactions for the experience and regulation of emotions, and particularly homeostatic emotions such as pain (Atzil & Barrett, 2017; Fotopoulou & Tsakiris, 2017). According to such theories, the perception of the social environment of pain can affect inferential processes about the perception of these modalities, by influencing the weighting of prior expectations about certain sensory signals versus the signals themselves in given contexts (Decety & Fotopoulou, 2015; Krahé et al., 2013). Accordingly, affective touch prior to a noxious stimulus can modulate pain by changing beliefs about how threatening a noxious stimulus is in a supportive social context. This notion of social modulation as salience modulation is compatible with previous theories such as the social baseline theory, which proposes that the presence of other people helps individuals to conserve metabolically costly somatic and neural resources through the social regulation of emotion (Beckes and Coan 2011; Coan 2011; for discussion see Decety and Fotopoulou 2015).

As mentioned above, (noxious) sensory salience is modulated by social context. In line with this thinking, one would expect different salience modulation by affective touch when provided by an unfamiliar other relative to a familiar, significant other. Indeed, a recent LEP study by our lab suggested that there are no main effects of affective touch on pain when a stranger (confederate) administers the touch, but rather these effects depend on attachment style, mostly modulating early stages of cortical processing, namely the N1 component. Specifically, even though the N2 mirrored the effects on the N1, such effects by attachment style (e.g., high anxiety) were observed only in relation to the other attachment dimension (e.g., low avoidance), and other later cortical responses to pain such as the P2 were not affected (Krahé et al., 2016). Thus, chapter 3 extended these earlier findings to suggest that this type of active embodied social support can modulate not only early (N1) but also later (N2-P2) stages of cortical processing. Critically, and unlike the first study with confederates, the current effects on early and later stages of cortical processing by affective touch were not moderated by adult attachment style, which may well pertain to the social context studied in the present study (i.e., romantic couples). Indeed, a romantic partner’s affective touch can be more powerful as affective touch is central to intimate, romantic relationships (Suvilehto et al., 2015; Croy et al., 2016) and the regulatory role of touch seems to be mediated by psychological intimacy (Debrot et al., 2013). Nevertheless, future research directly comparing the effects of partner vs. stranger slow, affective touch on pain is needed before drawing firm conclusions.

At a neurobiological level, the modulation of sensory salience is thought to be mediated by cholinergic neuromodulatory mechanisms that optimize attentional gain (Feldman & Friston, 2010), as well as by dopamine in fronto-striatal circuits (Fiorillo, Tobler, & Schultz, 2003) and by neuropeptides such as oxytocin in social contexts (Quattrocki & Friston, 2014). Interestingly, previous studies by our lab have found that intranasally administered oxytocin (vs. a placebo spray) attenuates subjective pain report and LEP responses as those observed in the current study (Paloyelis et al., 2016). Finally, there is evidence in non-human animals that oxytocin reduces pain behaviours (see Rash, Aguirre-Camacho, & Campbell, 2014 for a review), and that touch by conspecifics can activate endogenous analgesic processes mediated by opioid and oxytocinergic mechanisms (Agren, Lundeberg, Uvnäs-Moberg, & Sato, 1995; Kehoe & Blass, 1986). Thus, in light of all these findings, it is possible that this form of CT-optimal touch by one's partner can signal social support and safety and hence downregulate the salience of the impending noxious stimulation via such neuromodulatory mechanisms. These speculations will need to be specifically tested in future studies.

Adding to our knowledge on the regulatory effects of affective touch on physical pain, Chapter 2 examined whether slow, CT-optimal touch attenuated social pain. Indeed, as reviewed in Chapter 1, recent experimental and theoretical proposals have argued for an overlap between the physical and social pain systems, suggesting that the physical pain system has been co-opted to signal threats to social connection. Specifically, in Chapter 2, the experimenter (a stranger to the participant) administered slow, CT-optimal or fast, non-CT optimal touch to the participant shortly after two other players had excluded the participant in a ball-tossing game. As predicted, affective CT-optimal relative to non CT-optimal touch reduced feelings of distress caused by social exclusion, a form of social pain. These findings add to the growing literature on the overlap between the physical and social pain system reviewed in Chapter 1. Indeed, recent studies have found that CT-optimal touch reduces subjective (Liljencrantz et al., 2017) and neural responses to noxious stimulation (Krahé et al., 2016). The current study suggests that CT-optimal, affective touch affects the 'social pain' associated with ostracism, at least in the short run. These findings thereby support the notion that factors that influence physical pain can also modulate social pain, consistent with the physical-social pain overlap hypothesis (Eisenberger, 2012). More generally, the present findings corroborate and extend prior research on the beneficial effects of social support (Park et al., 2004; Ditzen & Heinricks, 2014), and particularly embodied social support (Coan et al., 2006) on threat and stressful life events (see Chapter 1 and 2 for details on other aspects of social support on pain), by suggesting that active embodied social support does not only buffer threats to physical safety but also threats to social connection, e.g., ostracism. Nevertheless, just like with physical pain, it is possible that such effects can be more powerful in a social context in which attachment is already established, such as a romantic relationship. Future studies are needed to examine this notion.

This type of slow, CT-optimal touch was powerful enough to significantly reduce feelings of distress caused by ostracism, even though there was no explicit knowledge about the touch (i.e., participants are assumed to not know consciously that slower versus faster touch can be socially supportive; also see section 7.4.1 for a full discussion on the advantages and disadvantages surrounding this manipulation). Thus, one can speculate that the supportive meaning associated with this specific type of touch has been learnt and reinforced behaviourally through social interactions (Kirsch et al., 2017). Indeed, this dynamic type of touch is homologous to grooming in non-human mammals, such as rodents and primates (see Chapter 1), and has been found to play a unique role in social attachment as well as to reduce social separation distress (Nelson & Panksepp, 1998). Similarly, in humans, research suggests that social exclusion motivates individuals to seek interpersonal reconnection (Chester, DeWall, & Pond, 2016; Maner, DeWall, Baumeister, & Schaller, 2007)., with touch playing a prominent role (Tai et al., 2011). As such, one possible explanation is that affective touch signals safety and social reconnection, which allows the organism to return to homeostatic balance following social exclusion. This interpretation is consistent with recent theories on the role of social, affective touch as a potent interpersonal homeostatic regulator (Fotopoulou & Tsakiris, 2017). Nevertheless, it should be noticed that contrary to past research (e.g., Leary, 2015; Williams, 2002) there were no differences in negative affect following conditions of social exclusion, possibly indicating that the mere presence of another individual providing touch, i.e., social reconnection, may attenuate the negative affect elicited by social exclusion. In fact, findings from Chapter 6 suggest that individuals show a bias to report the touch as ‘high-pleasant’ irrespective of the touch velocity, which could speak to such effects, i.e., the mere fact that there is actually another person touching you gently ‘feels intrinsically good’.

Critically, CT firing correlates with perceived pleasantness in response to dynamic stroking (Löken et al., 2009), with our own findings also suggesting increased perceived pleasantness in response to slow (versus faster) touch. Moreover, a recent study has implicated serotonin on the central processing of CT- targeted touch (Trotter et al., 2016). As such, one cannot discard that the current regulatory effects are mediated by positive mood. However, we think this is unlikely. Indeed, findings from this chapter suggest that affective touch did not have a more general effect on improving affect post-exclusion. Instead, it appears that affective touch is particularly effective in reducing feelings of social exclusion. Whereas one can assume that many other affective modulations may reduce the effects of social exclusion, the present findings are important because the only variable manipulated was the velocity of touch between individuals. Thus, many general mood effects and cognitive factors (e.g. social proximity, social desirability, attention) can be excluded as candidate explanations of our effect. These general mood and cognitive effects can also be excluded as candidate explanations of our effects on physical pain, as observed in Chapter 3. Specifically, even though our design did not allow us to collect mood ratings in this experiment, we examined as an off-line manipulation check, the relationship between perceived pleasantness of CT-optimal touch and pain (although see Chapter 6 for issues surrounding the use of pleasantness ratings to measure affective touch). Interestingly, the perceived pleasantness of the touch did not relate to any of our pain measures, including individual subjective pain ratings and LEPs in our critical comparison between touch conditions (note that similar effects have been also observed in earlier work by our lab, e.g., Krahé et al., 2016). Thus, although future studies should include specific online measures of mood to further explore this hypothesis, this mood proxy hints towards no relationship between affect and pain-attenuation by affective touch.

Although the precise neurobiological mechanisms remain to be examined, here we propose two potential candidates that could underpin such effects on Chapter 2, namely opioids and oxytocinergic mechanisms. These neurobiological mechanisms have not only been implicated in social contact, including dynamic touch likely activating CT-afferents have also been associated with separation distress. In particular, in non-human mammals, pro-social tactile stimulation by conspecifics (mostly grooming behaviour) is mediated by opioid mechanisms and oxytocinergic pathways implicated in the formation of social bonds (Insel, 2000; Nelson & Panksepp, 1998). Similarly, social touch has been shown to trigger pleasant sensations and modulate the opioid system in humans (Nummenmaa et al., 2016). Cumulative evidence further suggests that social grooming behaviour triggers opioid and oxytocin release, which in turn, attenuates separation distress behaviour (Nelson & Panksepp, 1998). While this notion seems to apply mostly to separation distress in infant rodents, further evidence suggests that opioid differences are due to specific motivational states, irrespective of the mammalian specie or developmental stage (i.e., State-dependent Opioid Modulation of Social Motivation model; Loseth et al., 2014).

Specifically, this model proposes that animals seek pro-social tactile contact during negative affective states in order to relief negative emotions (Loseth et al., 2014). Given the reduction in feelings of ostracism in response to CT-optimal affective touch presented here, we speculate that these neurobiological pathways could mediate the present effects. Direct examination of these neurobiological pathways is needed to confirm such hypothesis.

The aforementioned experimental chapters examined the effects of affective touch on physical and social pain, respectively. In addition to these chapters, Chapter 4 examined whether affective touch can also modulate the perception of space around the body, i.e. the part of space where we approach or try to avoid interesting or threatening objects, respectively. Indeed, under conditions of bodily threat, such as pain, one’s body induces action to mobilize withdrawal or act upon the threatening stimuli (see Chapter 1). Thus, the effective piloting of the body to avoid or manipulate threatening stimuli requires an integrated neural representation of the space surrounding the body, known as the PPS (Holmes & Spence, 2004). Given evidence suggesting that PPS representation grows or shrinks to optimize the processing of self-relevant events, which depends on the social context (Tennegi et al., 2013; Pellencin et al., 2017), this chapter examined the modulation of PPS by affective touch. Specifically, using a virtual reality version of a well-validated multisensory interaction task to measure shifts in PPS, this chapter investigated whether slow, CT-optimal touch modulated the segregation between close and far space in a social and non-social PPS context, i.e., in the presence and absence of a confederate. This research question was deemed important given that people need to respond to threat not only after but also before it actually happens and thus, it makes sense that they represent the space around their body in a protective way depending on the social context, such as receiving CT-optimal supportive touch. However, in this study, we were unable to reject the possibility that slow, CT-optimal touch versus slower, non CT-optimal touch can modulate the segregation between close and far space, in either a social and non-social PPS context. Thus, there is no evidence to suggest that the effects of affective touch on pain extend to the part of space critical for avoiding approaching threating stimuli that could eventually lead to pain.

Are these effects of affective touch on pain specific to the CT system? In these chapters, the touch was administered at velocities that activate the CT system optimally versus velocities of minimal known activation of this system (Löken et al., 2009), but always on CT skin (see section 7.4.1 for more details surrounding this issue). Therefore, the functional role of this system and its particular, neurophysiological contribution to our effects remain to be specified by future studies. For example, could relatively slow, CT-optimal touch on glabrous skin, that does not possess CT fibres (McGlone et al, 2014), lead to similar pain-attenuating effects as observed in Chapter 2 and 3? Examining such effects on glabrous skin is important, particularly given findings from Chapter 6 raising the possibility that the CT system is not the only afferent system contributing to tactile pleasantness (i.e., participants were also accurately determining CT-optimal speeds on the palm as 'high-pleasant' stimuli, although to a smaller extent than in the forearm). Thus, could such findings extend to other aspects of tactile perception, such as perceived support in the face of pain?

7.2.2 Does attachment style moderate the effects of affective touch on experimentally-induced pain?

As mentioned above, pain can be modulated by top-down factors, including the role of a socially supportive environment. In turn, the perception and interpretation of social variables themselves depends on individual prior beliefs, or generative models about interpersonal relating and associated behaviors. One influential way of conceptualizing prior beliefs about relating to others is attachment theory. Attachment theory posits that from early in life, attachment partners can serve as a "secure base" from which the infant explores the world (Bowlby, 1969). If a secure attachment bond is formed over repeated instances of responsive caregiving, the "secure base" signals safety to the infant, while insecure bonds lead to more ambivalent or even threatening signals from others. These bonds lead to the formation of attachment styles, which remain relatively stable into adulthood.

Most recently, differences in attachment style have been shown to influence the effects of interpersonal variables on subjective, behavioral, physiological and neural responses to pain. For example, higher attachment anxiety has been associated with reduced pain when there is provision of social empathy (Sambo et al., 2010) or affective touch (Krahé et al., 2016). Conversely, higher attachment avoidance has been associated with increased pain when there is social presence (Krahé et al., 2015) or affective touch (Krahé et al., 2016). However, given that the perception of pain depends on social context (Krahé et al., 2013), it was deemed important for future research to examine how differences in attachment style influence the effects of interpersonal variables on pain in different social contexts. For example, will differences in attachment style still play a role when affective touch is provided in a context in which attachment is already established? And could attachment style moderate the effects of touch on PPS in a social versus non-social context. Accordingly, this thesis examined the moderating role of attachment style on the effects of affective touch on pain and PPS in Chapter 3 and 4, respectively (such effects were not examined in Chapter 2 given that no adult attachment style measures were collected; and this measure was not collected due the nature of the design, i.e., the touch manipulation was a between-group factor making the comparison between attachment style and touch condition problematic). Findings from these chapters suggest that while attachment style does not moderate such effects in Chapter 4, attachment anxiety (but not attachment avoidance) plays a moderating role on physical pain but only on self-reported pain ratings. Specifically, the higher the attachment anxiety, the smaller the effects of slow versus fast touch were found on self-reported pain.

Thus, in contrast to other studies investigating social signals from others, including empathy (Sambo et al. 2010) or even affective touch by a stranger (Krahé et al., 2016), our findings on Chapter 3 suggest that affective touch by partner does not have beneficial effects on physical pain. In fact, given that anxious attachment is associated with craving closeness and reassurance from others (Hazan & Shaver, 1987b), these effects were interpreted as any kind of physical contact, in this case slow or faster touch from one’s partner, could be enough to ease attachment anxiety, signal closeness and hence attenuate self-reported pain. These effects therefore highlight the interplay between attachment style and social context. Furthermore, the fact that we did not observe moderating effects of both anxiety and avoidance on all our pain measures in Chapter 3 can be explained by two related factors. First, unlike the study by Krahé et al. (2016) who tested strangers, we tested romantic partners who were in a relationship for at least 12 months and had good relationship quality. Thus, a degree of social trust and bonding between partners can be assumed and hence perhaps there was less of a need to incorporate prior beliefs about interpersonal relationships to interpret the touch as supportive in the present study (i.e., more certainty). Indeed, social touch is highly prominent in couples (Suvilehto et al., 2015) and top-down learned expectations of pleasantness and support associated with this specific type touch could be reinforced in a romantic relationship (D. M. Ellingsen et al., 2016). Second, the fact that our participants were in such stable relationships may reflect on our sample's relatively secure attachment style. Indeed, the attachment anxiety and avoidance scores of our participants were significantly lower than those reported in the general population and our earlier work.

In sum, the findings from this thesis support the notion that prior beliefs about the availability and support of others (attachment style) can moderate the effects of affective touch on pain, although such effects are modulated by social context, and do not seem to extend to PPS. Future research is needed to examine whether these moderating effects extend to other aspects of pain, such as social pain elicited by social exclusion.

7.2.3 Does attachment style influence the perception of affective touch alone?

In addition to the moderating role of adult attachment style described above, this thesis showed that adult attachment style shapes the perception of affective touch alone. Indeed, affective touch perception is also influenced by top-down factors, such as socio-contextual factors; and as pre-existing beliefs about interpersonal relating, individual differences in attachment style could thus determine the top-down influences on the perception of affective touch. Even though this thesis did not sample for attachment style a priori (i.e., samples in this thesis were generally in line with population norms, see section 7.4.3 for full consideration of these methodological issues), Chapter 5 provides evidence to this notion. Specifically, as shown in Chapter 5, we found that insecure attachment was associated with reduced pleasantness discrimination between CT-optimal vs. non-CT optimal touch (as measured by the Adult Attachment Interview). Moreover, using a dimensional approach, we found that higher scores on an attachment anxiety dimension (but not an attachment avoidance) were associated with reduced pleasantness discrimination between CT-optimal vs. non-CT optimal, touch (as measured by the Experiences in Close Relationships-Revised; ECR-R questionnaire). Thus, these finding suggest that affective touch alone is modulated by individual differences in attachment style. In particular, in insecure attachment, others are perceived as unreliable and inattentive, and particularly in anxious insecure attachment this might generate anxiety (Nolte et al., 2011). Thus, these kinds of social expectations might affect the way in which CT-optimal, affective touch is perceived and enjoyed. One other possibility, however, is that these individual differences in touch perception are associated with epigenetic mechanisms (see Chapter 5 for more details).

Given these findings arising from Chapter 5, one can speculate that the findings from Chapters 2-4 may have been further shaped by the direct influence of attachment style on affective touch (that is, in addition to the potential moderating role of attachment style described in section 7.2.2). Thus, post-hoc analyses were conducted in Chapter 3 and 4 (but not in Chapter 2 as no measure of attachment style was collected here) to examine this potential issue, independently of the main results. However, post-hoc analyses conducted on the data of these chapters suggest that (at least in relation to our continuous self-reported measure of attachment, i.e., the ECR-R), there is no relationship between affective touch and attachment dimensions, as measured in each of these studies (see Appendix for exploratory results). However, it should be noticed that this discrepancy between the previous chapters and Chapter 5 could be due to several confounds, including differences in touch giver, differences in the number of touch trials and velocities examined, sample size, and carry-over effects associated with the main task (e.g., in Chapters 3-4, as the relationship between attachment style and affective touch perception was not our aim, all pleasantness ratings were collected only as manipulation checks at the end of the main experiment which examined other variables).

Moreover, despite these lack of findings, one cannot discard the possibility that adult attachment style could have directly influenced affective touch on Chapters 3 and 4 at a pre-perceptual level (i.e., outside of conscious awareness), which was not captured by our designs. Indeed, our measure of the affectivity of touch consists on self-reported pleasantness ratings, which may not tap into potential 'unconscious' mechanisms associated with affective touch (i.e., one can speculate that the effects of affective touch are in a large part outside of conscious awareness, including socially supportive aspects that might have been learnt behaviourally; see also section 7.3.2 below). In fact, it is likely that the effects of affective touch on pain (as well as the moderating role of attachment style) are greatly mediated by 'unconscious' processes, e.g., these variables can be affecting pain/threat at a level that would not be reflected by self-reported ratings (as indeed observed by the lack of relationship between pleasantness ratings and pain-related outcomes in Chapter 3). Thus, we cannot conclude with certainty that attachment style did not influence at a pre-perceptual level the perception of affective touch from the onset. Future research should better examine the mediating role of attachment style on affective touch and the effects of affective touch on pain.

In addition, it is worth highlighting certain similarities between our adult attachment effects across chapters. In particular, only was dimension of adult attachment dimensions, namely attachment anxiety, was implicated in Chapter 3 and Chapter 5. In particular, our findings from Chapter 3 suggest that for higher anxiously attached individuals, who crave closeness and reassurance from others (Hazan & Shaver, 1987), any kind of physical contact from their partners may be enough to attenuate self-reported pain. Consequently, this implies that higher anxiously attached individuals may not be able to clearly discriminate the support associated with CT-optimal versus non-CT optimal touch from their partner. Similar findings were observed in Chapter 5, in that the higher the attachment anxiety, the worst the pleasantness discrimination between CT-optimal vs. non-CT optimal, touch. Thus, could this moderating role of attachment style observed in Chapter 3 be a result of attachment style directly influencing affective touch perception from the onset? Future research is needed to address this question.

Finally, even though this was not a main aim of this thesis, findings from Chapter 4 suggested that one dimension of adult attachment style (namely attachment anxiety) modulated the segregation between close and far space depending on the social context, but irrespective of the touch. Indeed, as mentioned above, individual differences in attachment style have been linked directly with the perception of pain (Meredith et al., 2008; Meredith et al., 2013). Thus, this chapter extends such findings to suggest that adult attachment style also modulates the space surrounding one's body, which is critical for eliciting action in the face of bodily threat, such as pain. It is worth noticing, however, that attachment style did not directly modulate (physical) pain in this thesis. In fact, even though there was an interaction between attachment and avoidance on the N2 (see Chapter 3), follow-up tests were non-significant. Thus, together with the fact that attachment anxiety and avoidance, alone or in interaction, did not predict any of our pain-related outcomes, there is no evidence in the current thesis that attachment style directly influences pain. However, this was clearly not the main aim of any empirical chapter of the current thesis and consequently, there are many confounders that could have played a role (e.g., the fact that the partner was present, and this was examined in the experimental blocks, in which touch was already involved).

7.3 A proposed theoretical framework: Affective touch and pain casted under a Free Energy perspective

Recent evidence, including that arising from thesis, highlights the need to consider both bottom-up and top-down effects on the experience of affective touch and pain. However, as reviewed in Chapter 1, the history of the study of pain, and more recently of affective touch, can be said to be steeped in the debates between bottom-up, neurophysiological specificity at the periphery versus top-down convergence and gating at the spinal and brain levels. Thus, this section makes use of a Bayesian, predictive coding framework, namely the Free Energy Principle, also referred to as "Active Inference" (Friston, 2010) to put forward a unifying model of how bottom-up and top-down signals can be integrated to give rise to affective, pleasant touch and unpleasant, cutaneous pain more broadly. Although the proposed model presented below is in its most parts speculative, it aims to account for the complexity and interrelated phenomena covered in this thesis.

7.3.1 Action-perception loops and the control of physiological states

A recent neurocomputational theory of perception and action, namely Active Inference, assumes that the brain is an organ that learns and self-improves a generative model of the organism and its environment based on sensory signals and action (Friston, 2010). A basic tenet of such accounts is that perception is an active process, whereby top-down mechanisms are activated to make predictions about the upcoming bottom-up sensory signals. Thus, perception is an inferential process, whose aim is to minimize prediction errors or the difference between top-down hypotheses about the most likely causes of sensations (termed "empirical prior beliefs") and current sensations (note that probabilistic models that generate predictions are updated in Bayesian, probabilistic fashion). Recurrent message passing among several levels of the sensorimotor hierarchy allows the suppression of (small or irrelevant) prediction errors by priors, or the adjustment of (empirical) prior expectations by (large or highly salient) prediction errors (these ideas are similar to predictive coding schemes, in that there is minimization of prediction error with recurrent message passing). Furthermore, the relative influence of predictions versus prediction errors across several layers in this hierarchical organization is determined by the weighting (precision) of predictions versus prediction errors at each level. Precision can be regarded as a measure of signal-to-noise ratio or confidence, or mathematically, as the inverse variance, uncertainty, or reliability of a signal (H. Feldman & Friston, 2010; K. J. Friston, 2010). Uncertainty is thought of as encoded mainly by neuromodulations of synaptic gain (such as dopamine and acetylcholine) that encode the precision of random fluctuations about predicted states — the context in which sensory data is encountered (Quattrocki & Friston, 2014). For example, cholinergic or dopaminergic neuromodulatory mechanisms can optimize the attentional gain of populations encoding prediction errors, so that greater attention is allocated to certain salient events in the environment, influencing the relative weighting or importance of prediction errors.

The free energy principle also brings something new to the table, namely that action can also minimize free energy (Friston, Thornton, & Clark, 2012). Specifically, at different levels, prediction errors can also be minimized through action. At the simplest control loop level, peripheral reflexes are engaged to suppress proprioceptive prediction errors (Feldman & Friston, 2010), generated by comparing primary afferents from receptors in muscles, tendons, and joints with proprioceptive predictions regarding body position that descend to alpha motor neurons in the spinal cord and cranial nerve nuclei. Thus, action is driven by such predictions rather than descending motor commands. Ultimately, action is seen as a prediction-driven tendency to re-sample the world to generate more sensory evidence for one’s predictions (active inference). Critically, the organism could solve a discrepancy between prediction and error (e.g. unexpected noxious stimulation) by either changing its predictions (effectively convincing oneself that one is not in pain) or by generating protecting action (moving to avoid the noxious source of the prediction error). Both of these can be adaptive depending on the magnitude as well as the context of the noxious stimulation and hence, their relation needs to be optimized by weighting in each case. Thus, this framework emphasizes the tight interconnection of perception and action as well as the fundamental integration of bottom-up and top-down factors in all perceptual and active inference.

Recently several proposals have applied this framework to interoception (Barrett & Simmons, 2015; Geuter et al., 2017; Gu, Hof, Friston, & Fan, 2013; Paulus & Stein, 2006; Pezzulo, Rigoli, & Friston, 2015; Seth, 2013; Seth, Suzuki, &

Critchley, 2012), and by extension to the concepts of "homeostatic" and "allostatic" control. "Homeostasis" (Cannon, 1929) refers to the maintenance of a relative stability in one's physiological states despite ongoing internal and external changes. "Allostasis" refers to the idea that physiological changes need to be anticipated by adaptive changes and choices across different spatial and temporal scales, for example adjusting one's metabolic needs in certain environments where foraging is dangerous (Sterling & Eyer, 1988). In predictive coding frameworks, both homeostatic and allostatic control can be cast formally as active inference (Pezzulo et al., 2015; Stephan et al., 2016). Homeostatic control enslaves reflexes to produce corrective actions that fulfill beliefs about bodily states, and allostatic control entails changing homeostatic beliefs under guidance by higher predictive models about future perturbations of bodily states.

Moreover, as in the case of exteroceptive perception and action, the balance between homeostatic and allostatic regulation rests upon the precision (i.e. weighting) placed in deeper expectations about the organism and its environment. For example, during conditions of bodily threat or psychological stress, such as the anticipated pain from a sharp object approaching one's face, noxious signals on one's body may induce low-level proprioceptive predictions that mobilize withdrawal movements away from the source of the stimulation. However, high-precision predictions at a higher level of the neurocognitive hierarchy can indicate that the source of the noxious stimulation is actually our dentist, and then predictions of tooth pain can be fulfilled without engaging low-level motor reflexes and instead engage allostatic changes in the form of updated beliefs about the "safety" and tolerance (i.e. attenuated pain) of nociceptive signals in this context, in order to ensure future pain-free and healthy teeth.

7.3.2 Active, interoceptive inference, and feelings on the skin

Despite these proposals of interoceptive predictive coding (e.g., Paulus & Stein, 2006; Barrett & Simmons, 2015; Gu et al., 2013; Pezzulo, Rigoli, & Friston, 2015; Seth, 2013; Seth et al., 2011), there is currently no direct evidence for the proposal that interoceptive predictions, prediction errors, and their relation rest on a common neurocomputational framework (for a first step, see Kleckner et al., 2017). There are, however, ample circumstantial findings in the pain and affective touch literature that can be cast in this light and importantly, the framework can allow some specific predictions regarding the nature of pain and affective touch, and their modulation by cognitive and social factors, that we will focus on here.

First, this framework suggests that peripheral signals, such as nociceptive and CT tactile channels, do not cause homeostatic perceptions or emotions (e.g. pain or the affectivity of touch), or vice versa. Instead, there is a circular and multi-layered causality, where on one end of the neural hierarchy, neuronally encoded predictions about bodily states, including in this case states of the skin, engage autonomic, somatic, and motor reflexes in a top-down fashion. On the other end of the hierarchy, specialized skin organs and their spinal cord circuitry carry interoceptive signals in a bottom-up way that informs and updates predictions at the levels above (e.g., see Geuter et al., 2017 for the role of the anterior insula in encoding prediction and prediction errors in response to noxious stimuli, and the posterior insula in encoding stimulus intensity). These aspects can be linked to the cognitive and sensory aspects of pain, respectively. Moreover, the affective component of pain or touch can be seen as an attribute of the weighting (precision) of any representation that generates predictions and prediction errors about the physiological state of the skin (see also Ainley et al., 2016; Fotopoulou, 2013). In other terms, the subjective feelings of pain or affective touch can be linked to the neuromodulatory weighting of the corresponding sensory prediction errors in relation to higher-order predictions regarding these sensory states (see more below). Typically, the optimization of precision is linked with the function of neuromodulators in the brain but similar processes of synaptic gain modulation have long been described in the spinal cord, particularly in the context of pain (see Chapter 1). It has been previously proposed that in interoceptive modalities, optimizing the precision of internal body signals can be seen as optimizing *interoceptive sensitivity and related feelings* in perceptual inference (Ainley, Apps, Fotopoulou, & Tsakiris, 2016; Fotopoulou, 2013). We propose here that concepts such as “precision” and its inverse, uncertainty, relate to the affective, conscious components of pain and affective touch. The intensity of painful or pleasurable aspects of touch can be thus understood as our sensitivity to such tactile, interoceptive signals in a given context (e.g. a measurement of our subjective pain threshold in the lab) and our corresponding behavioral tendency to approach the world to gather more information (uncertainty) or to avoid resampling (the certainty of pain and affective touch). This view can offer a new integration of previous theories of pain and hence potentially also affective touch (i.e., classic theories such as the “gate control theory” versus more ‘active’ theories, e.g., see Baliki & Apkarian, 2015).

From the point of view of Active Inference, these latter theories are not competing but supplementary views. Allostatic control is an extension of homeostatic control and they both work to minimize prediction errors. Thus, these two perspectives can be integrated in the following way, illustrated here with specific reference to cutaneous pain and affective touch. For homeostatic control purposes, the organism entails (in an embodied manner) a set of inherited prior expectations of the state of the skin. Any stimulation of the skin that deviates from the range of such predicted states generates a prediction error (e.g., see Geuter et al., 2017; Ploghaus et al., 2000, 2003, for studies on pain expectation and violation). This prediction error is corrected in simple, unconscious loops, by reflexive motor or autonomic reactions that fulfill the initial beliefs about the state of the skin. If, however, these “homeostatic corrections” fail (i.e. the prediction error persists), then the prediction error travels up the hierarchy to generate posterior beliefs (updated predictions) at the above hierarchical level. These updated beliefs act as priors towards future positive or negative events, thus attempting to anticipate and avoid danger, or anticipate and approach pleasure, before these occur (allostasis). Specifically, more complex, generative, predictive models of the organism’s needs are better able to predict stimuli at the levels below and at different time-scales and hence ‘suppress’ any future, anticipated prediction errors at the level below by guiding autonomic function and action more effectively and under the control of higher-order predictive models. Please note that these homeostatic and allostatic control operations are understood to be processes of unconscious inference for the most part, so conscious feelings of skin pain and pleasure are not necessary for such processes.

Interestingly, although these two modalities, pain and affective touch, appear opposite in hedonic content and behavior tendencies towards their particular sensory stimulus (i.e. avoidance versus approach), from the point of view of the certainty–uncertainty axis described here, they are of similar characteristics. The greater the pain, or the felt pleasure of touch, the more one’s attention and behavior is captured in the experience and the less one is likely to engage in active, exploration of new sensations. Instead, the organism’s resources are focused on controlling or escaping pain, and enjoying or prolonging the feelings of affective touch. This view goes against the intuitive, long-standing view of core affective consciousness, pain and pleasure, as monitoring hedonic quality. Instead, the core quality of affective consciousness is a kind of certainty–uncertainty, or disambiguation principle (Fotopoulou, 2013). Pain and affective touch therefore are a measure of how important is for a given organism, in a given context, to be "certain" about what was predicted versus what occurred.

The unique feeling qualities of painful or affective touch may be associated with the CNS's capacity for synaptic gain modulation and large-scale integration of information arising from the body and the world in different time-scales. This is consistent with the fact that no single area or network in the brain has been reliably associated with the conscious perception of pain (Baliki & Apkarian, 2015). Instead, the various networks that have been associated with pain and its modulation, and with affective touch and its modulation, are not only common to these two modalities, but seem relevant to the processing of the salience of any sensory modality (Legrain et al., 2011). Indeed, several recent neuroimaging studies have included such areas and their observed functional connectivity in various hypothesized "salience networks" (Legrain et al., 2011; Medford & Critchley, 2010; K. Wiech et al., 2010). For instance, predictive signals from such a "salience network" process and integrate information about the significance of an impending noxious stimulus and determine whether or not such a stimulus will be consciously perceived as painful (Wiech et al., 2010).

More generally, a plethora of neuroimaging studies have shown that cognitive, affective, and social factors modulate our perception of cutaneous pain, with emerging evidence also making a case for these factors modulating the pleasantness of CT-optimal touch (see Chapter 1). For example, expectations may help an individual to adjust sensory, cognitive, and motor systems in order to process the noxious stimuli in terms of neural and behavioral responses optimally (Wiech et al., 2008; see also Villemure & Brushnell, 2002 for review). Most consistently with the present proposal, expectations in which there is a high level of certainty regarding the stimulus may activate descending control systems to attenuate pain, whereas in contrast, uncertainty may increase pain (Ploghaus et al., 2003). Critically, the role of these expectations on pain and affective touch are particularly relevant when it comes to social factors, as it will be outlined in the section below.

7.3.3 The mentalization of nociception and CT stimulation: homeostatic and allostatic control by proxy

As mentioned in section 7.2, the fact that pain is modulated by social context has received experimental support in recent years (see Krahé et al., 2013 for review). In the last decade, similar observations have also been made regarding the modulation of affective touch by social context (see Ellingsen et al., 2015). In this section, we will apply these insights from the active inference framework to propose some mechanisms by which this social modulation takes place. This application has the advantage that it can provide a mechanistic, unified account of the relation between bottom-up (e.g. neurophysiological) and top-down (e.g. psychosocial) influences on homeostasis and allostasis.

Specifically, we propose that the perception of the social environment of pain or affective touch can affect inferential processes about the perception of these modalities. As mentioned earlier, top-down predictions do not represent just the content of lower level representations but also predict their context, defined in mathematical terminology as the *precision* of a probability distribution (inverse variance or uncertainty). For example, the allocation of attention toward specific events can optimize their salience and ultimately influence the relative weighting or importance of prediction errors against predictions. This kind of top-down prediction in sensory cortices is thought to be mediated by cholinergic neuromodulatory mechanisms that optimize the attentional gain of populations encoding prediction errors (Feldman & Friston, 2010), as well as by dopamine in fronto-striatal circuits (Fiorillo, Tobler, & Schultz, 2003) and by neuropeptides such as oxytocin in social contexts (Quatrokki & Friston, 2014). In interoception, precision relates to attention to signals from the body or interoceptive sensitivity (Ainley et al., 2016; Fotopoulou, 2013) and can be modulated by several contextual factors. Therefore, factors such as active social support or empathy can modulate pain or affective touch by changing the precision of top-down predictions about nociception or CT stimulation. In such social contexts, individuals have learned to anticipate social support and thus the optimization of the weight allocated to bottom-up signals versus top-down predictions may be different than in conditions of experiencing similar stimuli alone, or in hostile environments. For example, previous studies have shown that the administration of intranasal oxytocin versus placebo, or the provision of high versus low empathy, or social support can modulate the subjective, behavioral and neural responses to noxious stimulation (Hurter et al., 2014; Krahé et al., 2015; Paloyelis et al., 2016). More generally, based on a systematic review of the experimental pain literature (Krahé et al., 2013), it has been concluded that precision modulation by interpersonal interactions takes place through social signals about the safety or threat and thus the salience of the impending stimulus itself, or through social signals about the threat or safety and thus the salience of the environment in which the stimulus occurs.

Integrating such notions within a predictive coding model has the advantage of placing them in a wider and neurobiologically plausible framework and hence integrating findings across many fields, as well as generating novel hypotheses. For example, this proposed active inference framework allows us to observe that the social modulation of pain and affective touch is not a simple “add-on” in our understanding of such modalities. Rather, it appears that interpersonal interactions are necessary in shaping all interoceptive modalities from the onset. This claim is supported by several observations (presented in detail elsewhere, see Fotopoulou & Tsakiris, 2017), the most important of which is outline here: namely, in early infancy, when the human motor system is not yet developed, interoceptive function and homeostasis are wholly dependent on embodied interactions with other bodies (Fotopoulou & Tsakiris, 2017). For example, infants use autonomic and motor reflexes in response to unpredicted physiological states (e.g. crying when hypothalamic function detect that glucose level are not within the predicted viable range) to elicit caregivers’ actions that can change the infant’s physiological state (e.g. by feeding it) until the homeostatic needs are met (i.e. glucose levels are within the predicted range). This example also extends to other interoceptive modalities such as pain, e.g., infants cannot protect themselves from accidentally cutting or burning themselves – beyond some reflexive avoidant movements (which makes this particular framework so relevant, i.e., it emphasizes action). Thus, the infant depends on the caregiver to modify key neurophysiological states relating to homeostasis and allostasis. As such, the origins of interoceptive active inference are thought to be by necessity social, and thus core subjective feelings such as hunger and satiation, pain and relief, cold or warmth, have actually social origins (see Fotopoulou & Tsakiris, 2017).

Critically, so far, this proposed framework has focused on casting pain and affective touch separately under a Free Energy framework. This was done in order to stress the complexity of the multiple and inter-dependent factors that may underpin each of these modalities. However, it is important to stress that as affective touch can and is frequently provided by other people, affective touch itself can be seen as a unique form of active embodied support during pain and more generally threat (see 7.2.1 for more discussion of this point). As such, one can further speculate that affective touch could also modulate pain (as indeed shown in Chapter 2 and 3), specifically by anticipating the social support and hence, adjusting the weight allocated to bottom-up signals versus top-down predictions (i.e., modulating the precision by signaling the presence of an active, socially supportive environment). For example, as observed in Chapter 3, affective touch (e.g., administered in anticipation to noxious stimulation) may work to minimize prediction errors in the face of impending pain (e.g., by signaling care and environmental safety) through allostatic control. In other terms, in order to maintain physiological stability and balance, our brain needs to predicts our physiological needs before they actually happen, and it constantly does this by using learnt social signals (e.g., care and safety resulting from affective touch) to prepare for allostatic changes (Atzil & Barrett, 2017), such as pain. Thus, even though affective touch is influenced by top-down predictions itself, it can also signal safety and support and therefore modulate pain by changing the precision of top-down predictions about nociception.

Furthermore, the conclusions about the social origins of interoceptive feelings such as pain and affective touch (see above, Fotopoulou & Tsakiris, 2017) are also consistent with the literature on the relation between these two modalities and social attachment (see also Panksepp, 1998). As mentioned earlier, pain and affective touch can be modulated by social factors. In turn, the perception and interpretation of social variables themselves depend on individual prior beliefs, or generative models about interpersonal relating and associated behaviors, such as adult attachment style. Thus, one can speculate that "off-line" predictions, about the availability of others (e.g., attachment style) can modulate both pain and affective touch by changing the precision of top-down predictions versus prediction errors from nociception and CT stimulation. In the current thesis, such modulation was mostly found to be two-way: (a) attachment style shapes the perception of affective touch; and (b) attachment style shapes the effects of affective touch on pain. Although see section 7.2 for context-specific effects. However, the role of precision modulation as social modulation described here is merely speculative and will need to be specifically tested in future studies.

7.4 Methodological discussion

Turning now to a methodological discussion, the current thesis employed an interdisciplinary approach and combined methods from normally independent domains, including experimental pain research, psychophysics of tactile perception, social psychology, social cognitive neuroscience and development psychology. As such, even though this thesis attempts to provide a solid methodology to investigate the soothing function of touch, using an interdisciplinary approach is in turn faced with several methodological challenges. Thus, the main methodological issues surrounding this thesis will be discussed below.

7.4.1 Methodological issues surrounding affective touch

There are several advantages as well as disadvantages that should be considered in this thesis. In this section we will first cover the advantages and disadvantages linked with using affective touch as an embodied form of social support. Regarding the former, this thesis aimed to address three major restrictions associated with manipulations of social support that are typically employed when assessing the role of social support on pain. The first restriction is that studies have mostly focused on passive support from a support provider versus control conditions of absence of such support, e.g., presence versus absence (Krahé et al., 2015), static hand-holding versus no or stranger hand-holding (Coan et al., 2006; Goldstein, Weissman-Fogel, Dumas, & Shamay-Tsoory, 2018), viewing pictures of one's partner versus a stranger (Eisenberger et al., 2011). However, these manipulations of passive social support are subject to several confounds such as social distraction, comfort and familiarity. The second restriction is that many of these studies have focused on verbal or visual communication of support (e.g., supportive text messages, viewing pictures of one's partner), while largely neglecting one important way to communicate support, namely via embodied forms of active support and particularly via touch, which is one of the most important ways to communicate support. Third, although some studies have employed social manipulations involving touch (e.g., Goldstein et al., 2018; see also Coan et al., 2006), these have used simultaneous manipulations of social touch (e.g. hand-holding) and this does not allow precise inferences about the mechanisms of pain modulation, given (1) the existing, consciously known meaning of hand-holding (i.e. it is not clear whether the observed pain modulation is the outcome of the feeling of being touched or the knowledge about the meaning of handholding), (2) the well-known analgesic effects of touch on pain (Liljencrantz et al., 2017; Mancini et al., 2015) and (3) the fact that these studies cannot control for skin-to-skin touch parameters (e.g. pressure of handholding, movement, sweating, temperature) or distraction effects.

The current thesis thus aimed to address most of these restrictions by comparing relatively slow touch, that is known to be mediated by the CT-system and is typically perceived as pleasant, with faster or slower but otherwise identical touch, that is known to not activate the CT system optimally. Specifically, given that slow, CT-optimal touch can specifically and without prior knowledge signal positive emotions and social support (Kirsch et al., 2017; von Mohr et al, 2017), this manipulation can be done off-line, i.e. not simultaneously with, but before or after the pain manipulation, to implicitly signal a socially supportive context to the individual about to, or after, receiving pain. Moreover, in comparison to other types of embodied social support, such as for example hand-holding, the tactile interaction studied here was manipulated with a degree of experimental control, at a time different than the pain manipulation and tested against control conditions that involve the same support provider. Therefore, the problematic comparison between partners and strangers or friends could be avoided and many confounding factors, such as social proximity, familiarity and social desirability can be excluded as potential explanations of our effects. Finally, there are no pre-existing conscious beliefs about the velocity of the touch, thus different to other embodied forms of support, e.g., handholding, we can assume with some certainty that the observed effects are the outcome of the feeling of being touched rather than the knowledge about the meaning of the support.

Despite these methodological advantages, there are some limitations intrinsic to this specific type of embodied support as examined in this thesis. For example, similar to other pain studies, one cannot discard with absolute certainty, that the effects observed here could be due to distraction effects associated with (1) the frequency of the stroking, e.g., there is always a necessity to compromise between the frequency of tactile stimulation and the duration of the stroking, and in our studies (except for Chapter 6), we opted to keep the duration of the stroking constant but consequently, there was always more strokes administered in the faster stroking velocities, or (2) general attentional demands associated with the speed, e.g., stroking delivered at fast speeds might have greater attentional demands than slow, affective touch (see also Davidovic et al., 2017 for an attenuation of the Default Mode Network in response to non-affective touch). In fact, it is possible that these confounds could have led to null results of touch on PPS as observed in Chapter 4 (please note that within our experimental modulation studies of touch, this was the only study that used slower rather than faster, non-CT optimal touch as a control condition). Thus, future studies should address these issues. One approach could be to include other frequencies or speeds of stimulation (within the CT-optimal range, e.g., 3 cm/s and 6 cm/s and outside the CT-optimal range, e.g., 0.3 cm/s and 30 cm/s) that are thought to give rise to similar feelings of pleasantness while allowing control over the frequency and speed of tactile stimulation.

More generally, the current thesis only examined the effects of CT-optimal affective touch on the forearm, i.e., CT skin (Chapters 2-5). Thus, it remains unknown whether the current effects are specific to the CT system. For example, could relatively slow, CT-optimal touch on glabrous skin, that does not possess CT fibres (McGlone et al, 2014), lead to similar pain-attenuating effects as observed in Chapter 2 and 3? Indeed, while this thesis examined the pain-attenuating effects of touch delivered at velocities that activate the CT system optimally versus velocities of minimal known activation of this system (Löken et al., 2009), the functional role of this system and its particular, neurophysiological contribution to our effects remain to be specified by future studies. Thus, future studies should include other control, non-CT skin conditions, such as the palm, to provide insight into the separate involvement of bottom-up CT-afferent signaling and top-down expectations of support in the face of pain. For instance, are the current effects on pain mediated by bottom-up physiological mechanisms or top-down learned expectations of pleasantness and support linked with this specific type of touch? Indeed, the pleasantness and support associated with affective touch do not only depend on bottom-up CT afferent signaling but is also influenced by top-down learned expectations (i.e., linked to the valence and social support of the relatively slow tactile stimuli, even though such process does not need to entail declarative preexisting knowledge, e.g., can be learnt behaviorally) and social context.

Nevertheless, given related bottom-up versus top-down issues surrounding the perceived pleasantness of the touch, Chapter 6 examined *affective touch sensitivity* in both forearm and palm, i.e., CT and non-CT skin, respectively. This was deemed important given numerous research consistently employing pleasantness ratings to assess the affectivity of touch, including Chapters 1-5 of the current thesis, although this measure is subject to individual response tendencies and biases, such as individual differences in the interpretation and use of the scale. Findings from this Chapter suggested that using a forced-choice task (Signal Detection paradigm) that asks for a binary response, i.e., to judge the touch as high- or low-pleasant, may provide a novel measure of affective touch sensitivity, in which higher sensitivity d' was found on the forearm relative to the palm, indicating that people are better at discriminating high-pleasure target stimuli (i.e., touch at CT-optimal speeds) on a skin site that contains CT afferents (consistent with CT bottom-up signaling). Even though findings from this chapter also suggest that participants in the present study were to a certain degree, also accurately judging CT-optimal speeds on the palm (i.e., stimuli predetermined as 'signal') as 'high-pleasant' stimuli, and stroking velocities outside the CT range (i.e., stimuli predetermined as 'noise') as 'low-pleasant' stimuli (where no CTs have been found), such sensitivity d' was significantly lower than that found in response to the forearm. While we speculate, on the one hand, that such effects on the palm are due to learned associations between stroking velocity and pleasantness, which have been well reinforced throughout the lifespan rather than a result of carry-over effects from preceding tactile stimulation from the forearm (CT skin), the precise role of CTs in such learning process still needs to be examined. On the other hand, however, these findings also raise the possibility that the CT system is not the only afferent system contributing to tactile pleasantness and further work is needed to establish its role in tactile perception, as well as the role of other fibres, spinal and brain mechanisms to perceived pleasantness.

This experimental chapter also showed that participant's tendency to judge the touch as high pleasant (i.e., negative response bias) was found both on forearm and palm, although to a larger extent on the forearm. This latter finding depended on the order of the block (with more exposure to touch being associated with a larger tendency to report the stimuli as high pleasant, irrespective of skin area) and was interpreted based on findings linking perceived pleasantness with touch exposure (Sailer & Ackerley, 2017) or merely the fact that that there is actually a person touching participants gently. More generally, this finding could speak as to why there were no differences in negative mood between social exclusion conditions as reported in Chapter 2, i.e., should this finding from Chapter reflect that the mere presence of another individual providing touch, i.e., social reconnection, can attenuate the negative affect elicited by social exclusion (see section 7.2.1), then this could relate to the fact that another person touching you gently may simply feel good, irrespective of the touch velocity; or going via a touch exposure route, as to why the effects of touch can be more powerful in romantic couples as reported in Chapter 3, i.e., more touch exposure is speculated in this particular social context (Suvilehto et al., 2016), and touch at CT-optimal speeds in particular has been observed in close, intimate relationships (Croy et al., 2016) perhaps reinforcing the bias to perceive affective, CT-optimal touch as high pleasant in the context of a romantic relationship. Clearly, these speculative ideas would need future testing. Nevertheless, this method is a promising valuable tool for future research on this modality given it provides a novel way to measure affective touch by taking into account bottom-up and top-down processes.

Last but not least, the ecological validity of this socio-tactile manipulation should be considered. Specifically there are two main restrictions pertaining to way this tactile social manipulation was employed, namely (1) the use of a brush to administer the touch and (2) the timing in which this tactile manipulation took place. Regarding the first restriction, the present study employed cosmetic-like soft brushes to deliver the touch, which is clearly not the same as receiving skin-to-skin tactile stimulation and therefore, such technique could have missed essential mechanisms of everyday socio-tactile interactions that convey support. In other words, gentle skin-to-skin touch plays a key role in social bonding as well as conveys social support (Field, 2010; Hertenstain et al., 2006) and the use of soft brushes, which do not necessarily reflect everyday social interactions, is likely to elicit different sensory-affective responses associated with social support. However, using cosmetic-like soft brushes to deliver the touch, as compared to skin-to-skin contact, allowed us greater experimental control – factors ranging from variations in skin temperature, sweating rates of the person delivering the touch to potential feelings of awkwardness of the person receiving skin-to-skin touch by a stranger could play a major role in how an individual interprets this kind of embodied social support. Similarly, regarding the second restriction, the touch was delivered in some cases before (e.g., Chapter 3 and 4) and not during or after the pain manipulation. This was done in order to be able to assess such effects on pain, such as in LEPs, as well as to avoid concurrent multisensory or distraction effects. However, it is likely that individuals will also use this type of embodied social support as a soothing, consoling touch during or after pain (as examined in Chapter 2) and future studies could explore any differences based on such timescales.

7.4.2 Methodological issues related to pain induction techniques

Different pain-induction techniques were used in the current thesis. Specifically, a laser stimulation device was used to administer physical pain (Chapter 3), whereas the Cyberball paradigm was used to elicit feelings of social exclusion, a form of social pain (Chapter 2). These two different methods were chosen based on the respective aims of each chapter, and particularly to measure different aspects of pain, i.e., physical versus social. Their specific advantages and disadvantages associated with each technique have been covered in the respective chapters. Thus, here we will simply outline two main limitations, namely the lack of other measures to assess pain, and its ecological validity.

With respect to the first limitation, it should be noticed that when assessing the subjective aspects of physical pain (Chapter 3), only one aspect of pain was assessed, namely pain intensity (assessing the sensory aspects of pain) and not feelings of unpleasantness. Indeed, in fields such as psychology and social neuroscience, pain is typically conceptualized as comprising sensory and affective-motivational dimensions (Auvray et al., 2010). Accordingly, these two components of pain are commonly assessed using visual scales (or verbal labels) measuring pain intensity and feelings of unpleasantness/motivated actions to alleviate these feelings, respectively. However, such dimension of subjective pain was not assessed given practical constraints. Specifically, in this study, participants received 180 laser pulses, each followed by a rating of the stimulus intensity, and thus it was not deemed feasible to include any other additional self-reported measures, e.g., pain unpleasantness ratings. Nevertheless, adding a self-report measure of pain unpleasantness could have provided some insight into the relationship between the affective-cognitive aspects of pain, which are thought to be reflected in the N2-P2 complex, and perceived feelings of unpleasantness (although please note that in LEPs research most correlations have been conducted with pain intensity ratings instead, in line with the notion that LEPs reflect sensory salience; e.g., Iannetti et al., 2005). Furthermore, given the nature of this study (namely the use of EEG and the need to remain as still as possible), other measures that assess implicit affective expressions, such as facial electromyography, that have been found to be modulated by pain (e.g., Lamm, Porges, Cacioppo, & Decety, 2008) and affective touch (e.g., Pawling et al., 2017) could not be included in our study. However, future studies may want to include these or other measures to provide a more holistic picture of pain experience.

Similarly, when assessing social pain (Chapter 2), the main outcome variable consisted on self-reported feelings of distress, namely the ‘Need-threat scale’ (Jamieson et al., 2010) indexing fundamental needs often threatened by ostracism (i.e., belonging, self-esteem, meaningful existence, control). Nevertheless, this research could be extended by adding physiological and neuroimaging measures that can provide insight to other aspects of regulatory functioning (e.g., autonomic response) or brain activity (e.g., are such effects of affective touch on social pain also related to higher-order pain regulation, e.g., reflected in the anterior insula and anterior cingulate cortex, typically implicated in the affective components of physical pain?). Relatedly, other interactive mechanisms, such as thermoregulation, could mediate the buffering effects of affective touch and such effects could easily be examined by assessing changes in skin temperature. Thus, other measures should be included to provide a more complete understanding of the soothing function of affective touch on social pain, as well as its link with physical pain.

Moving to our second limitation, both chapters examining physical and social pain, respectively, could be said to lack ecological validity. Indeed, an ongoing challenge for social cognitive neuroscience is to balance the need for an ecologically valid social environment with the need for experimental control (Schilbach et al., 2013) and such balance was aimed in the current thesis. In terms of ecological validity, our methodological approach in Chapter 3 did not only miss key mechanisms of everyday social interactions (Parsons, 2015; Schilbach et al., 2013) but also, participants *knew* that they would receive laser-evoked pain. Clearly this typically does not occur in everyday life, and the fact that participants could anticipate the induction of pain is an important confound, even more given its repetition likely given rise to habituation or sensitization effects (although the long and randomized ISI tried to minimize the latter). Similarly, the Cyberball paradigm employed in Chapter 2 could have missed ecological validity, as social exclusion is likely a more complex phenomenon, and even though a deception piece was included, some participants could have guessed that the other players were in fact not real participants, with the number and direction of ball-throws being preprogrammed. One way to increase both experimental control and ecological validity could be to employ virtual reality (Campbell et al., 2009) to elicit feelings of social exclusion. Advances in virtual technology could offer platforms in which three-dimensional objects are presented in a dynamic and controlled manner, while also allowing the individual to immerse in simulations that create a sense of ‘being there’, thus enhancing ecological validity in an experimentally controlled setting (Parsons, 2015).

7.4.3 Methodological issues surrounding the measurement of adult attachment style

Whilst there are many tools to examine adult attachment style, ranging from semi-structured interviews to self-reported questionnaires measuring implicit versus explicit awareness of attachment style, the current thesis mostly employed a self-reported questionnaire, namely the ECR-R (Fraley et al., 2000), to measure two continuous dimensions of attachment style: attachment anxiety and attachment avoidance. The main reason for employing this measure was that assessing attachment style on a broad continuous, dimensional approach tackles the problem of categorization, both in conceptual and methodological manner. Indeed, with respect to the former, different measures have categorized attachment style in a variety of ways. For instance, the Adult Attachment Interview (AAI; George et al., 1995) categorises individuals as “secure/autonomous” and “insecure”, with the latter being sub-classified into “avoidant/dismissing”, “anxious/preoccupied” or “unclassifiable”. Other questionnaires (based on a model of self and other; Bartholomew & Horowitz, 1991) group individuals as “secure”, “preoccupied”, “fearful” and “dismissing” or alternatively, into “secure”, “anxious/ambivalent“ and “avoidant”, akin to classifications in infants (Main et al., 1985; e.g., see the Attachment Styles questionnaire, Hazan & Shaver, 1987). Thus, such groups are conceptualized slightly differently depending on the adopted categorization scheme. Instead, all these these categories can be conceptualized more broadly into the attachment avoidance and anxiety dimensions. In addition, with respect to the latter problem, such categorical approach also leads to less variability within and between categories. For example, two individuals may be grouped into “anxious/preoccupied” category even though they differ in their avoidant level; or alternatively, two individuals scoring just above or below the cut-off point are assigned to different attachment categories, thus decreasing variability. In the current thesis for example, if such categorical approach had been adopted, most of the participants might have been assigned to a “security” category, as indexed by scoring low on both attachment dimensions. Hence, this dimensional, continuous approach (as measured by the ECR-R) allowed us to have more data variability in order to assess the modulating and moderating role of adult attachment style. Moreover, the ECR-R has excellent psychometric properties; as well as population (more than 17,000 subjects) norms have been published online, which allowed us to compare our attachment scores with the normal population in all Chapters. Indeed, the attachment avoidance and anxiety scores did not differ with the normal population, except for those reported in Chapter 3 (but note that participants in a current relationship, with a duration longer than 12 months, thus more attachment security was expected).

Despite these methodological advantages, however, some limitations associated with the ECR-R should be noticed. These limitations are intrinsic to the use of self-reported questionnaires, including potentials social desirability effects (e.g., participants can be inclined to appear and thus score themselves as ‘more secure’) as well as these measures are by necessity explicit rather than implicit, hence may not capture important attachment phenomena that occur outside of conscious awareness. Indeed, by contrast, implicit measures of attachment style such as the AAI have the advantage of reducing social desirability biases and the ability to assess autonomic attachment-related processes. In fact, based on these methodological constraints, the present thesis (specifically Chapter 5) went across traditions to assess whether attachment style determines sensitivity to affective touch using both a categorical (AAI) and dimensional approach (ECR-R). While the findings from this chapter indicated no difference between these two measures, i.e., ECR-R scores did not differ by AAI classification, differences in attachment security (categorical approach) and attachment anxiety (but not avoidance; dimensional approach) predicted worst sensitivity to affective touch. Therefore supporting the choice of two separate measures for this multi-dimensional construct.

7.4.4 Other methodological issues

In addition to the aforementioned methodological constraints, other general factors should be considered. First, since the experimenter administering touch in the present studies was female, almost all the experimental chapters tested only women to avoid gender effects associated with the perception of touch (e.g., Bendas et al., 2017; Gazzola et al., 2012; Suvilehto et al., 2015; although see Chapter 6 for no gender effects, and also see Ackerley et al., 2014; Jönsson et al., 2015; Sehlstedt et al., 2016);

however, future research is needed to examine whether the present results extend to men (see also Chapter 5 on how differences in gender by attachment style could contribute to differences in touch perception). Second, based on the social support literature, this thesis focused on interpersonal social contextual factors rather than intergroup characteristics. Nevertheless, it is likely that intergroup characteristics, such as social status, age, ethnicity, romantic relationship status, sexual orientation play a role in the social modulation of pain, or even on the perception of affective touch. For this reason, we tried to match the groups as much as possible (e.g., finding no differences in demographics in Chapter 2) or our main critical touch manipulation being a within-subject comparison. Third, although we tried to control for age (see above), it should be noticed that our samples consisted of young adults (18-30 years old). This age range was selected given it is relatively easy to recruit and to control for potential age-related effects, but it would be valuable to examine the modulation of and by affective touch across development to determine whether such effects occur across the lifespan. Indeed, although it has been reported that discriminative touch abilities decline with age, a positive correlation between perceived pleasantness of the touch and age has been observed (Sehlstedt et al., 2016), which could potentially play a role in our effects. Fourth, other individual differences variable could have been studied, e.g., pain catastrophising tendencies or the likelihood and likeability to receive and enjoy touch questionnaires, which have been found to shape pain and affective touch perception, respectively (e.g., Meredith, Strong, & Feeney, 2006; Voos, Pelphrey, & Kaiser, 2013). Nevertheless, other questionnaires were not included given practical constraints (e.g., duration of the experimental session and fatigue of the participants). Instead, we predominantly assessed adult attachment style, which has been consistently found to moderate the effects of social support and pain, and was critical to our hypotheses.

7.5 Clinical implications

The studies reported in the current thesis were conducted on an experimental rather than clinical setting. Moreover, such studies were always conducted on healthy subjects, i.e., without any history of chronic pain, psychiatric or neurological disorders. Thus, the findings of this thesis have no direct clinical applicability. Nevertheless, these findings provide tentative implications for clinically-based research. Indeed, clinical work suggests that tactile-based interventions improve clinical outcomes, including reduction of symptom severity in patients with rheumatoid arthritis and fibromyalgia, and reducing health complications in infants delivered pre-term (for reviews see Field, 2014; Hathaway et al., 2015). Thus, the findings of this thesis provide some degree of specificity by suggesting that affective, CT-optimal touch in particular possesses some soothing characteristics. Moreover, even though the regulatory effects of touch were mostly examined in relation to pain and in young adults, one can speculate that these effects extend to other domains and across development. For example, recent evidence suggests that early painful experiences (e.g., skin punctures, tube insertions) in newborns are associated with reduced brain responses to light touch in newborns (Maitre et al., 2017). Moreover, recent evidence suggests that CT-optimal stroking reduces noxious-evoked brain activity in newborns (Gursul et al., 2018). Thus, CT fibres may represent a biological target for early life interventions. Future research should examine whether CT-optimal may work as a non-pharmacological intervention in specific clinical populations such as pre-term infants, for example.

7.6 Directions for future research

Based on the findings from this thesis (section 7.3) and methodological considerations (section 7.4), there are several directions for future research that should be considered. Given space constraints, here we will outline just a few. First, this thesis highlighted the importance of social context as well as attachment style on the buffering role of pain by affective touch. Thus, future research should examine the role of social context and attachment style where these were not examined. For example, Chapter 2 did not examine the moderating role of individual differences in attachment style given design constraints. However, one can speculate that differences in attachment style may moderate such effects (e.g., higher attachment anxiety predicting lower feelings of distress caused by ostracism in response to CT-optimal versus non-CT optimal touch, with the opposite effects for attachment avoidance). Similarly, future research could examine how and whether social pain is modulated when a romantic partner is providing the touch. Relatedly, the effects on CT-optimal vs. non-CT optimal touch discrimination can be subject to social context, in which for instance, touch by an attachment figure could activate attachment behaviors that are not at display when strangers are involved (see Ravitz et al., 2010). Thus, adding to Chapter 5, future research could incorporate partner-administered touch when assessing how attachment style determines CT-optimal touch sensitivity alone.

Second, the neurobiological mechanisms that underpin the current effects remain unknown. As mentioned in section 7.3, opioid and oxytocin are potential neurobiological candidates. Intransally administered oxytocin has been found to attenuate subjective pain report and LEP responses as those observed in the current thesis (Paloyelis et al., 2016), thus following this line of work, it would be valuable to examine whether this neuropeptide hormone mediates the current effects. Similar effects could be examined by naloxone administration, an opioid antagonist.

Third, adding evidence to the proposed free energy framework (section 7.3), future research could use both live and primed tactile interactions, varying the possibility for action and 'safety' in the context of pain. Alternatively, future research may want to examine whether another's supportive actions leads to allostatic predictions and how this relates to the subject's possibility for action (see Fotopoulou & Tsakiris, 2017 for this hypothesis, and also section 7.2.3). Even though this notion was indirectly examined in Chapter 4, future research is needed to directly investigate this issue. In particular, one could examine this notion by physically restraining healthy subjects while administering the touch prior to the pain, or by using effort discounting tasks that involve social feed-back while varying the potential actions of others' in discounting one's probability to receive pain.

Fourth, in order to exclude several potential confounding factors (e.g., social disaribility, familiarity, distraction), the only variable manipulated across the experimental chapters was the velocity of the touch and as such, this thesis did not include other forms of embodied social support, e.g., handholding. Nevertheless, in order to assess how 'powerful' this specific tactile manipulation really is, future research may want to include other forms of passive embodied social support (e.g., hand-holding), or even contrast this specific manipulation with other non-tactile forms of active support, i.e., involving action from the support provider (e.g., supportive text-messages). Moreover, all the experimental chapters in this thesis involved an experimenter providing the touch, and as such, the tactile manipulation (including control) was always, to a certain degree, social. This was done not only because of practical reasons, but also to increase the ecological validity of the experiments (e.g., how many times are you really touched by a robot (remember this thesis was written in 2018)? And would this provide the same degree of social support?). However, to more fully understand the socially supportive aspects associated with the touch, future research could include control conditions wherein the touch is delivered by a robotic device. Indeed, similar effects of pleasantness, tuned to CT-optimal activation, have been reported when a robot versus a person administers the touch (Triscoli et al., 2013). Thus, finding differences between a person and a robot here, even though no differences exist in terms of perceived pleasantness, could speak to the critical social aspect involved in the current effects.

Finally, given the replication crisis in psychology (Maxwell, Lau, & Howard, 2015), the findings reported in this thesis should be replicated using larger sample sizes. Bayesian statistics, and as the literature grows, meta-analysis are also encouraged.

7.7 Concluding comments

Recent evidence suggests that a specific type of dynamic, low-pressure touch that is associated with the activation of a particular type of peripheral touch receptors (CT fibres) are a particularly effective form of active social support. This type of touch is termed affective touch and this thesis aimed to examine its role on the social buffering of somatic and social pain. It revealed that affective touch is a potent form of active social support, capable of attenuating both types of pain. However, such effects depend on the social context as well as on individual differences in adult attachment style, for example the moderating role of attachment style does not seem to play a major role in a context in which social attachment is already established. Moreover, socio-contextual factors, including adult attachment style, can further shape the perception of affective touch alone. Overall, these findings provide some empirical support to the notion that “on-line” social factors such as active social support, as well as “off-line” predictions about the availability of social help (e.g. attachment style), modulate pain or affective touch by changing the precision of top-down predictions versus prediction errors from nociception or CT stimulation. Finally, this thesis also provided a novel way to measure affective touch dimensions, revealing that while there is higher affective touch sensitivity and awareness on CT relative to non-CT skin sites, there is also a bias to report the touch as high pleasant on this same skin site. Future work is still needed to examine the optimal assessment of affective touch and also the functional role of the CT system and its particular, neurophysiological contribution to the current effects.

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Appendices

Appendix 1. Attachment style dimensions in our sample in Chapter 3.

We compared our attachment anxiety and attachment avoidance scores to those reported as the ECR-R norms (see Fraley, last modified 2012 on The Information on the Experiences in Close Relationships-Revised (ECR-R) Adult Attachment Questionnaire; internal.psychology.illinois. edu/~rcfraley/measures/ecrr.htm). These norms were obtained from more than 17,000 individuals completing the ECR-R online, with an average age of 27 (*SD*=10). Similarly, we also compared our attachment anxiety and attachment avoidance scores to our earlier work on the effects of affective touch (by stranger) on pain (see Table A2 for descriptive statistics). Our results suggest that our sample reported lower attachment anxiety and attachment avoidance as compared to the general population, t=-3.16, p=.003, t=-8.26, p=.001, respectively, as well as compared to our earlier work, t=-2.41, p=.02, t=-2.34, p=.02, respectively.

Table A1
Mean (SD) for attachment anxiety and attachment avoidance scores (ECR-R) collected from the current sample, our earlier work on affective touch and the normal population.

	Attachment anxiety	Attachment avoidance	N
The current study	2.50 (0.75)	2.55(.69)	32
Earlier work on affective touch and pain	2.97(1.01)	2.97(0.93)	50 (25 per group)
General population	3.56(1.12)	2.92(1.19)	17,000

Appendix 2. Relationship quality results in Chapter 3.

We employed the seven-item Dyadic Adjustment Scale (DAS-7; Sharpley & Rogers, 1984) to measure relationship quality. The DAS-7 consists of 7 items: three items assess dyadic consensus, three items assess dyadic cohesion, and one item assesses global dyadic satisfaction (the first six items rated on a 6-point scale, ranging from 0 to 5, and the last item rated on a 7-point scale, ranging from 0 to 6). The total score for the DAS-7 is the sum of the responses to the seven items (possible range 0 to 36). The DAS-7 is a well-validated measure (Hunsley, Best, Lefebvre, & Vito, 2001; Sharpley & Rogers, 1984). Prior studies in healthy participants in a current relationship (at least one year) have reported means ranging from 20.9 (*SD*=4.3) to 25.8 (*SD*=4.7), whereas lower means have been reported for participants in clinical settings (*M*=17.8, *SD*=5.5) or participants who are separated/ divorced (*M*=13.4-15.2) (see Hunsley, Best, Lefebvre, & Vito, 2001; Sharpley & Rogers, 1984). In the present sample, Cronbach's alpha was α=.52, and on average, participants reported high relationship quality/adjustment (*M*=25.84, *SD*=3.18), given the weighting of this mean towards high adjustment. Relationship quality did not correlate with attachment anxiety, Pearson's *r*=-.06, *p*=.743, or attachment avoidance, Pearson's *r*=-.03, *p*=.852. We further observed the same pattern of effects as reported in the main text when controlling for relationship quality on our slow versus fast multilevel modelling (see Table A1).

Table A2
Slow versus fast touch: multilevel modeling results for all outcome measures while also controlling for relationship quality as a covariate.

Effect	Dependent variable	b	*SE*	*p*-value	Confidence intervals	
					Lower	Upper

Slow touch vs. fast touch	**N1**	-1.01	.46	.029	-1.92	-.10
	N2	-2.06	.76	.007	-3.54	-.57
	P2	2.85	.88	.001	1.12	4.5
	Pain ratings	.62	.13	<.001	.37	.87
Attachment anxiety	N1	-.21	.53	.697	-1.25	.83
	N2	-1.35	.86	.114	-3.03	.33
	P2	1.54	1.15	.181	-.72	3.80
	Pain ratings	.01	.20	.967	-.39	.51
Attachment avoidance	N1	.01	.59	.981	-1.14	1.1
	N2	-.68	.96	.480	-2.56	1.21
	P2	-1.29	1.29	.317	-3.84	1.2
	Pain ratings	-.06	.22	.795	-.48	.37
Attachment anxiety * attachment avoidance	N1	-.77	.79	.334	-2.32	.78
	N2	-2.72	1.23	.027	-5.13	-.31
	P2	1.02	1.65	.538	-2.22	4.24
	Pain ratings	-.01	.29	.971	-.58	.56
Touch condition * attachment anxiety	N1	1.16	.64	.068	-.086	2.4
	N2	1.26	1.05	.229	-.79	3.31
	P2	-2.01	1.23	.101	-4.41	.393
	Pain ratings	-.41	.18	.023	-.76	-.06
Touch condition * attachment avoidance	N1	.34	.73	.639	-1.09	1.7
	N2	2.19	1.17	.061	-.10	4.49
	P2	1.78	1.37	.195	-.91	4.48
	Pain ratings	.15	.19	.4#7	-.22	.51
Touch condition * attachment avoidance * attachment anxiety	N1	.17	1.04	.867	-1.87	2.2
	N2	1.31	1.50	.384	-1.63	4.25
	P2	-2.21	1.76	.207	-5.67	1.23
	Pain ratings	-.26	.26	.305	-.76	.24
c. Relationship quality	N1	-.14	.10	.182	-.34	.06
	N2	.06	.17	.711	-.26	.39
	P2	-.35	.27	.193	-.87	.18
	Pain ratings	-.02	.04	.668	-.09	.06

Note. Significant main effects and interactions are highlighted in bold. Baseline pain as a covariate was statistically significant across all pain outcomes, $p<.05$.

Appendix 3. Attachment anxiety by avoidance on the N2 in Chapter 3

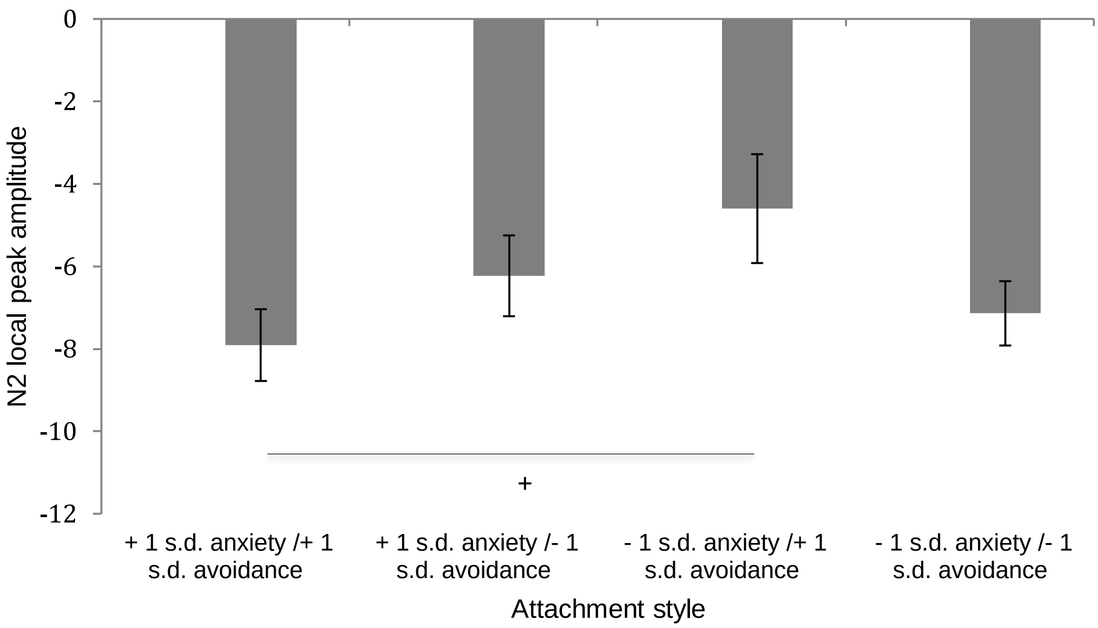

Figure A3: Effects of attachment anxiety by attachment avoidance on the N2 local peak amplitude plotted at low (-1 s.d.) and high (+1 s.d.) attachment anxiety and attachment avoidance scores. Error bars denote SE of the predicted margins. Note. No comparisons were statistically significant / plus sign indicates a trend towards significance between +1 s.d. anxiety/ +1 s.d. avoidance and -1 s.d. anxiety/ +1 s.d. avoidance.

Appendix 4. Attachment anxiety by avoidance on the N2 in Chapter 3

Table A4

Touch pleasantness ratings and pain relation outcomes – correlations results

Outcome	Stroking velocity condition	Perceived touch pleasantness	Pearson's r	*p* value
Pain rating	Slow touch	Pleasantness rating slow touch velocity	-.07	.715
	Fast Touch	Pleasantness rating fast velocity	-.02	.914
N1	Slow touch	Pleasantness rating slow touch velocity	.06	.758
	Fast Touch	Pleasantness rating fast velocity	.15	.474
N2	Slow touch	Pleasantness rating slow touch velocity	-.04	.827
	Fast Touch	Pleasantness rating fast velocity	-.34	.075
P2	Slow touch	Pleasantness rating slow touch velocity	-.13	.523
	Fast Touch	Pleasantness rating fast velocity	.21	.280

Appendix 5. Attachment style dimensions in our sample in Chapter 4

We compared our attachment anxiety and attachment avoidance scores to those reported as the ECR-R norms (see Fraley, last modified 2012 on The Information on the Experiences in Close Relationships-Revised (ECR-R) Adult Attachment Questionnaire; internal.psychology.illinois. edu/~rcfraley/measures/ecrr.htm). These norms were obtained from more than 17,000 individuals completing the ECR-R online, with an average age of 27 (*SD*=10). With respect to the social PPS group, our results suggest that there were no differences in attachment anxiety, t=.22, p=.827, nor attachment avoidance, t=.96, p=.336, between our sample and the general population. Similarly, with respect to the social PPS group, our results suggest that there were no differences in attachment anxiety, t=.66, p=.512, nor attachment avoidance, t=0, p=1, between our sample and the general population.

Table A5
Mean (SD) for attachment anxiety and attachment avoidance scores (ECR-R) collected from the current sample and the normal population.

	Attachment anxiety	Attachment avoidance	N
The current study (social PPS group)	3.51 (1.03)	3.51(.75)	24
The current study (non-social PPS group)	3.41(1.02)	2.92(1.31)	24
General population	3.56(1.12)	2.92(1.19)	17,000

Appendix 6. Association between questionnaire-assessed attachment style (ECR-R) and the perception of affective touch in Chapter 3

To test whether attachment style dimensions as measured by the ECR-R questionnaire were associated with the perception of pleasant touch, we specified a multilevel regression model with mean pleasantness rating as the outcome variable, and velocity (CT-optimal vs. non-CT-optimal), ECR-R attachment anxiety, ECR-R attachment avoidance, as well as all interaction terms, as predictor variables.

As shown in Table A6, neither attachment anxiety nor attachment avoidance, nor the interaction between the two dimensions were associated with pleasantness ratings across velocities, indicating that pleasantness of touch in general was not influenced by continuous attachment style scores.

Table A6
Model results for effects of attachment on the perception of affective touch on Chapter 3

	b	*SE*	*p* value	95% CI lower	95% CI higher
Velocity (slow, CT-optimal vs. fast, Non-CT-optimal)	-16.82	3.03	**< 0.001**	-22.76	-10.89
ECR-R anxiety	-4.56	3.62	0.207	-11.64	2.52
ECR-R avoidance	-2.73	3.77	0.468	-10.13	4.64
Velocity by ECR-R anxiety	-1.67	4.28	0.696	-10.06	6.72
Velocity by ECR-R avoidance	6.28	4.55	0.167	-2.64	15.22
ECR-R anxiety by ECR-R avoidance	-6.36	5.16	0.217	-16.47	3.74
Velocity by ECR-R anxiety by ECR-R avoidance	2.49	6.14	0.685	-9.54	14.53

Appendix 7. Association between questionnaire-assessed attachment style (ECR-R) and the perception of affective touch in Chapter 4

To test whether attachment style dimensions as measured by the ECR-R questionnaire were associated with the perception of pleasant touch, we specified a multilevel regression model with mean pleasantness rating as the outcome variable, and velocity (CT-optimal vs. non-CT-optimal), ECR-R attachment anxiety, ECR-R attachment avoidance, as well as all interaction terms, as predictor variables

As shown in Table A7, neither attachment anxiety nor attachment avoidance, nor the interaction between the two dimensions were associated with pleasantness ratings across velocities, indicating that pleasantness of touch in general was not influenced by continuous attachment style scores.

Table A7
Model results for effects of attachment on the perception of affective touch on Chapter 4

	b	*SE*	*p* value	95% CI lower	95% CI higher
Velocity (slow, CT-optimal vs. very slow, Non-CT-optimal)	-18.94	3.41	< **0.001**	-25.62	-12.25
ECR-R anxiety	-4.31	2.95	0.144	-10.10	1.47
ECR-R avoidance	-3.70	2.85	0.194	-9.29	1.88
Velocity by ECR-R anxiety	2.89	3.38	0.392	-3.73	9.53
Velocity by ECR-R avoidance	0.62	3.27	0.849	-5.78	7.03
ECR-R anxiety by ECR-R avoidance	-3.10	2.89	0.284	-8.76	2.57
Velocity by ECR-R anxiety by ECR-R avoidance	1.44	3.31	0.665	-5.06	7.93

Appendix 8. Gender effects in Chapter 6 (Experiment 1)

We conducted a mixed 2 (skin area: forearm, palm) x 2 (gender: female, male) ANOVAs to examine whether there were any gender differences separately in our main outcome measures, i.e., sensitivity d', response bias C and aROC. Results suggest that there was no between-group main effect of gender, p's>.274 (except for a trend, p=.097 on sensitivity d'), and gender did not interact with skin area, p's>.319, in any of our outcome measures. Similarly, a 2 (skin area: forearm, palm) x 2 (speed: CT-optimal speeds; CT non-optimal speeds) x 2 (gender: female, male) ANOVA was also conducted on our manipulation check of pleasantness ratings. As above, there was no main effect of gender, p=.284, and gender did not interact with skin area, p=.672 , speed, p= .363 , or their combination, p=.674. Thus, these results suggest that there are no effects of gender associated with our main SDT task or our manipulation checks consisting of pleasantness ratings.

Appendix 9. Interim analyses in Chapter 6 (Experiment 1)

Interim analyses where conducted on the first half of the sample (i.e., 47 participants) from Experiment 1. As shown in Figure A9, these interim analyses suggest significantly higher sensitivity (d') on the forearm (*M*=1.62, *SD*=.92), as compared to the palm (*M*=1.19, *SD*=.94), *t*(45)=3.16, *p*=.003, *d*=0.47, with a trend towards significance for the response bias, indicating more negative response bias (C) in the forearm (*M*=-.28, *SD*=.48), as compared to the palm (*M*=-.11, *SD*=.63), *t*(45)=-1.79, *p*=.081, *d*=-0.26. These are the same pattern of results shown in Chapter 6.

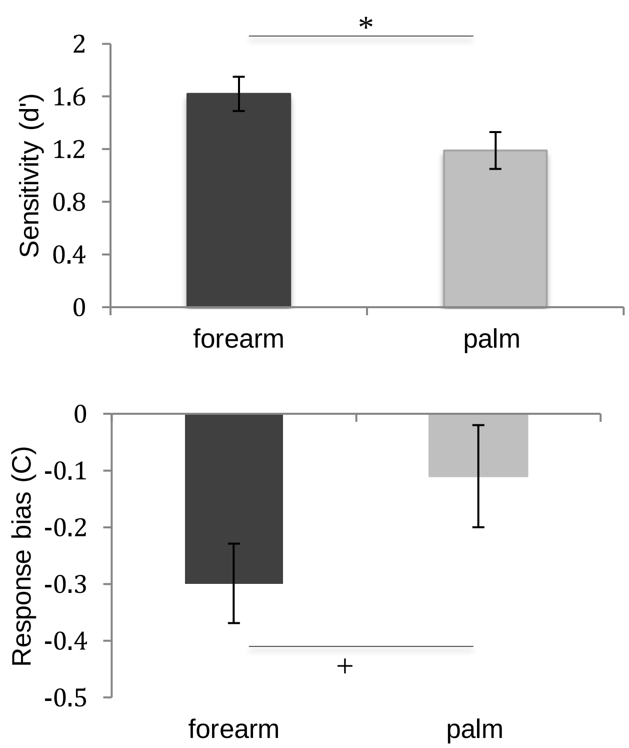

Figure A9: Sensitivity (d') for forearm (CT skin) and palm (non-CT skin); top panel. Response bias (C) for forearm (CT skin) and palm (non-CT skin); bottom panel. Error bars denote ± standard error of the mean for illustration purposes.

Appendix 10. Manipulation check (pleasantness ratings) in Chapter 6 (Experiment 1)

We conducted a 2 (skin area: forearm, palm) x 2 (CT-optimal speeds; CT non-optimal speeds) ANOVA on pleasantness ratings to examine whether on average participants experienced a CT-optimal velocity as more pleasant than a non-CT optimal velocity. Follow-up analysis used paired t-tests with Bonferroni correction when applicable.

Analyses conducted on the pleasantness ratings scores suggested that touch at CT-optimal speeds, versus non-CT optimal speeds, was perceived as expected at the group level. Specifically, across skin areas, participants perceived touch at CT optimal speed as more pleasant than touch at non-CT optimal speed, $F(1,93)=91.77$, $p<.001$, $\eta^2_{partial}=.49$. Similarly, participants perceived the touch as more pleasant on the forearm, versus the palm, $F(1,93)=5.90$, $p=.017$, $\eta^2_{partial}=.06$. Importantly, skin area interacted with speed, $F(1,93)=4.45$, $p=.038$, $\eta^2_{partial}=.05$. Post-hoc tests, using Bonferroni adjusted alpha level of .0125 per test (.05/4), showed that participants perceived touch at CT-optimal speed (forearm: M=69.73, SD=14.98; palm: M=64.95, SD=14.77) as more pleasant than touch at non-CT optimal speeds (forearm: M=46.23, SD=18.34; palm: M=45.03, SD=19.58) on both forearm, $t(93)=10.31$, $p<.001$, and palm, $t(93)=7.80$, $p<.001$, respectively. Importantly, while there was no difference between palm and forearm in the perceived pleasantness of touch at non-CT optimal speeds, $t(93)=.79$, $p=.431$, participants perceived touch at CT optimal speeds as more pleasant in the forearm as compared to the palm, $t(93)=3.22$, $p=.002$.

Appendix 11. Gender effects in Chapter 6 (Experiment 2)

We conducted a mixed 2 (skin area: forearm, palm) x 2 (gender: female, male) ANOVAs to examine whether there were any gender differences separately in our main outcome measures, i.e., sensitivity d', response bias C and aROC. Results suggest that there was no between-group main effect of gender, p's>.227, and gender did not interact with skin area, p's>.145, in any of our outcome measures. Similarly, a 2 (skin area: forearm, palm) x 2 (speed: CT-optimal speeds; CT non-optimal speeds) x 2 (gender: female, male) ANOVA was also conducted on our manipulation check of pleasantness ratings. As above, there was no main effect of gender, p=.750, and gender did not interact with skin area, p=.687 , speed, p= .319, or their combination, p=.946. Thus, similar to Experiment 1, these results suggest that there are no effects of gender associated with our main SDT task or our manipulation checks consisting of pleasantness ratings.

Appendix 12. Manipulation check (pleasantness ratings) in Chapter 6 (Experiment 2)

We conducted a 2 (skin area: forearm, palm) x 2 (CT-optimal speeds; CT non-optimal speeds) ANOVA on pleasantness ratings to examine whether on average participants experienced a CT-optimal velocity as more pleasant than a non-CT optimal velocity. Follow-up analysis used paired t-tests with Bonferroni correction when applicable.

Analyses conducted on the pleasantness ratings scores suggested that touch at CT-optimal speeds, versus non-CT optimal speeds, was perceived as expected at the group level. Specifically, across skin areas, participants perceived touch at CT optimal speed (M= 65.10, SD=11.62) as more pleasant than touch at non-CT optimal speeds, (M=44.91, SD= 12.86), $F(1,98)=202.65$, $p<.001$, $\eta^2_{partial}=.67$. There was a trend for a main effect of skin area, $F(1,98)=3.68$, $p=.058$, $\eta^2_{partial}=.04$, and skin by speed interaction, $F(1,98)=3.64$, $p=.059$, $\eta^2_{partial}=.04$.