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ORIGINAL ARTICLE

Multisensory experiences of affective touch in virtual reality enhance engagement, body ownership, pleasantness, and arousal modulation

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Abstract

When engaging in physical contact, our emotional response hinges not only on the nuanced sensory details and the receptive properties of the skin but also on contextual cues related to the situation and interpersonal dynamics. The consensus is that the nature of the affective interactive experience in social touch is shaped by a combination of ascending, C-tactile (CT) afferents mediated somatosensory information, and modulatory, top-down information. The question we pose here is whether, in the absence of somatosensory input, multisensory cues alone can suffice to create a genuinely pleasant, authentic, and engaging experience in virtual reality. The study aims to explore how affective touch is perceived in immersive virtual environments, considering varied social norms in neutral settings or settings like a physiotherapy room where the touch provider is a healthcare professional. We conducted an experiment with 58 male and female healthy adults, where we employed a within-group counterbalanced design featuring two factors: (a) visuo-tactile affective touch, and (B) visual-only affective touch. Findings, drawn from questionnaires and collected physiological data, shed light on how contextual factors influence implicit engagement, self-reported embodiment, co-presence, as well as the perceived realism and pleasantness of the touch experience. Our findings, in line with the literature, indicate that to experience the advantages of touch in immersive virtual worlds, it is essential to incorporate haptic feedback, as depending solely on visual input may not be adequate for fully realising the optimal benefits of interpersonal touch. Furthermore, in contradiction with our hypothesis, a less ambiguous context (specifically, the physiotherapy room and touch from a physiotherapist) is not linked to heightened touch pleasantness.

Keywords Affective touch · Virtual embodiment · Copresence · Mediated touch · Social virtual reality

1 Introduction

When we engage in physical contact with others, our emotional response is determined in large part not only by the tactile receptors activated in our skin, but also by the context of the social exchange (Sailer and Leknes 2022). Despite evidence for a subset of skin receptors that are preferably tuned to soft gentle touch (Löken et al. 2009), whether touch is evaluated as pleasant depends on various factors, including the identity of the person we are interacting with and the circumstances surrounding the touch (where and why we are being touched). Much of this contextual information is derived through activation of touch receptors but is, to a significant extent, determined in advance through our visual, auditory, and even olfactory senses (Spence 2022). The multisensory contributions to how we perceive affective touch are therefore key to understanding the important role that touch plays in shaping our interactions and sense

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of connection with others. Furthermore, this understanding is particularly relevant to our interactions with others in remote environments, for example virtual meetings over platforms like Zoom or virtual reality (VR) collaboration spaces. In this study, we investigate how virtual experiences of touch are evaluated and how they change as a function of the multisensory nature of the touch encounter.

2 Socialtouch: contextual and multisensory foundations

Indeed, touch never happens in a contextual void, but is intricately influenced by a multitude of factors. Socialtouch is an essential form of interpersonal communication (Fairhurst at al. 2022; Fairhurst and Valori 2023), with its own alphabet, lexicon, and norms of use (Poggi et al. 2004). The same tactile interaction between intimate partners can invoke feelings of pleasure and desire, or conversely, feelings of awkwardness or even abuse (Saarinen et al. 2021). The identity of the person touching us and their reasons for doing so can significantly influence our subjective evaluation of that experience (Suvilehto et al. 2023), which can be mirrored by changes in our physiological arousal (Triscoli et al. 2017) and correlated patterns of brain activity (Gazzola et al. 2012). The role of additional social cues in decoding the affective nature of a touch encounter appears to be important, even as early as five months of age (Pirazzoli et al. 2019). These cues may provide insight into the nature of the relationship between the individual delivering the touch and the one receiving it, with a greater degree of acceptance for touch when it involves close family members or intimate partners compared to strangers (Suvilehto et al. 2015).

Additional sources of variability may be determined by individual differences of the receiver, for example gender differences in touch evaluation and acceptance (Russo et al. 2020). It appears that there are variations in how men and women experience the sensory pleasantness of touch, suggesting also that each gender assigns different levels of importance of touch within broader social contexts. For example, women are more likely to express comfort with touch, even from less familiar or even unfamiliar individuals (particularly women) and feel more comfortable with touch to the forearm (Schirmer et al. 2022). More generally, people exhibit divergent preferences for touch and engage in tactile communication differently, which is partially modulated by their behavioural inhibition system sensitivity (Harjunen et al. 2017), and their attitudes towards various forms of intimate touch (e.g., hugging) (Dûren 2022).

The context in which touch occurs can also significantly shape its perception. In professional settings, such as medical treatment, factors like attachment style and levels of extraversion may influence touch perception (Vafeiadou et al. 2022). The perception of affective touch depends not only on contextual information related to the situation and the relationship between individuals, but also on low-level sensory aspects, and the receptive properties of the skin on which this thermo-mechanical information is deposited (McGlone and Reilly 2010). Any given tactile experience constitutes a mechanical stimulation with discriminative sensory properties such as spatio-temporal dynamics and texture features that enable us to recognise external objects and events when they touch our skin. Tactile information is projected to the cortex via various fibers with different degrees of myelination and conduction speed. While Aβ afferents are highly myelinated and fast conducting fibers, C fibers are slow-conducting unmyelinated afferents, and Aδ fibers have thin myelin sheaths and conduct at intermediate velocities (Owens and Lumpkin, 2014). Aβ afferents display conduction velocities ranging from 20 to 80 m/s, whereas the so-called C-tactile afferents or CT fibers respond optimally to gentle, caress-like stroking (McGlone et al. 2014). Seemingly tuned to social touch, these afferents selectively respond to touch with specific features, including a slow velocity of 1 to 10 cm/s, gentle force of 0.3 to2.5 mN, and a temperature resembling that of human skin (Vallbo et al. 1999; Ackerley et al. 2014). Certain areas of the body, such as the arm, are particularly dense with CT-afferents, suggesting they may have evolved to be particularly attuned to affective touch (Löken et al. 2022).

There is a consensus in the literature to define CT-mediated touch as affective touch, as it conveys socio-affective connotations (McGlone et al. 2014). These C-tactile afferents project directly to important nodes within the social-brain network involved in social and interoceptive processing. These include the posterior insula, the medial prefrontal cortex, and the dorsal anterior cingulate cortex (Morrison 2016; Gordon et al. 2013; Voos et al. 2013; Björnsdotter et al. 2014). Additionally, there is a positive correlation between the activation of C-tactile afferents and self-reported feelings of pleasantness (Löken et al. 2009). Moreover, research has shown that affective touch modulates the activity of the autonomic nervous system, with a relaxing effect that is supported by various physiological processes. For example, studies have found that CT optimal touch, as opposed to CT suboptimal touch, can lead to a reduction in heart rate and a decrease in skin conductance response, both of which serve as physiological indicators of arousal. This touch also decreases sympathetic activity and increases parasympathetic activity, as indicated by measures of vagal tone such as heart rate variability (Walker et al. 2022). It is generally accepted that a combination of the ascending, CT mediated somatosensory information (bottom-up) and modulatory, top-down information shapes the nature of the affective interactive experience of social touch (Fairhurst et al. 2022). The question we pose here however is whether multisensory cues alone, in the absence of somatosensory input, can be sufficient to generate a pleasant, real, and engaging experience in virtual reality.

2.1 In a virtual world: different norms and sensory experiences

Previous research has investigated the influence that somatosensory feedback can have on the immersion of a virtual environment or the experience of a virtual body as one's own. For example, researchers have explored the use of vibrotactile and force feedback actuators, as well as air- or electricity-based haptic devices in an attempt to recreate or simulate the sensation of social touch within a digital context (Gallace and Girondini 2022). While some studies support the idea that integrating these devices in VR can evoke sensations akin to those experienced in real-life scenarios involving physical touch, others yield inconclusive results, overall lacking sufficient evidence regarding the neurophysiological underpinnings (Gallace and Girondini 2022). Some authors have endeavored to understand the optimal characteristics of haptic feedback for simulating virtual hugs (Cui et al. 2021), while others investigated whether affective touch at CT-optimal versus suboptimal velocities can enhance one's sense of body ownership over a virtual body (de Jong et al. 2017). Altogether, the transition from real to virtual social touch involves changes in both sensory aspects and adherence to social norms.

Entering the realm of immersive VR, multisensory processes can greatly differ from reality, resulting in disrupted integration of visual and proprioceptive information for action (Petrini et al. 2016; Harris et al. 2019; Valori et al. 2020) and increased variability in social behaviours such as interpersonal comfort distance (Simões et al. 2020). Although the mere sight of one's own virtual body from a first-person perspective can trigger a sense of body ownership (Slater et al. 2010), researchers often employ spatiotemporally congruent visuo-tactile stimulation to facilitate the integration of external visual and somatosensory information, thereby promoting embodiment in a virtual body (Rubo and Gamer 2019). However, most VR experiences lack the powerful effects of actual touch (i.e., haptic feedback), limiting the potential for non-verbal affective communication in virtual social exchanges (Della Longa et al. 2022). This limitation is primarily due to the technical difficulty of incorporating touch in virtual environments, as well as broader considerations regarding the nature of digital touch (for further reading, see the Digital touch manifesto, Jewitt et al. 2021). But the question that arises is whether more is necessarily better with the technical and theoretical considerations laid out by Jewitt and colleagues (Jewitt et al. 2021). Do we truly need or desire the incorporation of affective touch in virtual social interactions?

The human mind does not always rely on complete information to make sense of sensory events. Despite encountering uncertainty, it can effectively resolve ambiguity and construct a coherent interpretation of events. This cognitive process, as demonstrated by sensory illusions, elucidates the mind's remarkable ability to fill sensory incongruencies and gaps to process and understand the world (Buonomano 2011). For example, mirror therapy research for phantom limb pain shows that by using bodily visual cues, like reflecting the existing limb in a mirror to create the illusion of the missing limb, people can feel like they are moving and touching the missing limb, even without any physical sensations (Ramachandran and Rogers-Ramachandran 1996). Therefore, researchers have attempted to explore whether the mere sight of a person interacting with (touching) one's virtual body in VR, even in the absence of tactile input, can elicit the subjective and neurophysiological effects associated with affective touch. Some studies found that simply observing touch being applied to an embodied virtual body can lead to an increase in skin conductance, which serves as a proxy of emotional arousal. This effect was found to be modulated by bottom-up factors such as the location of the virtual body (Fusaro et al. 2021). In a comparison study between visual only and visuo-tactile exposure to affective touch, it was found that visuo-tactile conditions enhance the sense of body ownership over the virtual body (i.e., ownership, location, control, agency), as well as the feeling of being touched in an affective manner (Seinfeld et al. 2022). In the visuo-tactile condition, touch was also rated as more pleasant and arousing, with greater skin conductance responses.

The present study seeks to disentangle the contribution of sensory attributes associated with affective touch, which is either conveyed solely through visual means or with both visual and tactile inputs, directed at participants' arms or backs. Furthermore, we intend to explore how affective touch is perceived within immersive virtual contexts where different social norms may apply, such as in a neutral setting versus an environment resembling a physiotherapy room where the individual delivering the touch is a healthcare professional. We seek to examine how these aspects influence factors like body ownership, assessment of the virtual toucher, and judgements regarding the realism and pleasantness of the touch experience. Additionally, we delve into the physiological effects of touch-mediated by CT afferents, specifically focusing on heart rate changes. We anticipate that heart rate will decrease in response to heightened affect (i.e., visuo-tactile versus visual only stimulation, touch on the back versus the arm). The exploration of physiological measurements in VR has been extensively addressed to discern varying degrees of arousal, valence, anxiety, stress, or cognitive workload within virtual environments (Halbig and Latoschik 2021; Wood et al. 2021; Siriborvornratanakul 2016). These effects may also vary depending on the context and individual differences related to gender.

3 Materials & Methods

3.1 Participants

Participants between 18 and 25 years of age were recruited within the Bundeswehr University Munich using a student email distribution list. Initially, 70 participants (35 in the neutral context, and 35 in the clinical context) were recruited, but data from some participants were excluded due to technical issues in hardware, software, and physiological recordings. Valid data for a total of 58 participants were obtained, out of which 28 were in the neutral context (13 males, 15 females), and 30 were in the clinical context (18 males, 12 females). Participants gave written consent. The experiment was approved by the ethics committee of the Institute of Psychology, Bundeswehr University Munich.

3.2 Design

The experiment was conducted using a mixed-group counterbalanced design with two within-group factors *sensory information* and *body site*, and one between-group factor *context*.

The factor sensory information has two levels, (**a**) visuo-tactile affective touch, and (**b**) visual only affective touch. In (**a**), participants observed a virtual agent inside the VR environment delivering tactile strokes to them at C-tactile (CT) optimal speed of 5 cm/s (Löken et al. 2009), while simultaneously receiving synchronous physical strokes from the experimenter. In (**b**) participants only observed the touch within the VR environment, but did not receive any physical tactile stimulation. The factor body site refers to the specific location on the participants' body where the touch was administered, either to their back (Fig. 1A) or left forearm (Fig. 1B). This resulted in four experimental conditions referred to as blocks 'visuo-tactile arm', 'visuo-tactile back', 'visual only arm', 'visual only back'.

The order of the blocks was randomised across participants, and each block consisted of six to eight trials. After the sixth trial, participants were given the option to choose whether they wished to continue with more trials (yes/no response) before the next block started (see section Measures for more details).

We included an additional between-subjects factor of *context*, whereby the VR environment was either (**a**) neutral or (**b**) clinical, in a physiotherapy room. The neutral condition depicted a plain neutral room with no particular context and featured the same virtual agent, although she did not identify herself as a therapist (neutral condition). Conversely, participants in the condition were provided with information about the virtual affective scenario occurring in a physiotherapist's office. Within this context, the virtual agent introduced herself as the physiotherapist and guided participants through the process (clinical condition). The virtual agent was accompanied by bodily and facial animations as well as lip sync. The inclusion of context as a factor in our analyses focused on the evaluation and interpretation of interpersonal touch in different VR settings. For more

Fig. 1 Virtual reality setup. Third-person perspective of a male participant embodied in a gender-matched virtual body. The virtual female is delivering touch on the participant's (**A**) back or (**B**) arm (Body site). The figure also depicts the variable Context where (**A**) demonstrates the Clinical condition and (**B**) the Neutral condition

details on the design (Fig. 2A) see section Procedures and also supplementary MovieS1.

3.3 Measures

The data collected included subjective ratings and physiological data in the form of continuous heart rate measurements. We also gathered an implicit measurement of engagement with participants asked after the sixth trial in each block whether or not they would be willing to participate in additional optional trials. Our hypothesis was that participants' willingness to continue with more trials would be influenced by their previous ratings of the touch experience, their perceptions of pleasantness of their back or arm, and the contextual setting.

3.4 VR Questionnaire

During the VR experience, participants answered two questions with respect to the sensation of touch, namely how "pleasant" and how "real" it felt (Supplementary Material Table S1 - Touch). The questions were presented to them every second **trial** (trials: 2, 4, 6, and 8 for those who decided to continue). After each condition or **block**, participants answered four questions about embodiment in the virtual body (Supplementary Material Table S1 - Embodiment), and three questions about the virtual female avatar delivering the touch to assess co-presence (Supplementary Material Table S1 - Co-presence). All questions were presented to them within the virtual environment and answered on a 1 (not at all) to 7 (completely) Likert scale. The Embodiment section was based on previous studies and addresses possession of a virtual body (Gallagher 2006; Lenggenhager et al. 2007; Lopez et al. 2008), agency over a virtual body (Heater 1992; Lenggenhager et al. 2007; Lopez et al. 2008) and the perceived change in body schema (Tsakiris et al. 2006, 2010; Gallagher 2000). The questionnaire was adapted from the Avatar Embodiment Questionnaire (Peck and Gonzalez-Franco 2021). All questions are listed in Supplementary Material Table S1.

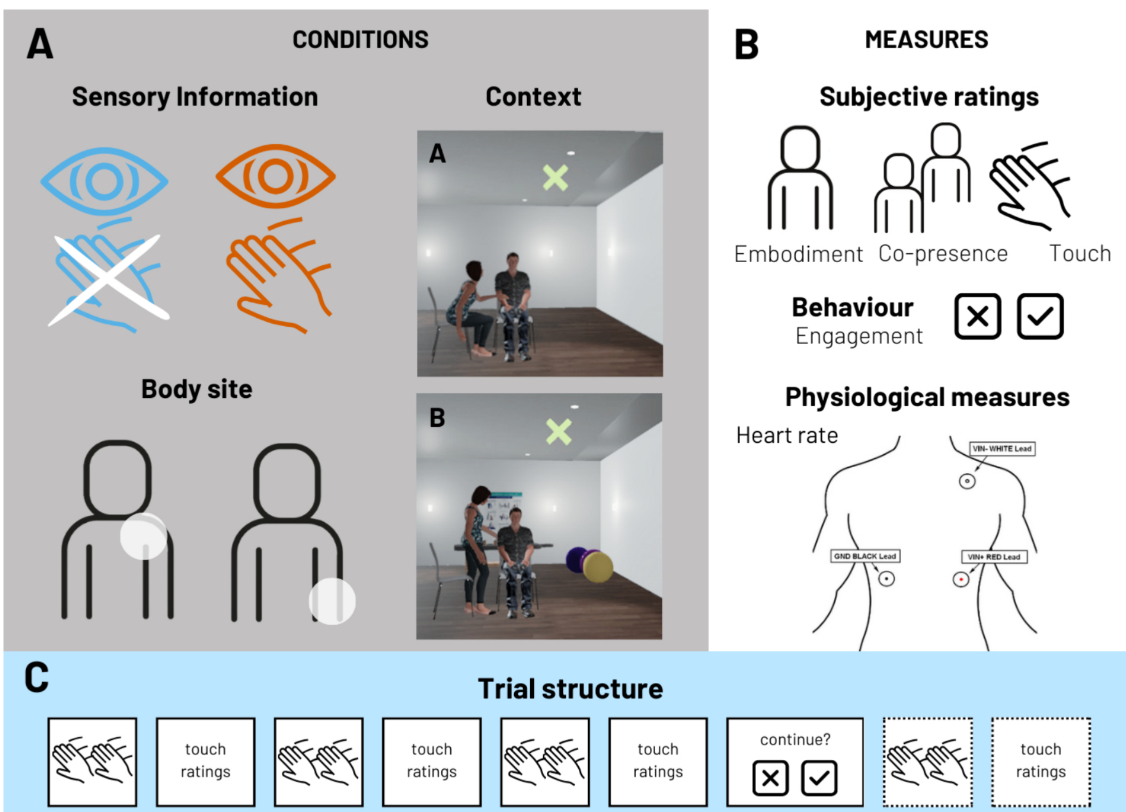

Fig. 2 Study Design. (**A**) Conditions. On the left the within-subjects conditions: *Sensory information* (visual only vs. visuo-tactile) and *Body site* (back vs. arm), and on the right the between-subjects condition of *context*, which depicts also the VR scene neutral (top) and clinical (bottom). A male participant embodied in a gender-matched virtual body seeing himself from a first-person perspective (1PP) as reflected in the mirror in front of him, fixating on the green cross while the virtual woman delivers touch on his forearm (top) versus on his back (bottom). (**B**) Measures, including subjective ratings related to embodiment, co-presence, and the *pleasantness* and *realness* of a touch event. At the behavioural level, participant's willingness to continue was taken as an index of *engagement*. A representation of the electrodes positioning to record *heart rate*. (**C**) Visualisation of **trial structure**

3.5 Physiological Measures

We measured heart rate (ECG) as a physiological index of parasympathetic nervous system activity (Pawling et al. 2017). Participants were asked to place three disposable electrodes on their upper body, and two on the foot as shown in Fig. 2B. Conductivity gel was applied to each electrode before they were adhered to the skin. The disposable electrodes were then connected to a data recording and analysis system (BIOPAC) using a connecting cable. BIOPAC then started. After the start of recording, participants were given 3 min or longer to rest, so that their heart rate would return to a normal resting level. Data were collected during the entire experiment. Timestamps separated each block and each trial, so that they could be clearly assigned during analysis.

3.6 Apparatus

The experiment was conducted in a VR lab and participants were equipped with the VIVE Pro 2 headset (https://www.vive.com/us/product/#pro%20series). This has dual RGB low persistence displays with 120° (degrees) horizontal field-of-view (FoV) and a resolution of 2448 × 2448 pixels per eye. Two hand-held controllers with SteamVR tracking 2.0 sensors were used for upper body (arms, torso) tracking. The virtual environment was implemented on the Unity 3D platform (https://unity.com/) using the QuickVR library (Oliva et al. 2022). The virtual characters were taken from the Microsoft Rocketbox Avatar Library (Gonzalez-Franco et al. 2020). The virtual touch animation was recorded with the Glycon3D (https://www.glycon3d.com/) software and edited in Autodesk MotionBuilder 2019 (https://www.autodesk.com/products/motionbuilder).

The BIOPAC (https://www.biopac.com) data recording and analysis system for life science research was used (BIOPAC Systems, 2017). Physiological data were collected using MP160 at a sampling rate of 1000 frames per second.

3.7 Procedures

Upon arrival, participants were given the study information sheet. After they agreed to continue with the experiment and signed the informed consent form, they completed the pre-VR questionnaire as described in the Measures section. Next, they were seated in a chair, and disposable BIOPAC electrodes were attached to their body and foot. They were then equipped with the VR headset and controllers and after the physiological recording software was calibrated, the VR experience started.

Participants entered a virtual room that was decorated accordingly for the neutral vs. the clinical context (Fig. 1). They embodied a gender-matched avatar, seen from a first-person perspective (1PP). The participants' head and upper body movements were mapped in real-time to the virtual body. They could see their virtual body by looking down directly towards it, also reflected in a virtual mirror that was placed in front of them. During the initial familiarisation phase, participants found themselves alone in the virtual room, and they were instructed through audio recordings to perform a set of exercises with their upper body while remaining seated, as well as to explore the room around them and describe what they saw. They were also trained to use the hand-held controllers to answer the questionnaires that would appear to them later during the experience. Next, the screen faded out. When it faded in again, the virtual female agent appeared in front of them, welcoming them to the study and giving them instructions on how to proceed. In the neutral condition, the virtual agent introduced herself as follows: *"I hope you are having a wonderful day. Today we want to carry out different kinds of touch*, *which you will later evaluate …"* whereas in the clinical condition, the virtual agent additionally introduced her role as: *"I hope you are having a wonderful day. I am your physiotherapist today. Today we want to carry out different kinds of touch*, *which you will later evaluate …"*. The rest of the script was identical for both setups. Then the experimental blocks were presented in a randomised order as introduced earlier. Each trial was composed of a fixation phase (1-2 s) and a touch phase (approx. 8 s), and an inter-trial interval (approx. 10 s). For every second trial, the Touch items of the VR Questionnaire (Supplementary Material Table S1) was presented (approx. 10 s) before the inter-trial interval. Each pair of trials lasted approximately 40–45 s, and the sequence was repeated until the end of the block. During the fixation phase, the fixation point marked with X on the virtual mirror lit green, accompanied by a word stimulus (arm or back) informing the participants the location on which they had to focus while the visual touch was performed by the virtual character (touch phase). During this time, the experimenter performed either physical touch on the arm or back that matched the visual output or did not perform touch at all according to the experimental block. Every 2 trials after the touch phase, the touch questionnaire appeared on the virtual board next to the participants, and they were prompted to submit their ratings. After the sixth trial, participants were asked if they would want to continue for two additional trials. Acceptance of additional trials is used as a measure of *engagement*. At the end of each block, participants completed the Questionnaire items related to embodiment and co-presence (Supplementary Material Table S1). The whole procedure lasted approximately 45 min, with each block lasting 7–10 min. The headset was then removed with the help of the experimenter and participants were debriefed. For additional details on the procedures, see supplementary MovieS1.

3.8 Data Analysis

3.8.1 Preprocessing

All data were then analysed using open-source R software version 4.2.2 (R Core Team, 2022). Questionnaire data were organised and directly used for analysis. Participants' electrocardiograms (ECG) were first processed in AcqKnowledge 5.0.6 (https://www.biopac.com/product/acqknowledge-software*)*. The ECGs were bandpass filtered between 0.1 Hz and 30 Hz offline, and an algorithm identified R peaks, time between adjacent R peaks in ms, and heart rates. The data were then analysed using R. Time period for each trial was identified using timestamps from AcqKnowledge and Unity. The mean heart rate for each trial and all trials in each condition were calculated based on R peaks within given time windows. For each participant, heart rate values within trial windows falling outside 3 standard deviations from the mean were identified and replaced by a non-artifactual mean[1]. The heart rate data were then entered into regression models.

3.8.2 Variables

The dependent variables of interest are block ratings of embodiment (*ownership*, *features*, and *agency*), co-presence (*realisticavatar* and *interaction*), and trial ratings of touch (*pleasantness* and *realness*) (see Supplementary Material Table S1), as well as heart rate. The variables *ownership* and *agency* were used to capture the level to which participants experienced illusory ownership over the virtual body and agency over the virtual body's movements, which together contribute to embodiment. *Ownership* was calculated as a new variable from the questionnaire variables *ownbody* and *notme* (Table S1) as the mean of *ownbody* and *notme*, where *notme* is a control question and represents a reverse-scored version of the variable *ownbody*. The variable *features* is considered a control question to the illusion and refers to the extent to which participants affirmed that the virtual body had physical features in common with themselves. Based on previous research, we expected to find no difference among conditions with respect to *ownership*, with generally high ratings. For co-presence, *realisticavatar* was calculated as a mean of the *realisticmovement* and *realperson* (Table S1).

The main predictors of interest include *sensory information* (2-level, within-subjects categorical factor of available sensory information: visual only or visuo-tactile), *body site* (2-level, within-subjects categorical factor of body site: arm or back), and *context* (2-level, between-subjects categorical factor: neutral or clinical). We also included *gender* (female or male) as a predictor, and included the random effect of participants to account for the repeated-measure design of the experiment (sensory information and body site are within-subjects conditions).

3.8.3 Statistical models

Separate sets of Linear Mixed Effect Regressions (LMERs) were used to test whether each dependent variable is affected by the predictors of interest. With a model comparison method, we first assessed whether the factors *sensory information* and *body site* interacted with each other. For this, we computed Schwarz's Bayesian Information Criterion (BIC) for each regression model, with and without an interaction term between *sensory information* and *body site*. All models without the interaction term resulted as the most plausible ones (lower BIC) and have been used in the main analyses (see Supplementary Material Table S3). Therefore, the models include main, additive effects of all fixed (*sensory information*, *body site*, *context*, *gender*) and random (*participant*) effects. The default baselines for comparison are visual only for *sensory information*, arm for *body site*, neutral for *context*, and female for *gender*.

4 Results

4.1 Multisensory virtual interpersonal touch influences how we feel about ourselves and others

To measure the quality of the virtual reality experience, we ran a set of LMERs for participants' ratings at the end of each block for embodiment (*ownership*, *agency*, and *features*) and co-presence (*realisticavatar*, and *interaction*) (Table S1). The mean and SD for each rating can be found in Supplementary Material Table S2.

In the visuo-tactile condition, participants gave higher ratings for *ownership* ($\beta = 0.711$, $SE = 0.134$, $p < .001$), *features* ($\beta = 0.200$, $SE = 0.095$, $p = .038$), *realisticavatar* ($\beta = 0.594$, $SE = 0.109$, $p < .001$), *interaction* ($\beta = 1.036$, $SE = 0.124$, $p < .001$), but not for *agency* ($\beta = 0.107$, $SE = 0.115$, $p = .351$).

Context (neutral or clinical) did not have any effect on block ratings.

Body site (arm, back) and *gender* had no effect on most block ratings. One exception is *realisticavatar*, for which participants gave higher ratings for the back ($\beta = 0.251$, $SE = 0.109$, $p = .023$), and overall male participants gave lower ratings ($\beta = -1.137$, $SE = 0.367$, $p < .01$).

[1] We used this replacement method following Pawling et al. (2017). We acknowledge this is not standard in ECG analysis.

Figure 3 shows the effects of *sensory information* and *body site* on the 4 ratings. See Supplementary Material Table S4 for a full report of results.

4.2 Multisensory experiences of interpersonal touch influence how it is evaluated

To determine how the multisensory nature of a virtual touch event was evaluated, trial ratings of subjective *pleasantness* and *realness* of the touch events were presented and analysed. We ran a set of LMERs for participants' trial ratings during each block. The mean and SD for each rating can be found in Supplementary Material Table S2.

As *realness* ratings for visual only and visuo-tactile conditions are clustered at two extremes, our LMER may have resulted in an overfit. In order to validate the effect of factors, we ran an additional Two-way Repeated Ordinal Regression (2WROR) for realness, where *realness* ratings are treated as an ordinal factor. While LMER is particularly suitable for continuous or categorical data, the 2WROR is specifically designed for ordinal data, where categories have an intrinsic order but are not equidistant. The latter statistical approach helps us overcome the issues resulting from the assumption of linearity and having a limited discrete scale with clusters extremes. Full results from both methods are presented in Supplementary Material Table S5.

In the visuo-tactile condition, participants rated touch as higher in *pleasantness* ($\beta = 1.594$, $SE = 0.091$, $p < .001$), and higher in *realness* (LMER: $\beta = 4.087$, $SE = 0.077$, $p < .001$; 2WROR: $\chi 2 = 947.27$, $p < .001$). Touch on the back is rated as slightly more pleasant ($\beta = 0.183$, $SE = 0.091$, $p = .044$). *Context* and *gender* did not have an effect on ratings of *pleasantness* nor *realness*. Figure 4 visualises the effects of *sensory information* and *body site* on the two ratings. See Supplementary Material Table S5 for a full report of results.

4.3 Multisensory touch experiences enhance engagement

As an implicit measure of engagement, participants were given the choice to continue for two additional trials at the end of each block. To determine what factors influence engagement, we performed a Mixed Effect Logistic Regression (MELR), predicting engagement (choice for more

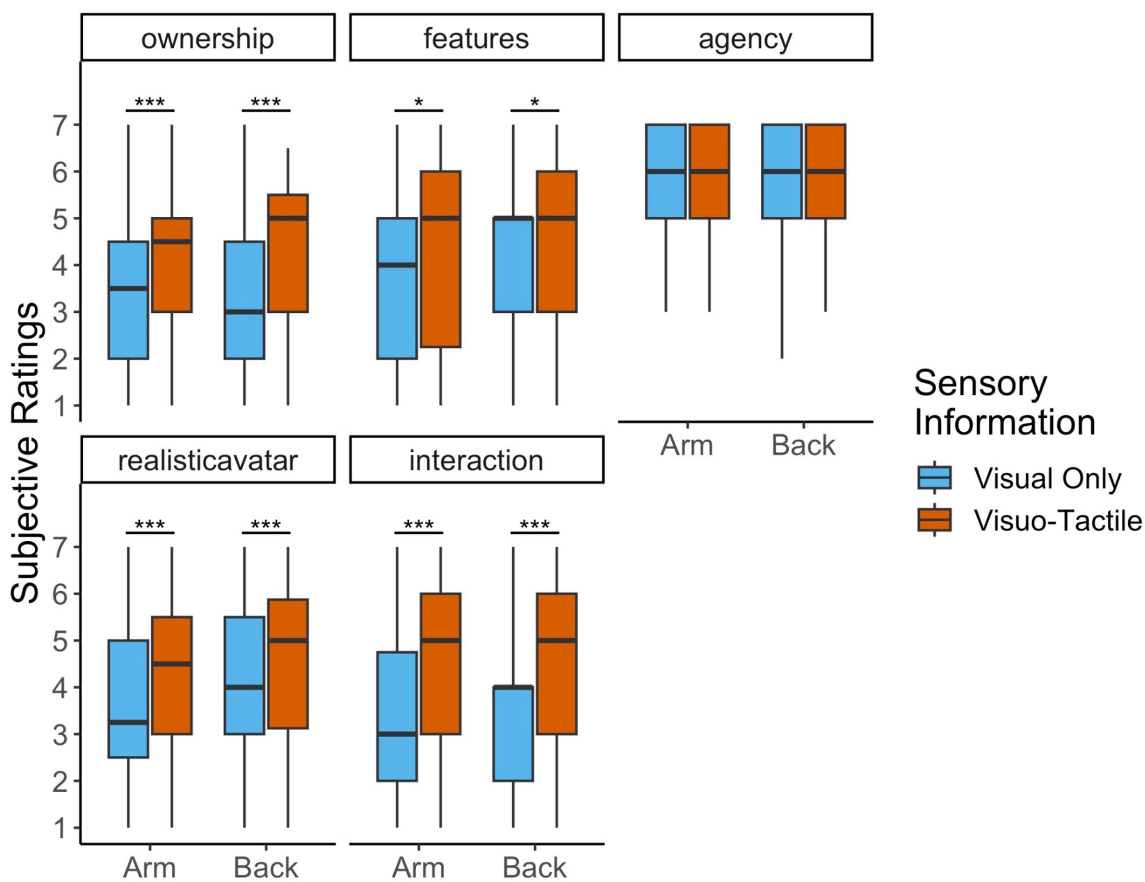

Fig. 3 Box plots of the post-VR questionnaire by *sensory information* and *body site*. The ratings relate to embodiment and co-presence (Table S1). The thick black horizontal lines are the medians, the boxes are the interquartile ranges, and the whiskers extend to ± 1.5 × IQR, or the range. Significance levels depict the results from LMERs reported in Supplementary Material Table S4

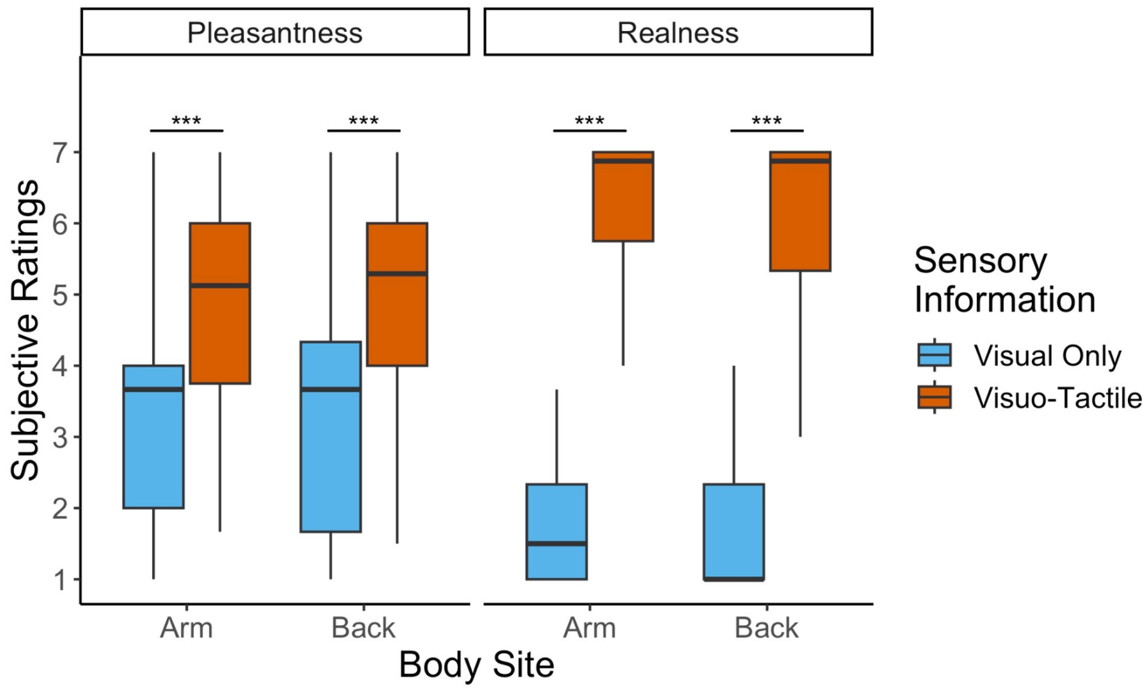

Fig. 4 Box plots of the post-VR questionnaire on *sensory information* and *body site* on *pleasantness* and *realness*. The thick black horizontal lines are the medians, the boxes are the interquartile ranges, and the whiskers extend to ± 1.5 × IQR, or the range. Significance level depicts the results from a LMER for pleasantness and 2WROR for realness in Supplementary Material Table S5

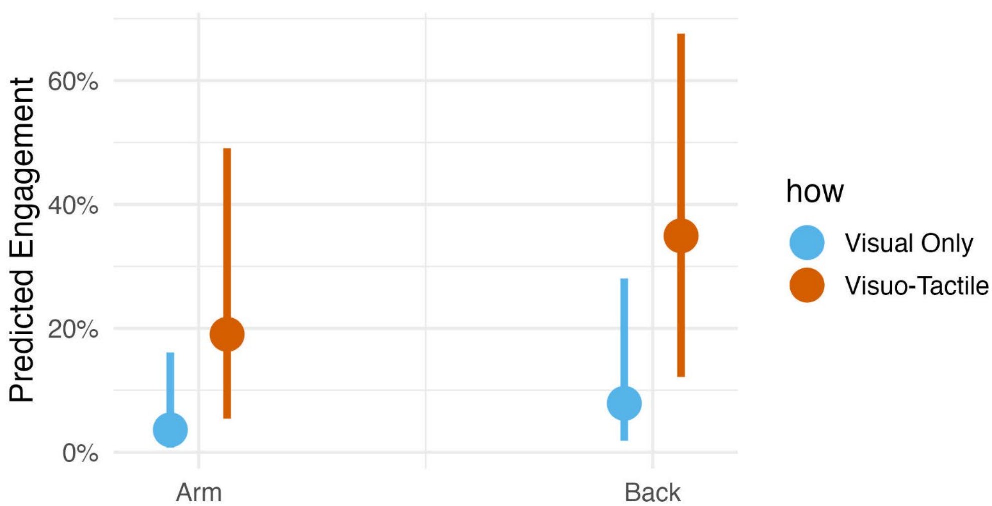

Fig. 5 Predicted probability of engagement in additional trials according to different *sensory information* and *body site*. The results depict the predicted outcome of a Mixed Effect Logistic Regression detailed in Supplementary Material Table S6. The central dots represent the predicted means, and vertical line segments represent 95% confidence intervals

trials) as a factor, with *sensory information*, *body site*, *context*, *gender*, and with random individual effects.

The analysis revealed that participants are more likely to engage in additional trials in the visuo-tactile condition ($\beta = 1.835$, $SE = 0.465$, $p < .001$), and the effect is highly significant. When touch is delivered to the back, participants are also more likely to engage in additional trials ($\beta = 0.826$, $SE = 0.415$, $p = .046$). *Gender* and *context* show no significant effects. Figure 5 visualises the effects of *sensory information* and *body site* on our implicit measure of engagement. See Table S6 in Supplementary Material for a full report of results.

4.4 Physiological responses to multisensory touch experiences in VR

Beyond the observed difference in perceived pleasantness for multisensory touch events, we investigated changes in physiological arousal in response to affective touch in a virtual environment. Specifically, we collected heart rate data to probe whether a CT-mediated decrease in heart rate typically associated with affective touch would also be found for touch encounters in VR. For this, we ran an LMER to determine the effect of *sensory information*, *body site*, and *context* on participants' mean heart rate during each trial, controlling for participants' *gender* and individual variability (*participant*).

In the visuo-tactile condition, we observe lower mean heart rates (β=-2.206, $SE = 0.482$, $p < .01$) compared to the visual only condition. *Body site*, *context*, and *gender* do not have any significant effects on heart rate (Fig. 6). See Table S7 in Supplementary Material for a full report of results.

Additionally, in order to investigate whether changes in heat rate are predicted by ratings of pleasantness or realness, we performed LMERs based on mean heart rate and ratings per condition, with the random effect of participants to account for individual variability. Given that previous models show that *body site* has no effect on heart rate, and that *sensory information* has strong effects on both heart rate and ratings, we also included a random individual slope for sensory information in order to control for its effect. Both *pleasantness* and *realness* are negatively associated with heart rate (pleasantness: β=-0.624, $SE = 0.187$, $p = .001$; realness: β=-0.414 $SE = 0.110$, $p < .001$). This general trend is not affected by *body site*, *sensory information*, *context*, *or gender* (see Fig. 7 and Table S8 in Supplementary Material for a full report of results).

5 Discussion

The present study investigated how affective touch is evaluated in immersive virtual contexts where different social norms may apply, such as a neutral environment or an environment described as a physiotherapy room where the toucher is a healthcare professional. We explored the contribution of sensory properties of an affective touch encounter that is delivered only visually or one in which both visual and tactile feedback is presented, and where touch is delivered either to the participants' arm or back. We investigated how these contextual aspects influence implicit engagement, self-reported embodiment, co-presence, as well as how realistic and pleasant the touch experience was. Furthermore, we delved into the CT-mediated physiological effect of touch on heart rate and controlled for potential gender differences.

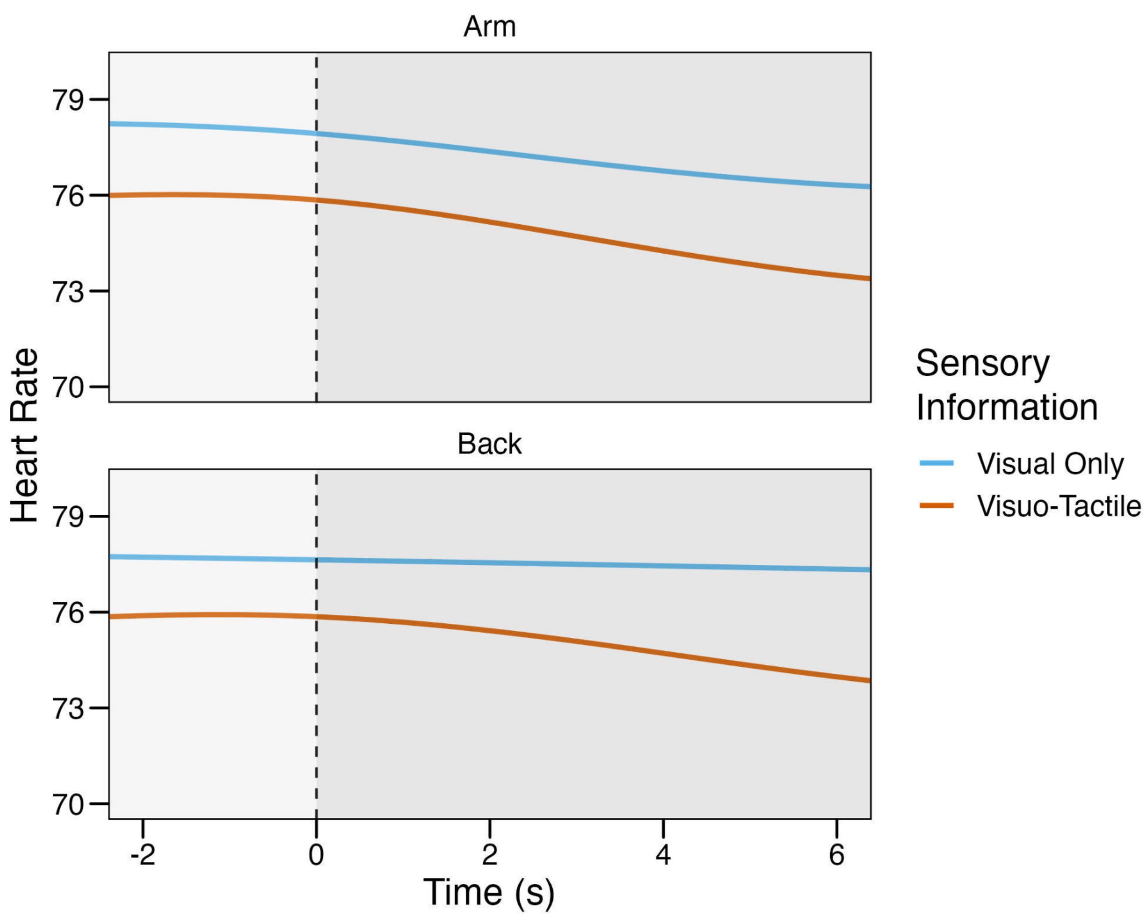

Fig. 6 Heart Rate responses to multisensory touch experiences in VR over time by sensory input. Smoothed conditional means of participants' heart rate during touch trials (Time), in each *sensory information* and *body site* conditions. Data from Generalised Additive Model. The x-Axis shows the time to trial onset, measured in seconds

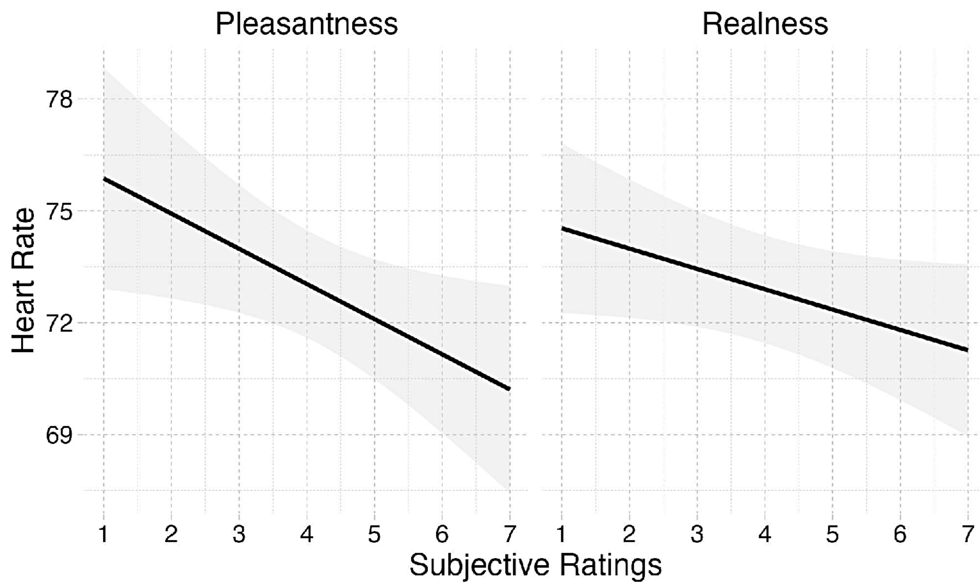

Fig. 7 Relationship between Mean Heart Rate, and Subjective Ratings of *Pleasantness* and *Realness*. Black lines represent estimated linear regression lines, accompanied by zones depicting 95% confidence intervals

5.1 The self and the other

Affective touch is by its very nature interactive (Huisman 2022). Its inherent mutuality makes it special because it reduces self-other boundaries, and simultaneously increases the salience of somatosensory information about one's bodily and internal status (Gentsch et al. 2016; Panagiotopoulou et al. 2017), while also making the presence of the other very vivid, thereby modulating one's perception of social cues from very early in infancy (Della Longa et al. 2019). Starting from the *self*, our results on embodiment indicate that participants experienced higher ownership over the virtual body in visuo-tactile vs. visual only conditions. On the other hand, unlike de Jong et al. (2017), we did not find any effects of touch on agency, perhaps because of methodological differences. In our study, touch was applied with the same stroking speed across conditions (unlike fast vs. slow stroking in the referenced study). Notably, participants could move during the embodiment instructions and their movements were always in synchrony with their avatar's movements, which usually is sufficient to raise a strong illusion of agency. Moreover, the absence of an effect of body site on embodiment does not support the hypothesis of a body-part specific influence of affective touch in enhancing multisensory integration (Carey et al. 2021). Looking at how the *other* (i.e., the toucher) was perceived, we found that the visuo-tactile condition, compared to the visual only, increased the realism of the virtual character and the interaction with her. This corroborates existing evidence that mediated social touch increases the subjective human-likeness of virtual agents (Hoppe et al. 2020).

5.2 Multisensory touch: more is more

Participants in the visual only condition reported touch events to be less pleasant and less real, in comparison to the visuo-tactile touch condition. Additional tactile input through experimenter touch increases both how real and how pleasant the touch event is rated. Also, touch on the back was rated as slightly more pleasant than touch on the arm. Moreover, touch in the visuo-tactile condition was associated with lower heart rate compared to the visual only condition. This expands on previous literature looking at the physiological effects of painful or affective touch in VR, where no haptic input was provided (Fusaro et al. 2016). Our results highlight that affective touch is a multisensory experience where *more is more*, and confirm that visuo-tactile (compared to visual only) stimulation leads to an overall higher quality of a virtual experience (Apostolou and Liarokapis 2022; Maunsbach et al. 2023). Beyond confirming previous findings on the soothing effects that affective touch has on heart rate in real environments (Triscoli et al.), our findings show that this is also true for touch in virtual environments, specifically when haptic input is provided. This underlines the importance of bringing the whole multisensory experience of affective touch into hybrid social interactions, where visual information may not be enough to elicit the associated complex neurophysiological mechanisms (Eid and Al Osman 2015). As Della Longa et al. (2022) propose, interpersonal virtual touch may positively impact virtual social exchanges, promote social presence and connection, and potentially reduce sensory loneliness. Our results suggest that to observe these benefits of touch, some sort of affective haptic feedback is necessary, and relying solely on visual input may not be sufficient to derive the maximum benefits of interpersonal touch. As a result, researchers are tasked with the challenge of discovering effective haptic solutions that go beyond discriminative feedback to object exploration but can authentically emulate and convey the social features of touching and being touched by another person (Price et al. 2021, 2022).

One limitation of this interpretation is the challenge in distinguishing between multisensory input and touch specifically. The experimental conditions involve the addition of touch alongside visual stimuli. The absence of a tactile-only condition makes it difficult to isolate the unique contribution of touch to the observed effects. Moreover, future research may use alternative comparisons with different sensory modalities (e.g., audio-visual vs. visual-only conditions) to provide insights into the importance of multisensoriality in shaping virtual experiences. A novel approach for incorporating touch in VR, without relying on haptic systems, is through the use of pseudo-haptics, which leverage sensory substitution and augmentation to provide audio-visual cues to touch and proximity, thus creating illusions of interpersonal touch (Desnoyers-Stewart et al. 2023).

5.3 Psychometric challenges and limitations

An interesting challenge to investigating social touch in VR is how to measure the touch experience, since self-reported measures may be biased and the responses may vary significantly depending on participants' prior knowledge of a system's capabilities (such as expecting touch).

In our study, we wanted to examine whether visual feedback alone is adequate, as well as how touch is experienced (whether it is pleasant or not) concerning both the identity of the touch provider and the naturalness of the virtual touch. We employed the implicit measure *engagement*, indicated by whether participants opted for additional touch trials. We have used the term because opting to persist or invest more time suggests that participants did not find the task unpleasant, and preferred to further interact within the VR environment. This served to ascertain if, in addition to increased ratings of pleasantness regarding the touch, there are concurrent behavioural shifts alongside measured physiological responses. We did find that in the visuo-tactile condition the probability of complying was higher.

We acknowledge that engagement can also be measured by other means. Indeed, engagement in VR has been assessed through various means in research studies, including behavioural correlates. For example, Hassan et al. (2020) delved into the correlation between flow in VR (where individuals are deeply absorbed in activities that pique their interest) and the inclination to persist in VR usage and prolong sessions. Similarly, Jo and Park (2023) suggested that the intention to continue (referred to as sustaining VR engagement) can be influenced by perceived usefulness and enjoyment, among other factors. Nonetheless, although our implicit measure corroborates the results obtained with the questionnaires and physiological data, it is limited in terms of its internal validity and requires more studies, perhaps integrating additional behavioural measures such as eye tracking, which could provide deeper insights into participants' actions.

5.4 Unexpected findings and future perspectives

Interpersonal touch always happens in a particular sociocultural context and evokes individual differences, which shapes its meaning and acceptability (Gallace and Spence 2010). One unexpected finding was that male participants perceived the other avatar as slightly less realistic. Previous findings suggest that gender plays an important role in the evaluation of avatars, particularly when avatars are used to communicate emotions (Bailey and Blackmore 2017; Bailey et al. 2021). Additionally, to our surprise, in our results, context did not have any significant effects on ratings of the experience or heart rate. Social context, that is "who" is touching us and our relationship to them, plays a significant role in how affective touch is perceived (Sailer and Leknes 2022), with higher pleasantness in an intimate or romantic context, such as between partners and family members, and lower pleasantness in situations where there is little or no familiarity (Suvilehto et al. 2015). However, touch from a stranger can still be pleasant in specific contexts where social norms make it appropriate. For instance, in a physiotherapy room, affective touch may be associated with therapeutic treatment aimed at improving health and well-being. In this case, touch may be evaluated as pleasant because it is seen as part of a healing process. Although we expected the context (neutral vs. clinical) to modulate pleasantness ratings, it had no influence on the quality of the virtual experience, including the interaction with the other character, nor the pleasantness of touch. Our results do not support the hypothesis of a less ambiguous context (i.e., physiotherapy room and touch from a physiotherapist) being associated with increased touch pleasantness. This may be caused by our two contexts not being sufficiently different, the clinical context not characterised or salient enough, or the influence of testing being conducted in a laboratory. It may also be a ceiling effect due to the touch being already experienced as pleasant, even in the more ambiguous neutral context. Similarly, we did not find any gender effect, which may have been predicted based on Russo et al. (2020), whose meta-analysis found a preference for affective touch in women. Despite being unfamiliar, in all cases the toucher was a female avatar, and it is well established in literature that touch from women is more pleasant than touch from men (Gazzola et al. 2012). Therefore, we may have found greater context and gender differences for a touch delivered by a male avatar, which is the subject of future investigation.

In the present work, we used the type of affective touch that is classically associated with the activation of CT afferents (gentle stroking at optimal velocity on areas of the skin with a high density of CT fibers). Recently, there has been a growing interest in broadening the focus to a wider spectrum of tactile gestures with affective meanings, going beyond the gentle stroking that has long been studied as optimal for activating CT afferents. Research showed that the combination of several physical parameters of touch, such as velocity, amplitude, intensity (or amount of force applied), duration, body site, type of touch (e.g., holding, shaking, tapping, stroking, squeezing, poking) and temperature affect the individual's emotional experience of social touch (Schirmer et al. 2023). For example, someone holding another's arm with their whole hand could be perceived as communicating sadness, a gentle stroking may be comforting and a fast tapping with multiple fingers could express happiness (McIntyre et al. 2022). Given the diversity of multisensory processes in immersive VR, we may ask whether optimal affective tactile interactions in this environment may be different from those that people adopt and prefer in real-world settings. For instance, previous studies in the literature found mixed results about the optimal velocity of affective touch to promote embodiment in VR, with no clear benefit of CT-optimal touch (Bourdin et al. 2013; de Jong et al. 2017; Carey et al. 2021). Further studies are needed to delve into the optimal characteristics of interpersonal touch in VR, exploring various touch gestures, social contexts, and individual differences to unveil the full potential and perhaps limitations of virtual affective touch. This will gain greater prominence in the coming years, especially with the growing prevalence of VR devices in domestic settings and the increasing accessibility of online social VR platforms that enable individuals to interact with others within diverse contexts and across various cultural backgrounds.

Enhancing social touch experiences in VR offers practical implications across various domains, including healthcare, mental health, education, and edutainment. In healthcare, VR can aid remote rehabilitation by providing tactile feedback and guidance when assisting patients with motor impairments. Similarly, within mental health practices, immersive VR environments with realistic social interactions and touch can provide interventions for conditions benefiting from social skills development and interventions to body-related representations. In education and edutainment, VR-based simulations can enrich learning experiences by incorporating social touch in collaborative activities and team-based tasks, fostering engagement and skill acquisition. Moreover, VR offers opportunities for immersive training scenarios focusing on interpersonal communication and coordination through realistic social touch interactions in team cooperation and joint activities. By prioritising the refinement of social touch interactions in VR, various fields can harness the technology's potential to enhance human connection and interaction across diverse practical contexts.

6 Conclusions

The significance of social touch is indisputable, and with the increasing extension of social interactions into the realm of cyberspace, including immersive VR and metaverses, the role of mediated social touch will become a key element in fostering meaningful affective relationships and social interactions among people. Our study has demonstrated the necessity of a complete multisensory experience as a means to achieve this goal. These observations are particularly relevant to sectors such as the gaming industry and business - two areas in which building and maintaining cohesive teams is crucial for success. Extensive and fully embodied immersive interactions within 3D spaces can be particularly significant for the youngest generation. Given their upbringing in a digital age where XR technologies are becoming increasingly integrated into their daily lives, such immersive interactions hold the promise of addressing pressing contemporary challenges such as mental health issues and teenage isolation. To realise this potential, it is imperative to invest significantly in enhancing and enriching tactile experiences and gain a more comprehensive understanding of how diverse social situations influence the evaluation of such experiences. Future studies aimed at the analysis of the social context in touch perception may benefit from applying more various types of touch and avatars to understand how different social contexts shape the virtual touch experiences.

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Data Availability The data can be provided by the authors upon request.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial, financial or non-financial relationships that could be construed as a potential conflict of interest.

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