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iPillowPal: Exploring affective gesture-based interactive textile design for long-distance relationship couples

Mengqi Jiang [a], Vijayakumar Nanjappan [b,c], Ziming Li [d], Zhen Wu [e], Ziqian Bai [f], Hai-Ning Liang [d,*]

[a] *Future Design School, Harbin Institute of Technology (Shenzhen), Shenzhen, China*
[b] *School of Computer Science and Information Technology, University College Cork, Ireland*
[c] *Center for Ubiquitous Computing, University of Oulu, Finland*
[d] *Computational Media and Arts Thrust, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, China*
[e] *Division of Integrative System and Design, The Hong Kong University of Science and Technology, Hong Kong, China*
[f] *School of System Design and Intelligent Manufacturing, Southern University of Science and Technology, Shenzhen, China*

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ABSTRACT

People in long-distance relationships (LDR) often experience deprivations of somatosensory interaction for intimate communication. Researchers have used affective gestures to mediate emotional requirements and physical constraints. However, most studies focused on gestures, such as hugs or touches, which may not fully represent the characteristics of gesture-based interactions in LDR. We explore the affective gestures that people perform and develop connections in LDR communication, engagement, and interaction. This research includes three phases: user interview, lab experiment, and field experiment. First, we interviewed LDR couples to investigate their experiences and perceptions of affective gestures. The results revealed that affective gestures varied depending on the scenario and generated specific emotional responses. Then, we selected Poke, Stroke, Pull, and Hug as affective gestures and designed four gesture-based textile interfaces with two interaction modes to encourage LDR couples to participate in embodied interaction and observe what emotional connections and experiences they elicit. Last, we designed *iPillowPal*, a gesture-based interactive pillow, and had LDR couples use it daily to probe in-situ user experience. Our results show that *iPillowPal* shortened LDR couples' emotional distance and improved their emotional state. The findings contribute to the understanding of mediated affective gesture-based interaction and interactive textile design for LDR interaction.

1. Introduction

Long-distance relationships (LDR) are prevalent among couples/partners who are separated by geographic distance, work patterns, and individual circumstances (Stafford, 2004). Couples/partners are often defined as "being together" in a temporal and spatial sense, which is called short-distance relationships (SDR), while long-distance couples/partners contradict this definition by spending at least some of their time apart and in separate spaces (Kolozsvari, 2015). Dainton and Aylor also defined LDR as couples/partners with limited face-to-face contact (Dainton and Aylor, 2002). LDR in this work refers to couples/partners who have some temporal together sense but have limited spatial contact. LDR challenges their social and emotional bonds and well-being. Humans are exposed to many types of social and physical touches since childhood (Wang and Quek, 2010). Studies have indicated that interpersonal physical contact is essential in developing cognitive and socio-emotional skills (Andersen and Guerrero, 2008). Light et al. (2005) studied partner hugs, linked to higher oxytocin levels and lower blood pressure. Different touch gestures (e.g., patting, stroking, hugging, squeezing, poking, and jabbing) can have strong instant affective consequences (Vetere et al., 2005; Rico and Brewster, 2009). People in LDR suffer from the deprivation of such affection, contact, and bonding, and they have difficulties communicating emotions with current technologies (Rognon et al., 2022).

Mediated social touch is defined as the ability of one actor to touch another actor over a distance using tactile or kinaesthetic feedback technology (Haans and IJsselsteijn, 2006). People use either explicit somatosensory actions or gestures (e.g., handholding, stroking, or hugging) or implicit ones (e.g., heart rate, sleep patterns) as a kind of mediated physical contact (Hassenzahl et al., 2012; Singhal et al., 2017; Werner et al., 2008), allowing users to see, hear and feel their distant

* Corresponding author.
E-mail address: hainingliang@hkust-gz.edu.cn (H.-N. Liang).

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loved ones (Li et al., 2018). Haans et al. (2007) revealed that mediated social touch is perceived just like unmediated touch.

Various mediated social touch solutions have been proposed in recent years to bridge the emotional and social gaps among LDR couples. Daily wearable products such as gloves (Gooch and Watts, 2012), jackets (Vetere et al., 2005), and armbands (Wang and Quek, 2010) were used as the mediums for delivering "physical contact" to complement conventional communication via mobile phones or similar devices (Mullenbach et al., 2014). In particular, 'meaningful' gestures were favoured in mediated touch interaction (Nunez et al., 2019). For example, the hug is a typical gesture used in conveying affection, as summarized in Angelini et al. (2014), which also includes several instantiations such as *Huggy Pajama* (Teh et al., 2008), *HaptiHug* (Tsetserukou, 2010), *Hug over a distance* (Vetere et al., 2005), *HugMe* (Cha et al., 2008), and *Hugginess* (Angelini et al., 2014). Other gestures have been designed in LDR-mediated touches like squeezing a partner's arm through an armband (Wang and Quek, 2010) or using gloves to experience holding hands (Gooch and Watts, 2012). Although multiple gestures have emerged in affection communication, most research on LDR gestures focuses on mediated hugging or touching. As mentioned in Angelini et al. (2014), gestures such as squeezing, stroking, and patting could be used to support emotional communication between remote users but have not yet been utilized. Gesture-based textile interfaces enable us to communicate with remote partners in novel ways, but they also necessitate considerations on how to design gesture-based textiles, how we feel about these textile interfaces, and which gestures are regarded as acceptable and appropriate (Gooch and Watts, 2012).

This research intends to investigate mediated affective gestures among LDR couples and probe the design opportunities for interactive textile interfaces that can mediate this communication. It should be noted that the term "*gesture*" in *mediated affective gesture* in this work refers to gestures that interact with an interface via hand actions, not tactile sensation.

We aim to **design an interactive textile prototype that allows communication via remote presence, evokes an emotional connection, and creates an emotional experience for LDR couples via affective gestural interactions.** To do this, this research has gone through three phases (see Fig. 1):

- *Study 1: User interview – Identifying the missing affective gestures in LDR and their corresponding affections and scenarios.* To identify the absent affective gestures among LDR couples, we designed a semi-structured interview to ascertain two aspects: (1) What types of gestures couples perform in SDR and LDR, and (2) in which scenarios are they used, and what affection would each gesture elicit?
- *Study 2: Lab experiment – Investigating affective gesture-based interaction on textile interfaces.* We designed four affective gesture-based textile interfaces and compared their emotional impact on potential LDR users in two interaction modes. In this experiment, we explored three aspects: (1) How to design textile interfaces that support gesture interaction for LDR couples; (2) how interactive gestures and interfaces influence LDR couples' emotional connection and experience in the lab; (3) What impact affective gesture-based textile might have on people in their daily lives.
- *Study 3: Field trial – Designing iPillowPal, probing user experience and feedback.* Based on the results of the lab experiment, we designed *iPillowPal* and sent it out to LDR couples to use for a seven-day in-situ experiment to probe: (1) When, where, and how LDR couples interact with their partners using *iPillowPal*; (2) How *iPillowPal* influences users' emotions; and (3) What are their perception of it and feedback after using *iPillowPal* for seven days.

There are three critical areas to which this research makes an original contribution:

- *Revealing affective gestures in LDR.* Five distinct affective gestures were identified from LDR couples in the user study, and the results showed that affective gestures vary for each scenario, serve a specific emotional purpose, and generate a particular emotional response.
- *Affective gesture-based interactive interfaces and iPillowPal designed for LDR.* Four textile interfaces and one interactive pillow prototype were developed to support affective gesture-based interaction with gesture affordance and feedback. The textile interfaces and *iPillowPal* also facilitated our understanding of the LDR user experience, user behaviour, and feedback from the lab experiment and seven-day in-situ field trial.
- *Design implication of affective gesture-based interaction and emotional interaction design for LDR.* From the three study results, we derive design implications for affective gesture-based interaction based on gesture type, interaction scenario, emotional impact, and user perception. These implications could also apply to not only LDR intimate couples but also to those in other types of relationships, such as friends and parent–child.

2. Related work

2.1. Gestural interaction for LDR

Novel input methods, which adopt gestures and natural interactions with real-world items instead of buttons or touch screens, have been developed as gestural interfaces (Dong, 2019; Wicaksono and Paradiso, 2017; Jiang et al., 2022; Huisman, 2012). With gestural interfaces, users can reach a higher level of sensation and engagement because they require bodily interaction and provide users with natural tactile sensation (Norman, 2010). Implementations that support gestural interaction have been utilized to mediate remote communication (Gansohr et al., 2016; Stawarz et al., 2012). However, there is still a gap in our understanding of what type of gestures people make when interacting with interfaces designed to communicate affective information and their emotional response to these gestures (Giles and van der Linden, 2014), especially those that can bridge emotional and physical gaps that LDR couples often face (Hassenzahl et al., 2012).

Huisman (2017) reviewed mediated social touch design cases and found that mediated social touch can not only communicate affection but also create affective responses and enhance social presence. Price et al. (2022) researched the sense-making of affective touch interaction with vibration, pressure and temperature feedback mechanisms in long-distance. For LDR partners, the result shows that there was also a sense of connection and sharing through a tactile emotion device. Wang et al. (2012) investigated how mediated social touch (touch and squeeze) was perceived and influenced the speaker' affective state (Dong, 2019) with an armband. Results showed that communicative touch resulted in a significant increase in the sense of connectedness with the storyteller over the speech-only condition and a trend towards greater affective conveyance.

Hassenzahl et al. (2012) emphasized that designers should focus more on finding possible tactile experiences from remote touch devices, such as gestures for comforting, empathizing, and caring. For example, Yohanan and MacLean (2012) established a dictionary of 'touches' and designed a mouse-like fluffy creature robot for social affection interaction. Chien et al. (2016) designed a fluffy robot to create feelings of closeness and togetherness for LDR couples. Rognon et al. (2022) investigated user perception of mediated touch interaction via an online survey for missed social touch, emotions, and scenarios in LDRs. Their result showed that stuffed animals would make users feel comfortable when communicating emotion.

Besides, multi-sensory tactile devices have enabled users to see, hear, and feel their distant loved ones (Li et al., 2018). *TapTap*, for example, is a wearable scarf with vibrotactile actuators that can replicate touch actions such as tap, press, stroke, and contact for emotional

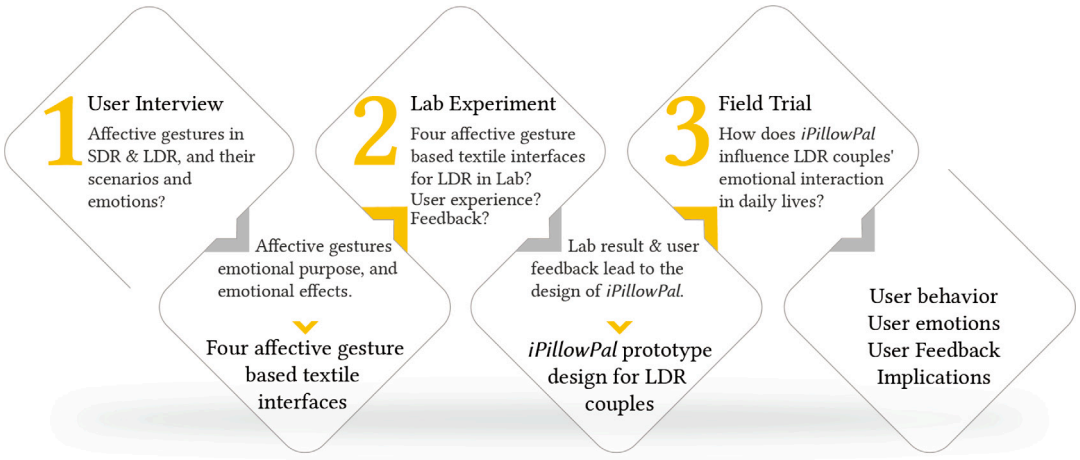

Fig. 1. Overall organization and procedure of this research and outcomes: (1) User interview, (2) Lab experiment, and (3) Field trial.

touch therapy (Bonanni et al., 2006). *CheekTouch*, is a device in which vibrotactile actuators are attached to the backside of a touch screen phone to imitate gestures such as pat, slap, pinch, stroke, kiss, and tickle. Their participant couples found it useful for non-verbal communication and feeling more closely connected to their partners (Wang et al., 2012). Mullenbach et al. (2014) concluded that users readily associate haptic with emotion, especially in the context of intimate partners. The physical embodiment concurs naturally with the strong connection between body and emotion (Fagerberg et al., 2003).

These studies contribute to a growing understanding of how technology can help maintain interpersonal connections despite physical separation, thereby enhancing the emotional well-being of individuals in LDRs.

As summarized in Table 1, existing findings indicate that remote gesture interaction has potential in emotional connection, communication, and therapy. Gestures or touch were used to trigger the interaction conversation or manipulate the devices. However, there has been relatively little research on emotional characteristics or scenarios accompanying these mediated remote gestures, which could prove beneficial for designing interaction gestures for LDR. This work explores the emotional impact of mediated affective gestures using interactive pillows, *iPillowPal*, specifically designed for LDR couples. Unlike previous studies that often focus on single modalities or predefined interaction patterns, this research investigates how the textile interface can facilitate affective gestures–such as Hug, Stroke, Poke, and Pull—integrated with real-time sensory feedback. The aim is to improve emotional well-being and enhance emotional connections.

2.2. Gesture-based E-textile interfaces

E-textile interfaces manifested as tangible objects or wearable items, enable computational environments to be embedded seamlessly into our lives and can be used to enable more natural and familiar remote tactile communications (Eid and Al Osman, 2015; Mullenbach et al., 2014). These have led to a variety of fabric-based microcontrollers, sensors, and actuators, which can pick up and detect physical movements through the way the fabric stretches or reacts to touch as people hold, squeeze, or press against fabric layers to activate the electronics (Giles and van der Linden, 2014). For example, *Textile Mirror*, is a textile wall panel that seeks to impact a person's affection through its changing texture (Davis et al., 2013). Then, researchers compared users' feelings when interacting with static & dynamic textile interfaces, look & touch textile interfaces (Davis, 2015). *FabricKeyboard* is a novel deformable keyboard interface based on a multimodal textile sensate surface. It enables unique tactile experiences and new interaction gestures: physical by pressing, pulling, stretching, and twisting the keys or the fabric and non-contact by hovering and waving towards the keyboard and an electromagnetic source (Wicaksono and Paradiso, 2017). Traditional textile materials were embedded with electronic components, resulting in a series of novel textile interfaces (Zeagler et al., 2012; Mlakar and Haller, 2020) and enabling various kinds of gestural interaction with its texture (Dong, 2019). Jiang et al. (2022) explored the gesture affordance of textile textures and developed five interaction gestures with five distinctive textile textures. They also investigated the emotional experiences with each gesture-based textile interface using visual and audio feedback modes.

These studies laid the groundwork for gesture-based interactive textile design; however, their applicability can be further explored in multiuser interaction or for LDR couples. Several studies have explored gesture interaction with e-textiles in LDR, like *Hold Me Tight* pillow (Gansohr et al., 2016), which mediated closeness to overcome physical separation, *AMISA* cushion (Fagerberg et al., 2003) that facilitated emotional support with friends over long-distance, and *Hug Over a Distance* coat Vetere et al. (2005) which aided couples in expressing intimacy. What these prototypes have in common is they were initiated by hug gestures. Another example is the *Flex-N-Feel* gloves (Singhal et al., 2017), which allowed LDR couples to feel the flexing of their partner's fingers with haptic feedback and imitate gestures. Participants found that while wearing gloves, they enjoyed their conversation more, felt more emotionally connected, and experienced intimate moments together. However, this research is more focused on shared action. There has been little discussion about affective gesture-based interaction via e-textiles. This research investigates affective behaviours and emotions among LDR couples and how to design affective gesture-based interactive textiles to enhance their emotional connection, expression, and interaction over distance.

3. Study 1: Understanding affective gestures for couples in long distance relationship

This study aims to investigate affective gestures among LDR couples and probe the design opportunities for non-traditional interfaces that can mediate this communication. We designed a semi-structured interview to answer the following probing questions in SDR and LDR scenarios separately:

The **SDR scenario**: To derive affective gestures often performed by couples, we asked participants what gestures they would perform to connect emotionally and socially with their partner.

Q1. What types of affective gestures did you perform in SDR when interacting with your partner?

Q2. What affection did each SDR gesture elicit?

Q3. In which scenarios did you use them?

Table 1
Comparison table of related gestural interaction for LDR work.

Work	Prototype	Focus	Finding	Medium	Gesture
Price et al. (2022)	*Tactile Emoticon*	Sense-making of distance affective touch.	There was also a sense of connection and sharing through a tactile emotion device.	Glove-like device	Affective gestures
Wang et al. (2012)	*Remote touch system*	How mediated social touch was perceived and influenced users' affective state in story-telling.	Remote touch and contextual expectations significantly affect people's empathy and emotional experience towards speakers.	Armband	Touch, squeeze
Hassenzahl et al. (2012)	–	Proposed six strategies for mediating intimate relationships.	Designers should focus more on finding possible tactile experiences from the remote touch devices, such as gestures for comforting, empathizing, and caring.	–	–
Chien et al. (2016)	*Furfur*	Use fluffy robot to create feelings of closeness and togetherness for LDR couples.	Provides a new intimate relationship maintenance strategy for LDR couples.	Furry robot	Knock, touch
Rognon et al. (2022)	–	User perception of mediated touch interaction for missed social touch, emotions, and scenarios in LDRs.	Mediated Social Touch devices should focus on conveying positive emotions and maintaining a multi sensory experience.	–	–
This work	*iPillowPal*	Emotional effects of mediated LDR affective gesture interaction via interactive pillow	*iPillowPal* shortened LDR couples' emotional distance and improved their emotional state.	Pillow	Hug, poke, stroke, pull

Note: – means non applicable

The **LDR scenario**:

Q4. Could you please rank the top three affective gestures you would like to perform in LDR but limited in SDR?

Q5. In which emotions would you like to perform the chosen LDR gesture?

3.1. Participants

The study recruited ten heterosexual couples (N = 20; 10 males and 10 females) who were all Chinese university students in LDR at the time of the interview. The couple's ages ranged from 20 to 34 (22.45 ± 3.35 on average). At the time of the study, their average SDR experience was 15.9 ± 6.67 months, and they had 7.5 ± 7.67 months of LDR experience on average.

3.2. Apparatus

The study was conducted as a one-to-one online interview using the WeChat PC version, a popular social media platform. Interview questions were available in both English and Chinese via a dedicated web page. Two HCI practitioners observed the interviews to ensure the process was upheld professionally. With the participants' informed consent, all interview sessions were recorded in terms of both audio and video. Participants were thoroughly briefed on the study objectives, how their data would be used, and their rights, including the option to withdraw at any time. Recorded data were anonymized, encrypted, and securely stored, with access limited only to the research team. This setup fostered a private and supportive environment, allowing participants to freely share their experiences and enhancing the authenticity and reliability of the data collected.

3.3. Procedure

After a brief introduction to the study, we presented the questions during the online interview via a web link for reference. The questions were divided into two sections (SDR and LDR), and each participant was asked to complete the semi-structured questions in the same order. In the first section, the participants were asked to inform us of the affective gestures they performed in SDR and asked them to inform us of the associated emotions and the situations in which they performed. Then, participants were asked to choose the gestures that could not be performed because they were physically away from each other. After selecting the gestures, they were asked to rank the top three gestures they desired to use with their partner while in an LDR. After ranking these gestures, they were asked to provide us with the reasons and scenarios in which they would like to perform these gestures.

Watson and Tellegen's emotion model (Watson and Tellegen, 1985) is a self-reported emotion scale with two key factors (emotion valence and arousal) and eight detailed major emotion categories, which can remind participants of their emotion types. For Q2 and Q5, we adopted Watson and Tellegen's emotion model to help the participants associate the affective dispositions with gestures and divide their emotions into eight categories: High positive affect, Low positive affect, Pleasantness, Unpleasantness, High negative affect, Low negative affect, Strong engagement, and Disengagement, see the detailed emotion items in Fig. 2. A bilingual (English and their native language) Watson and Tellegen's emotion model was presented to each participant to help them recall emotions during the interview.

3.4. Data collection & analysis

A total of 32 emotions were correlated with 8 gestures from 20 participants. The collected data includes video and audio recordings, questionnaire responses, and transcripts from the interviews. Each interview lasted approximately 15 to 25 min per participant. We used "F" and "M" to represent the female and male participants. The qualitative data were analysed using thematic analysis, with independent coding performed by two researchers. Any discrepancies in the coding were resolved to ensure reliability.

After tallying the votes for each gesture, we computed an agreement score of 0–1.0, where 0 indicates no agreement among participants, and 1.0 indicates complete (high) agreement. The agreement score was calculated as follows: Agreement Score = Number of participants selecting the gesture/Total number of participants. This score was then applied to user-preferred gestures in both SDR and LDR to calculate the level of consensus among affective gestures.

3.5. Results

First, **Q1. What types of affective gestures did you perform in SDR when interacting with your partner?** Q1 resulted in a series

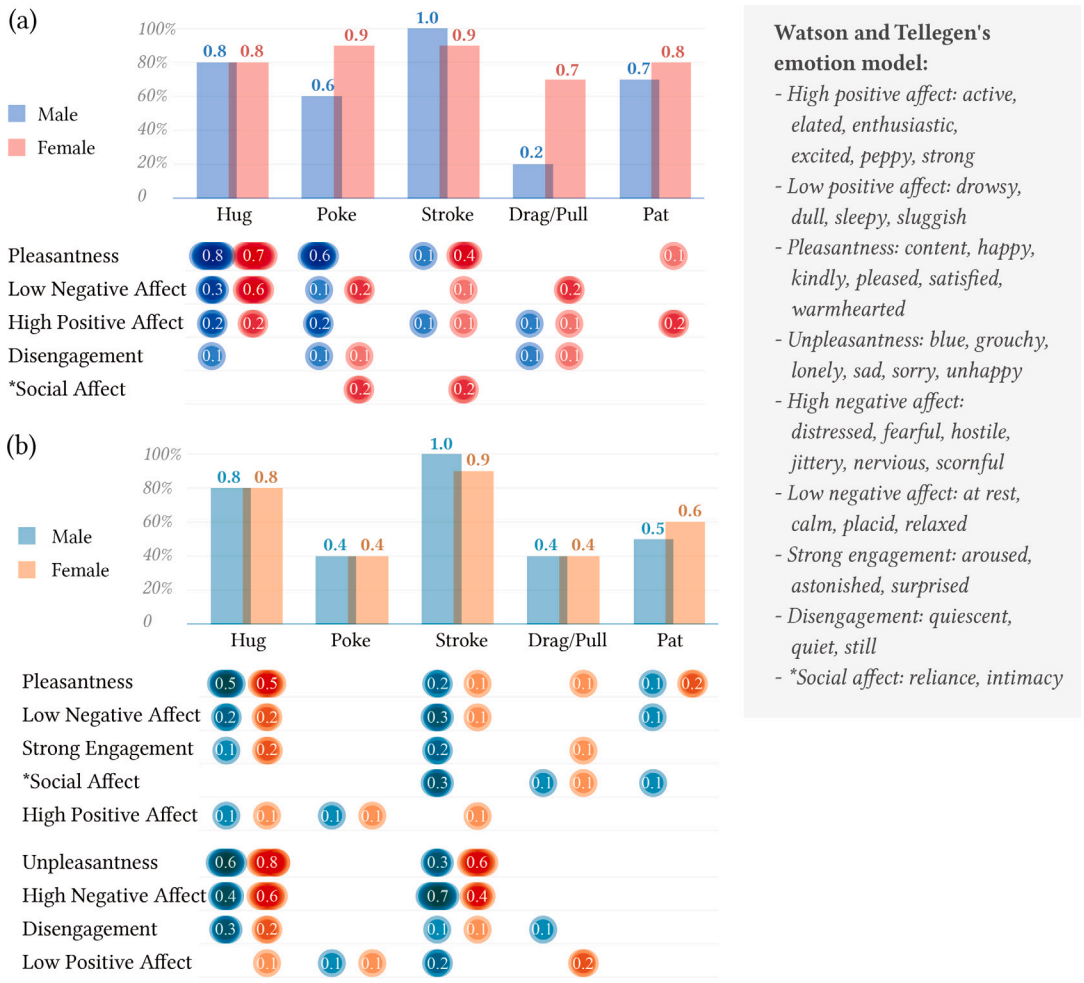

Fig. 2. Results of emotions associated with affective gestures in (a) SDR scenario and the emotion scenario of (b) LDR presented with agreement rates.

of affective gestures in SDR, including Hug, Poke, Stroke, Pat, Pull (clothes), Punch, Scratch, and Squeeze.

The **Q2. What affection did each SDR gesture elicit?** represents the gestures' associated emotions in SDR; see Fig. 2a. Both male and female participants associated the five gestures with expressing their positive emotions in SDR. Males favoured the Hug and Poke gestures to indicate positive emotions, while females showed interest in all five gestures. Hugs were frequently used by couples in SDR to express pleasantness (warm-hearted, content, happy, satisfied), low negative affect (placid, relaxed), and high positive affect (elated). Pull gestures in SDR made some participants (2M, 3F) feel relaxed and quiescent. Apart from these two gestures, there are no other similarities between male and female participants in the other gestures. For instance, four females regarded the Stroke gesture as warm-hearted or satisfied; however, males considered otherwise. Six males believed the Poke gesture to be warm-hearted, happy, or at rest, but two female participants thought it was peppy.

When we asked the couples about the scenarios where affective gestures were used in SDR in **Q3. In which scenarios did you use them?**, we discovered several motifs. Of the five affective gestures, Hug (4M) and Stroke (3M, 1F) gestures were used to comfort each other. Hugs (2M, 4F) were also used to express happiness, joy, and sorrow. Nine participants mentioned that they would hug their partners when meeting them after a long time of separation. On the other hand, Poke and Stroke gestures were frequently used when the couple (5M, 1F) played, chatted, or joked around. Both males and females used Stroke gestures to express good mood in SDR. Interestingly, Poke and Pat gestures were used in SDR to seek attention. Two females stated that they used the Pat gesture to their partner while feeling unhappy. The Pull gesture was primarily performed outdoors, mainly while walking together or with a pet or in crowded places. One female participant said she pulled her partner's clothes after a quarrel as friendly overtures.

For **Q4 :Could you please rank the top three affective gestures you would like to perform in LDR but limited in SDR?**, from these SDR affective gestures, they chose the top three they would like to perform in LDR. The most frequently referred five ones were: (a) Hug, (b) Poke, (c) Stroke, (d) Pat, (e) Pull (clothes) (see Fig. 3). Gestures (Punch, Scratch, and Squeeze) that achieved the lowest consensus were excluded in Fig. 3.

After applying the agreement score, from Fig. 2 we can see that the agreement scores ranged from 0.2 (low agreement) to 1.0 (very high agreement) for SDR (M = 0.74, SD = 0.21), and 0.4 to 1.0 for LDR situation (M = 0.62, SD = 0.22). In LDR, the Hug, Stroke, and Pat gestures had high agreement scores for both male and female participants, with a notable difference from Pull and Poke gestures. For Q4, of the five gestures, Hug (8M, 8F) and Stroke (10M, 8F) were more popular among couples as their expected affective gestures in LDR. The Poke gesture was the least favourite among the couples in LDR.

During the interviews of Q2 and Q5, most of the participants' emotion types can be found in Watson and Tellegen's emotion items, while two social affections (reliance and intimacy) emerged in the participants' responses, which were out of the scale of Watson and Tellegen's emotion items. Since these social affections could not be unequivocally mapped to Watson and Tellegen's emotion model, we categorized them as "Social Affect" separately (see Fig. 2).

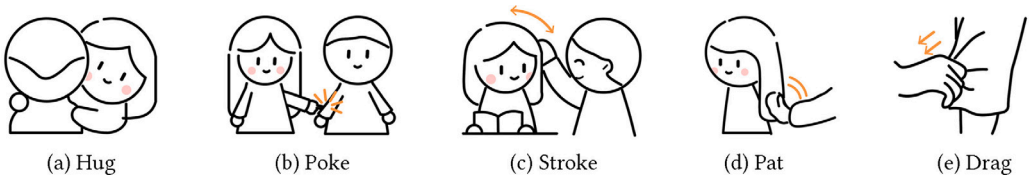

Fig. 3. The five most desired LDR affective gestures mentioned by participants in Q4.

Q5:In which emotions would you like to perform the chosen LDR gesture? represents the emotional atmosphere in which they would like to elicit affective gestures, as shown in Fig. 2b. Hug and Stroke gestures related to expressing negative emotions, such as Unpleasantness (blue, sad, unhappy) and high negative affect (distressed, fearful, nervous) in LDR. Also, compared to SDR, males associated several kinds of positive and negative emotions with Stroke.

Our participants mentioned that Hugs made them feel happy or relaxed and gave comfort, encouragement, and a sense of security. Besides, one male participant stated that gestures would be more significant with the partner's response. This could explain why individuals find Hugs so meaningful. On the other hand, Stroke gesture was expected in LDR to convey intimacy and closeness to their partner. Similarly, Pull (1M, 3F) and Poke (1M, 1F) gestures were reserved in LDR to express playfulness and as a nudge or reminder, respectively.

3.6. Summary and discussion of study 1

The results of this study show that Stroke and Hug gestures are the favourite for both male and female participants in both SDR and LDR scenarios (see Fig. 2). According to Yohanan and MacLean's 2012 study of touch gestures, Hug, Stroke, and Pat gestures are the most distinctive ones in emotional communication; this result is almost consistent with ours. This finding also aligns with prior work, which particularly mentions the positive emotional effects of Hug and Touch gestures (Angelini et al., 2014). Additionally, Watson and Tellegen's emotion model indicates potential positive effects on users' emotions for the five affective gestures, implying affective gestures differ across scenarios and generate various emotions. However, except for Pat, the other gestures are more or less associated with negative emotional expressions in LDR. The data presented in Fig. 2b shows almost similar emotional expressions for male and female participants for affective gestures in LDR. This similarity suggests that gender differences are not critical in designing affective gestures for couples in LDR.

Many studies, such as *TapTap* (Bonanni et al., 2006) and *CheekTouch* (Wang et al., 2012), investigated hand gestures for LDR cases. However, none of these has investigated the emotional effect, particularly for Poke, Stroke, Pat, and Pull gestures. Previous research demonstrated that textile interfaces could provide users with a range of emotional experiences through self-gesture-based interaction (Jiang et al., 2022), but also did not investigate the effect of affective gestures on expressing emotions in LDR using smart textiles. This study helped us understand affective gesture types, accompanying emotional characters, and scenarios of LDR couples, which guided our design in Study 2.

4. Study 2: Probing affective gesture-based interaction for textile interfaces

After understanding affective gestures from Study 1, there are still several challenges in building interactive textiles that enable users to perform affective gestures to support emotional communication or interaction. First, we need to identify a suitable method to enable the users to perform affective gestures using smart textile interfaces. Second, we need to develop appropriate sensing and feedback mechanisms to express or communicate emotions remotely. Third, the smart textile interfaces should seamlessly enable partners to establish an emotional connection and experience in LDR.

To achieve these objectives, we designed the second study to investigate affective gesture-based interactions on textile interfaces for LDR by (a) identifying the appropriate textile textures suitable for the identified affective gestures and (b) implementing different feedback mechanisms. Additionally, based on our participants' reflections on the affective gestures from Study 1, we decided to investigate Poke, Pull, Stroke, and Hug gestures for textile interfaces. The Pat gesture was dropped because it was associated with less affection in SDR (see Fig. 2a). We next detail the identification of textile textures, assigning affective gestures to each textile, sensing, and feedback mechanisms, and procedure based on Study 1.

4.1. Textile interfaces design

4.1.1. Textile textures

Texture is an essential aspect of textile interface design, which influences both the aesthetic appearance and the tactile feeling of a piece of textile (when a person contacts it using their hands). To identify the appropriate textures for affective gestures identified in Study 1, we borrowed previous research results from Jiang et al.'s 2022, which introduced a set of interactive textile interfaces with distinct textures that can afford specific gestures and elicit specific emotional responses. We adopted their texture manipulation and electronic textile fabrication methods for our textile interfaces as their structure would trigger touch gestures intuitively (Jiang et al., 2022): (a) stuffed quilting afforded Poke gesture interaction, (b) flounce afforded Pull gesture interaction, (c) pleating afforded Stroke gesture interaction, (d) the pillow-shape cushion for Hug gesture interaction. These methods would allow the deployment of sensors and electronics underneath their shape-changing portions. We use a creamy-white stretch scuba-knitted fabric with a 1.3 mm thickness as the primary surface material for all our interfaces to eliminate the potential influence of the textile's colour and materials.

4.1.2. Textile interface design for affective gestures

We follow a multiple-layer approach to build our textile interfaces. All our interfaces use scuba-knitted fabric as base layers. We enable the sensing capabilities of the scuba-knitted fabrics by replacing the standard fabric with conductive fabric elements. The details of the implementation are described below:

- *Poke gesture with stuffed quilting texture interface.* We use the quilting manipulation method to build this interface. Straight lines are stitched with a machine in a grid format with specific spaces to stuff the cotton. We embed Velostat,[1] a pressure-sensitive material, above the base layer (made of scuba-knitted fabric), to detect Poke gestures and monitor the applied pressure (see Fig. 4a).
- *Pull gesture with flounces texture interface.* This structure includes two types of custom-made scuba knitting fabrics: (a) spiral-cut flounces and (b) strips. We sew a 5 cm wide scuba fabric to achieve the spiral-cut flounces. To build the strips, we cut a 0.75*9 cm strip with a round end and machine stitch a stainless

[1] https://www.adafruit.com/product/1361.

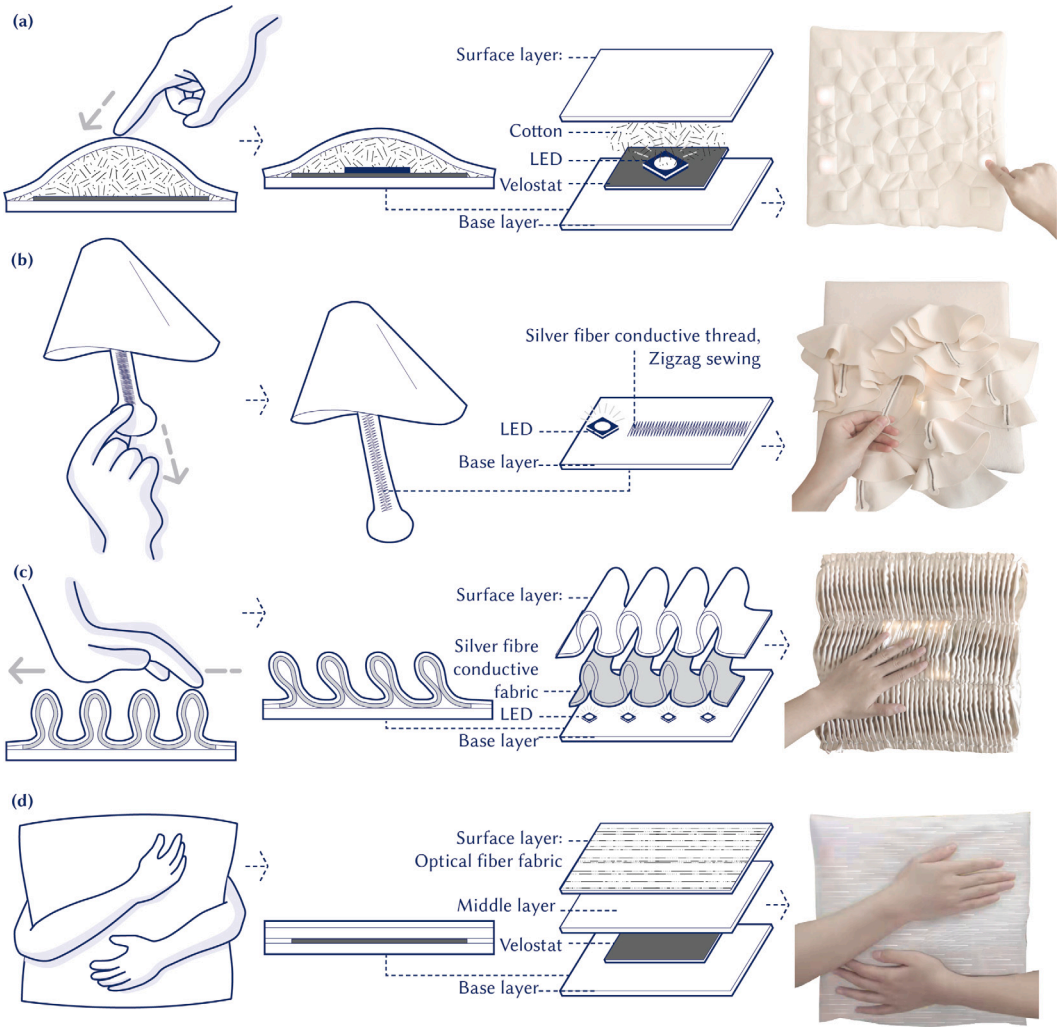

Fig. 4. Textile interfaces design and production: (a) Poke gesture, (b) Pull gesture, (c) Stroke gesture, (d) Hug gesture.

steel conductive thread in a 0.4 cm wide zigzag trace with them (see Fig. 4b). We stitch spiral-cut flounces with conductive stripes on the base layer. The contact density of the conductive thread reduces when the strip is pulled, resulting in increased resistance.

- *Stroke gesture with pleating texture interface.* We use two layers of scuba fabric (base and surface) and one layer of conductive fabric (middle) to build this interface. The surface and middle layer fabrics are folded to achieve a pleats style (Fig. 4c). When the user strokes the surface, the pleating structure deforms and increases the contact area of the conductive fabric, resulting in decreased resistance.
- *Hug gesture with cushion interface.* We use optical fabric as the surface layer suitable for diffused light feedback and Velostat, a pressure-sensitive material, for capturing the hug gesture. The optical fibre illuminates when the user hugs the interface (see Fig. 4d).

Each interface is equally divided into nine different sensing areas. We use an ESP8266 board to power each textile interface and LED lights or optical fabric to enable visual feedback. Two sets of devices for each textile interface are developed for this study. The connection between these devices is achieved using Bluetooth and the OSC protocols.

4.1.3. Interaction modes of textile interfaces

To further explore the design requirements of affective gestures for smart textile interfaces, we considered the collaboration and relaxation aspects of the affective gestural interactions for LDR couples. These two aspects would allow investigation of the implications of enabling LDR couples to remotely connect via affective gestural interactions, which would give them the desired comfort. Prior studies (Hassenzahl et al., 2012; Singhal et al., 2017; Werner et al., 2008) reported that people use either explicit actions (gestures) or implicit ones (e.g., heart rate, sleep patterns) to achieve physical contact via interfaces with their partners. Inspired by these studies, we considered (1) *Gesture-only* and (2) *Biological-data&Gesture* interaction modes for our textile interfaces. We use galvanic skin response (GSR) sensors worn on the index and middle fingers to collect the users' biological data (biodata). In *Gesture-only mode*, the LEDs' hue changes, and the light dot moves to the next one for each touch interaction. The gesture sensors are gradual mechanisms and are able to detect degrees of gesture pressure (Jiang et al., 2022), see Fig. 4. The coloured LED dot's leap distance and brightness are proportional to the gesture pressure. We use rainbow colours to indicate the successful completion of each session. On the other hand, for *Biodata&Gesture mode*, users' GSR variations and touch pressure are mapped with LED hue, saturation, and brightness.

4.2. Participants

Twelve heterogeneous adult couples (24 participants, aged between 19–28, M = 22.6 ± 2.3) with an average of 3.08 ± 5.56 months LDR experience volunteered to participate in this study. They were students from a local university recruited via popular social media platforms

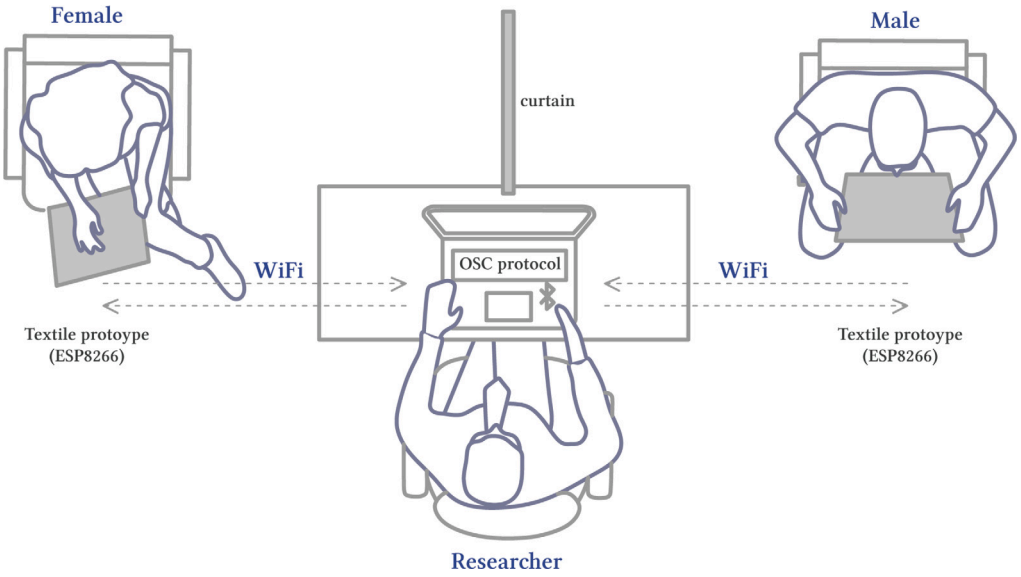

Fig. 5. Illustration of the experiment apparatus and set up. The two couple partners are separated from each other.

and consented to participate voluntarily. These participants did not participate in previous questionnaire research. Each couple was invited to a dedicated laboratory for the experiment simultaneously.

4.3. Procedure & measures

We introduced the purpose of the experiment and asked them to occupy different seats in the laboratory. The seats were arranged at a distance of three meters from each other and separated by a long curtain to simulate long-distance interaction scenarios in the laboratory. One researcher oversaw the couples from the experiment desk with a PC running the OSC protocol to pair the interfaces (see Fig. 5). They were shown how to use different gestures to interact with four interfaces.

This study used a 4 × 2 two-way repeated factorial design with two variables:

(1) Gesture-based interface (Poke, Pull, Stroke, Hug)

(2) Interaction mode (*Gesture-only* mode, *Biodata&Gesture* mode)

All couples were given the same prototype to interact and play with for each combination. The four gesture-based textile interfaces were provided to the couples using a Latin square order to avoid carry-over effects.

The Emotion Valence-Arousal Questionnaire (Bradley and Lang, 1994) and the Game Experience Questionnaire (GEQ)–Social Presence scale (Brockmyer et al., 2009) are all widely used self-report emotion scales. To record their emotional effect after interacting in each sector, the couples were asked to complete the Emotion Valence-Arousal Questionnaire and the GEQ–Social Presence scale[2] individually after using each interface with a five-minute break in between. All couples were encouraged to express their feelings while interacting with the textile interfaces together. We use the prefix N, followed by a number, to represent the couple number in the rest of the paper.

4.4. Results

4.4.1. Emotion valence & arousal

We analysed Emotion Valence and Arousal data using a two-way repeated-measures ANOVA and Bonferroni corrections for pair-wise comparisons where necessary. We used Greenhouse–Geisser correction to address the violations to sphericity.

First, no significant interaction effect was found with Emotion Valence, but there is a significant main effect in both Interaction Mode ($F_{(1,19)} = 10.796$, $p < 0.01$) and Gesture-based interface ($F_{(2.187,41.55)} = 3.809$, $p < 0.05$) variables (see Fig. 6a). The *Biodata&Gesture* mode led to higher emotion Valence than the *Gesture-only* mode ($p = 0.004$). As Emotion Arousal data showed an interaction effect between two variables, $F_{(3,57)} = 3.205$, $p < 0.05$, the effects of variables were examined separately (see Fig. 6b). When interacting with the Hug gesture interface, the *Biodata&Gesture* mode was significantly higher than the *Gesture-only* mode in the Arousal level, $F_{(1,19)} = 8.636$, $p = 0.008$. Likewise, in *Biodata&Gesture* mode, the Hug gesture interface showed a higher Arousal level than Poke ($p = 0.005$).

4.4.2. GEQ - social presence scale

Four items of the GEQ – Social Presence Scale showed significance, as presented in Fig. 6. For item "I felt connected to the other(s)", the interaction effect was found between Interaction Mode and Gesture-based interface variables, $F_{(1.886,26.401)} = 2.588$, $p = 0.049$. When interacting with the Stroke gesture interface, participants felt more connected in Biodata&Gesture mode ($p = 0.043$).

For item "I found it enjoyable to be with the other(s)", the Gesture-based interface factor showed significance, $F_{(3,36)} = 4.37$, $p = 0.01$, and Hug gesture interface got a higher score than Poke gesture interface ($p = 0.042$). The item "When I was happy, the other(s) was(were) happy" showed a similar result in Gesture-based interface factor $F_{(1.689,20.274)} = 3.365$, $p = 0.029$, Hug gesture interface was significantly higher than Poke gesture interface ($p = 0.003$).

For item "I was influenced by the other(s) moods", Interaction mode was found to be significant, $F_{(1,12)} = 6.03$, $p = 0.03$, and the *Biodata&Gesture* mode recorded a higher value ($p = 0.03$) than the *Gesture-only* mode.

4.4.3. Qualitative feedback

During the interaction, the couples stated that using affective gestures with textile interfaces is *Illusive* (N1, N2, N5, N8, N12), *Attentive* (N1, N2, N9), *Fun* (N2), *Casual* (N9), *Playful* (N3), *Remindful* (N1, N4, N9) and *Comfortable* (N4).

Couples also noted that they were delighted to see synchronous feedback from their partner in real-time and agreed that they were able to express their emotional state by interacting with the textile interfaces (N5). One couple (N9) compared affective gesture-based interaction to a Whack-A-Mole game when her partner was remotely operating

[2] https://www.wjx.cn/vm/eqJyT42.aspx.

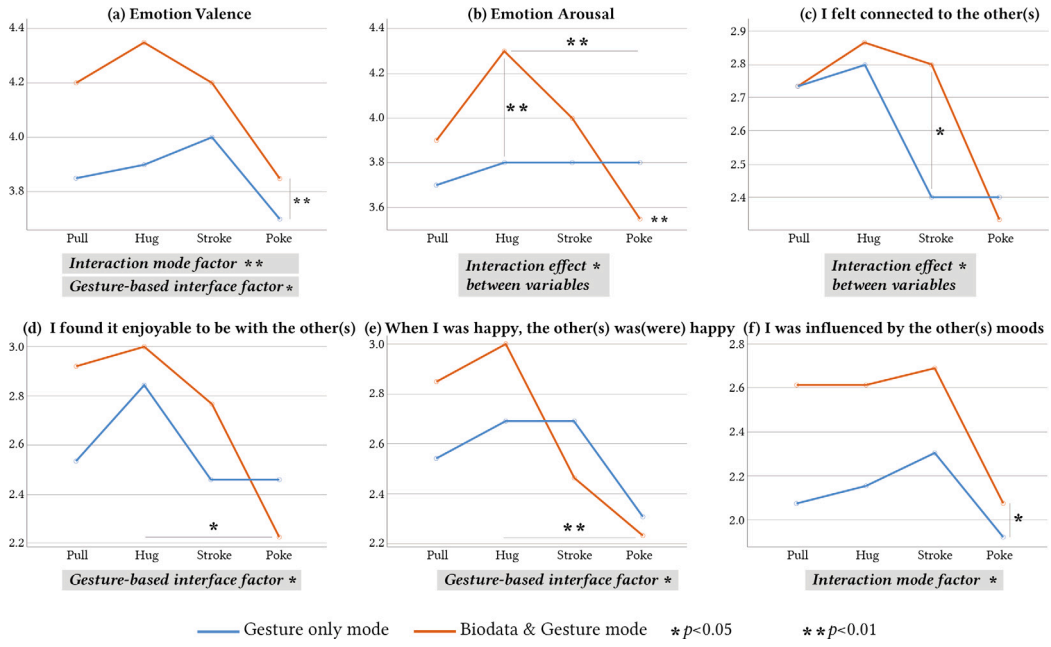

Fig. 6. The result of (a) Emotional Valence, (b) Arousal and GEQ-Social Presence Scale items (c), (d), (e), (f).

her device. N4 said they wanted the indicator of their partner's online signal. Besides, N7 and N9 expected special feedback to demonstrate the value of collaboration when two persons made the same gesture in the same position.

Couples also provided valuable suggestions and concerns to improve the design of affective gesture-based interfaces further. Several couples (N2, N4, N7, N9, N12) preferred to express their emotions via gesture pressure and frequency and suggested receiving this feedback on the interface. They also expressed their unwillingness to share their emotions in real life via a biodata device. One participant expressed that it was worrisome to wear the GSR electrodes to use them together with the affective gesture-based textile interfaces.

Almost all participants (22 out of 24) favoured the pillow prototype, and 17 of them expressed their interest in using it with their partners when they were physically distant from each other. Five couples preferred vibration feedback over visual feedback for pillow-based interfaces (N1, N2, N3, N9, N11). Furthermore, they also suggested considering ergonomic aspects of the interface while choosing the sensing regions (N12):

> *"For example, the Poke gesture is attention-seeking; thus, its interaction area could be placed in the middle of a pillow interface. In contrast, I perform Stroke gestures while I am in a relaxed state; thus, the gesture amplitude can be limited due to the length of my arm. So I think it would be good to have Stroke sensing area on the edges".*

4.5. Summary and discussion of study 2

Study 2 confirmed the results of Study 1, with additional implications for the design of smart textile interfaces, which could support multiple affective gesture interactions in the textile interfaces. Our participants expressed emotional experiences, preferences for the four textile interfaces, and associated affective gestures. Their response suggests that no single textile interface or affective gesture could meet all the requirements highlighted by the couples in LDR for emotional communication and engagement.

17 (out of 24) participants favoured a throw-pillow design for performing affective gestures. However, they also highlighted that the affective gestural interaction area should be ergonomically placed to support all four affective gestures in a single throw-pillow style design. Our participants favoured employing gesture frequency and pressure to express emotional intensity in affective textile interfaces for LDR communication. Last, they favoured haptic feedback over visual feedback for the Hug gesture.

To meet these recommendations, a new prototype that would support all four affective gestures and interaction mechanisms in a single throw-pillow design is needed. We went on to develop a prototype with these features and then ran a third study to validate whether the prototype was supportive of emotional communication and interaction for LDR couples via affective gestures in their daily lives.

5. Study 3: Design and field trial of *iPillowPal* with LDR couples

To investigate the real-life interaction experience of the affective-gesture-based interface for LDR, we designed *iPillowPal* based on the findings from Study 2 to incorporate the four textile textures, four affective gestures, and two feedback mechanisms in a single pillow-based prototype. We used this prototype to investigate how couples who were in LDR would perform affective gestures to express their emotions in their daily lives. We recruited a new set of heterogeneous LDR couples for this experiment. Additionally, we were interested in how the affective gestures supported by a pillow prototype would affect different usage scenarios and locations and increase the social presence of LDR couples. Finally, it was important to understand the participants' experience with the prototype, so we added questionnaires to gather their subjective feedback.

5.1. iPillowPal system design

In this section, we discuss the design of interactions enabled by *iPillowPal*, followed by the hardware and software implementation of the prototype.

iPillowPal is implemented as a throw-pillow-based system as pillows enable the most affordable way to implement the four affective gestures on both sides of the pillow. Our six-pointed star-style pillow with a size of 40*40 cm consists of two independent sensing and feedback layers (front and back sides). The front side of the pillow includes six dependent sensing areas to enable Poke, Stroke and Pull gestures with visual feedback. The two larger sensing areas at the backside support the Hug gesture with visual and haptic feedback. Thus, *iPillowPal*

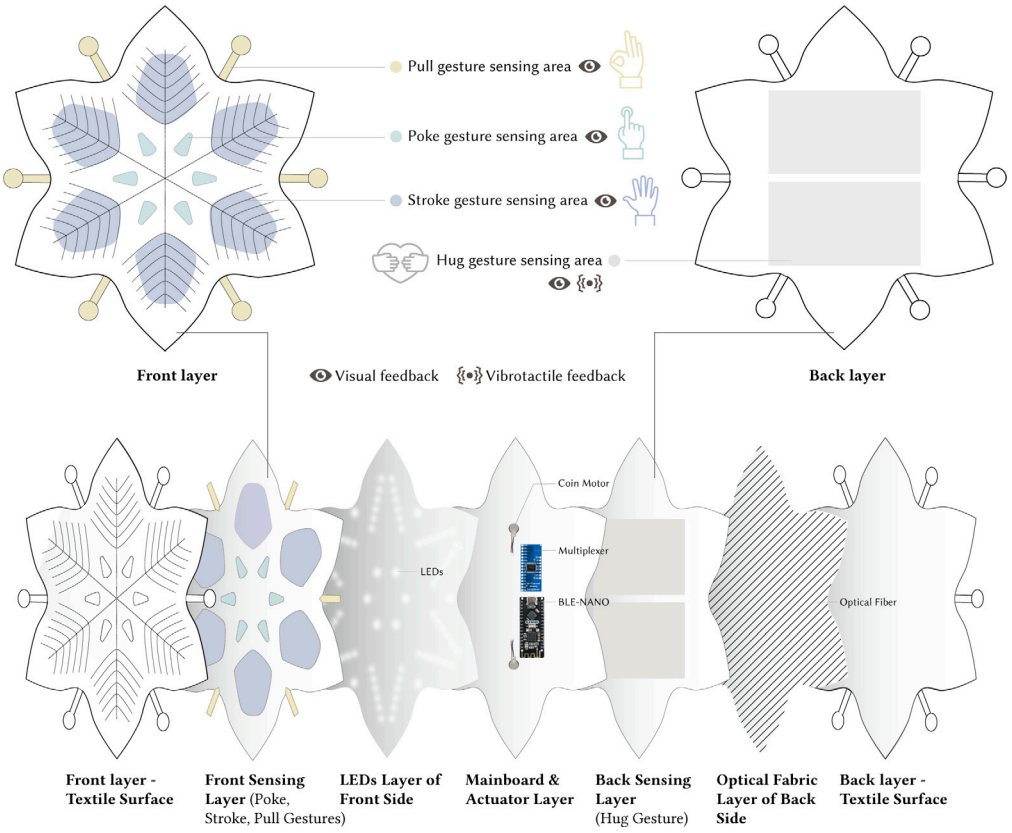

Fig. 7. The *iPillowPal* design illustration: sensing areas and the placement of the hardware.

Fig. 8. *iPillowPal* in dual-person mode.

provides 20 different gesture sensing areas (6 sensing areas at the front side x 3 gestures + 2 sensing areas at the backside) with two feedback modes (see Fig. 7). Our *iPillowPal* prototype is powered by an Arduino Nano 33 BLE with a multiplexer that streams data in real time to a cloud server via a mobile APP over a Bluetooth connection.

iPillowPal supports single and dual-person modes with visual and haptic feedback. However, single-person mode only provides monochromatic (white light) visual feedback. In both modes, the *iPillowPal* systems are paired/connected via the mobile APP to the cloud server. For the dual-person mode, the sensor data, including the feedback details from the sensing areas of the two paired pillows, are exchanged in real-time with a two-second delay through the APP via the cloud server. Thus, the system only works in the dual-person mode when two pillows are connected to the mobile APP. Fig. 8 illustrates *iPillowPal* system implementation in a dual-person mode.

The chromatic colour visual feedback is provided in the dual-mode, the brightness of the lights determined by the duration of the gesture (see Fig. 9c, d, e, f). The pressure applied on the sensing areas to perform a particular affective gesture is used to determine the saturation of the lights and the vibration intensity. For instance, any applied gentle pressure on the sensing areas will respond in mellow chromatic colours, while the more powerful pressure will result in bright colours. The colour phases of the sensing areas are diverse and change gradually with time (see Fig. 9a, b).

5.2. Field trial

5.2.1. Participants

Ten heterogeneous couples (20 participants) currently in an LDR were recruited via a popular social media platform. Their age ranged from 18 to 35 (M = 25.5 ± 4.37), with an average LDR duration of 19.1 ± 12.3 months. We ensured that the couples were in the same time zone, maintained daily communications (via text messages or phone calls), and used Android smartphones at the time of the study. All participants received a small payment (an equivalent of $10) for their participation.

5.2.2. Measures

We recorded the following measures during the experiment to investigate the effects of *iPillowPal* for heterogeneous LDR couples, their reactions, attitudes, and feedback towards affective gesture-based textile interfaces in their daily lives. The collected data included questionnaires and logged data from the server.

The questionnaires completed before each interaction were composed of four parts. The first part investigated the preferred usage locations for the textile interface (home, study place, workplace, outdoor location, and others for the supplement). The second addressed different usage scenarios (in a daze, text chatting, audio chatting, video chatting, watching the video, studying, working, and others for the

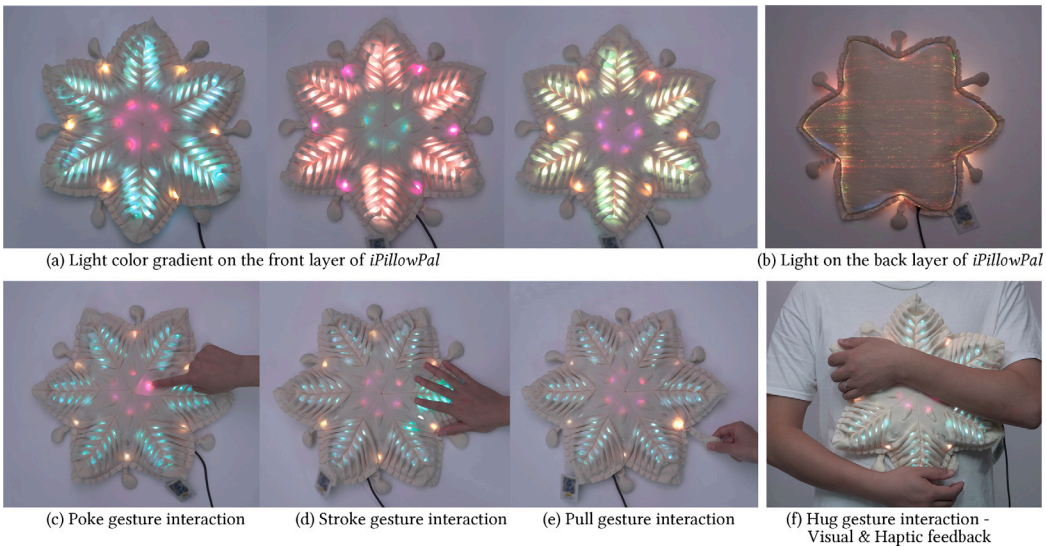

Fig. 9. Interaction feedback of chromatic colour mode (a) Light colour gradient on the front side of *iPillowPal*, (b) Light on the back side of *iPillowPal*, (c) Poke gesture interaction, (d) Stroke gesture interaction, (e) Pull gesture interaction, (f) Hug gesture interaction with visual and haptic feedback.

supplement). The third section investigated social presence in connectedness to partner, feeling up to date on the state of the partner, the extent to which one felt the social, level of cohesion, and the extent to which one's experiences were shared with the partner on a 0–10 score. The final part of the questionnaire addressed the couples' self-reported emotions using Watson and Tellegen's emotion model (Watson and Tellegen, 1985).

The questionnaires completed after each interaction collected the couples' emotional experience, social presence, and Watson and Tellegen's emotion model. Finally, the questionnaires completed after the entire study explored the overall feeling about the *iPillowPal*, user experience, user acceptance of our prototype, and our LDR couples' subjective preferences for emotional communication methods. A User Experience Questionnaire (UEQ) (Rauschenberger et al., 2013) and a System Usability Scale (SUS) (Brooke et al., 1996) questionnaires were filled in before they returned the prototype to the researcher to investigate user experience and system usability.

5.2.3. Procedure

The couples provided informed consent, which explained study objectives, data collection methods, and their rights, they were informed they could withdraw the expriment at any time. They provided their address to deliver a functional *iPillowPal* prototype. The deliver package also included a charger and a user manual. We created a dedicated group for each couple involving the same researcher on a popular social media platform to deliver the instructions. Each interaction gesture and procedure to complete the questionnaires using the mobile APP were explained and demonstrated in the dedicated group chat via text messages, pictures, and pre-recorded videos. Once the participants familiarized themselves with the prototype, the formal experiment began, which lasted for seven consecutive days for each couple. Participants were encouraged to use the *iPillowPal* as many times as possible during the experiment period. The *iPillowPal* prototype can only be turned on/off via the mobile APP by completing the corresponding questionnaires. Thus, each interaction with the *iPillowPal* required the completion of two questionnaires before[3] and after[4] each interaction. After completing the formal experiment, UEQ[5] and SUS[6] questionnaires were filled out to evaluate the overall experience. A short questionnaire regarding their subjective preferences for emotional communication methods was filled out before the participants returned the prototypes. The qualitative data regarding the user experience, were analysed using thematic analysis, with independent coding by two researchers and resolved discrepancies to ensure reliability.

After the study concluded, all prototypes were securely retrieved by the research team. To protect participant privacy and ensure ethical handling of data, the devices were reset to remove any stored information after we retrieved the related data for analysis, and all physical components were stored for future research with appropriate anonymization of data.

5.3. Results

At the end of the experiment, we collected 40 effective questionnaires of the emotion communication method (20 each for before and after the experiment), 110 "Before-use" and "After-use" questionnaires, 20 UEQ and SUS, and interaction data from the cloud server.

5.3.1. IPillowPal acceptability

The location and scenario when the couples interacted with *iPillowPal* were measured through the "Before-use" questionnaire. The percentage of preferred usage locations and scenarios for each dimension can be seen in Fig. 10a and b. Our couples generally showed a positive attitude towards using the *iPillowPal* at home rather than in public places. 85.45% of our participants used the prototype at home; 12.73% used it at their workplace. Nearly half of the participants used the prototype while chatting/talking over the phone or in a daze. 52.73% used it while on the video call and 45% on the audio conversation. Only 1.82% used the prototype while at work.

The time and type of affective gestures used to express their emotions were analysed from the cloud data, which can be seen in Fig. 11 (The data reading interval is 0.5 s). The bar chart shows the sum of all gestures, and the line graph represents the reading frequency of each gesture. In general, our participants interacted with *iPillowPal* day and night, except at bedtime. In particular, the use of affective gestures to their emotions using our prototype peaked in the evening, after 7 pm until midnight. The Poke gesture was performed between 10 to 11 pm. At midnight, the Stroke, Pull, and Hug gestures were performed to express their emotions.

[3] https://www.wjx.cn/vm/tvqU2f3.aspx.
[4] https://www.wjx.cn/vm/e9IPA7R.aspx.
[5] https://www.wjx.cn/vm/w6hK8yg.aspx.
[6] https://www.wjx.cn/vm/rXXRWpn.aspx.

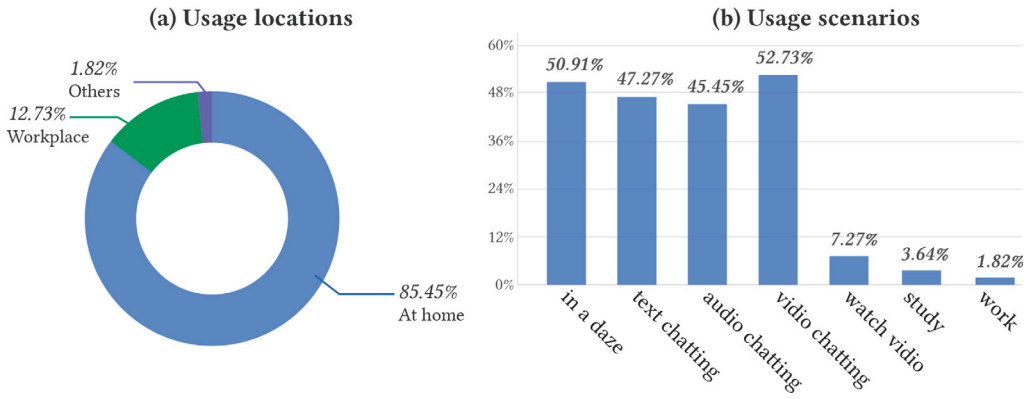

Fig. 10. (a) Usage locations of *iPillowPal*; (b) Usage scenarios of *iPillowPal* (multi option questionnaire).

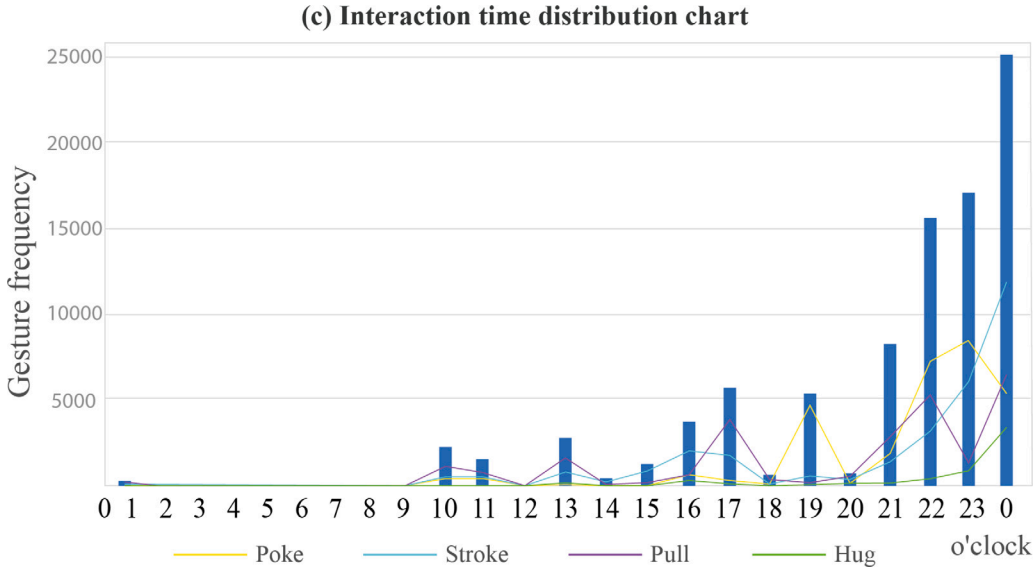

Fig. 11. Time distribution of interaction gestures with *iPillowPal*.

5.3.2. Social presence

By comparing the subjective scoring for the Social Presence of connectedness before and after performing every affective gesture, we found that all five items were rated significantly higher for all five items after performing affective gestures with our prototype (see Fig. 12). The item "Extent to which one's experiences were shared with the partner" ($t = 3.463$, $p < 0.001$), "Extent to which one felt social" ($t = 2.743$, $p = 0.009 < 0.01$), "connectedness to partner" ($t = 2.138$, $p = 0.038 < 0.05$), "feeling up to date on the state of partner" ($t = 2.066$, $p = 0.045 < 0.05$), and "level of cohesion" ($t = 2.535$, $p = 0.015 < 0.05$). Fig. 12 summarizes the social presence scores before and after performing affective gestures with our prototype.

5.3.3. Emotional state of participants

The measurement of participants' emotional fluctuations used Watson and Tellegen's self-reporting emotional model before and after performing affective gestures with *iPillowPal*. Similar to Study 1, emotions were classified into four dimensions: positive affect, negative affect, pleasantness, and engagement (Watson and Tellegen, 1985). The percentage of positive/negative, pleasant/unpleasant, and other affections for each emotion before and after using our prototype can be seen in Fig. 13.

The colour coding in Fig. 13 represents different emotional states: Red represents positive emotions (e.g., happiness and contentment) and blue represents negative emotions (e.g., sadness or distress) after interacting with *iPillowPal*. While light blue indicates neutral or low affective states (e.g., calmness or relaxation), and light orange corresponds to positive affects before interacting with *iPillowPal*. This colour scheme helps visually highlight the emotional changes observed before and after interaction with the prototype, showing the increase in positive emotions and decrease in negative emotions.

Of the two (High and Low) positive effects, all six elements in the High positive effect increased after using our prototype. In contrast, all elements in the Low positive effect decreased for our participants. A similar pattern was found for the pleasantness and unpleasantness as well. On the other hand, our participants felt that using our prototype minimized the two negative emotions (except for the "relaxed" element in the Low negative effect). The Social affect dimension appeared to have mixed results; particularly, the "reliant" and "intimate" emotions increased after using our prototype. Finally, 75% (vs. 25% before using *iPillowPal*) of our participants showed a positive attitude towards performing affective gestures using interactive textile-based interfaces for emotional communication methods after using our prototype.

5.3.4. User experience and system usability

After using *iPillowPal* prototype for seven consecutive days, our participants individually completed UEQ and SUS questionnaires. Table

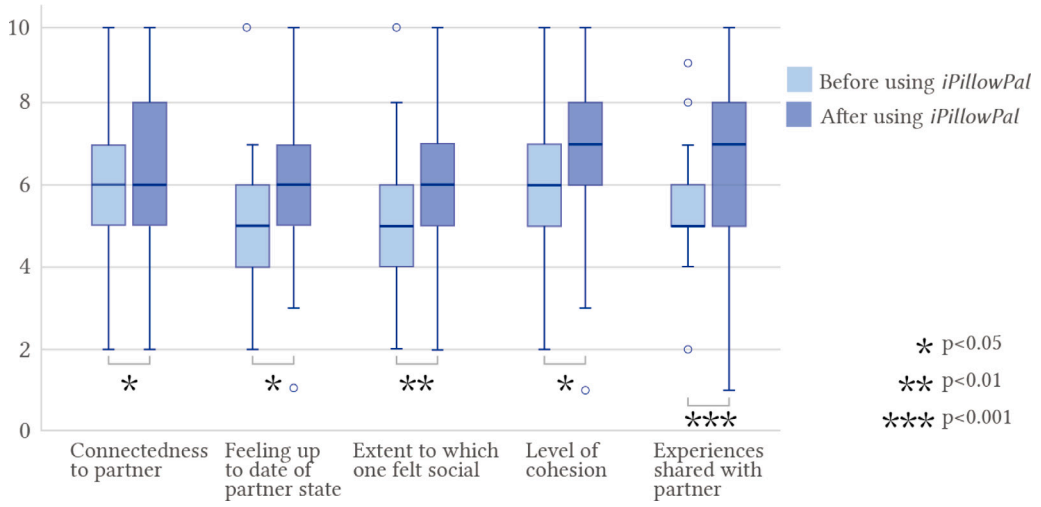

Fig. 12. Social presence questionnaire result, before and after interacting with *iPillowPal*.

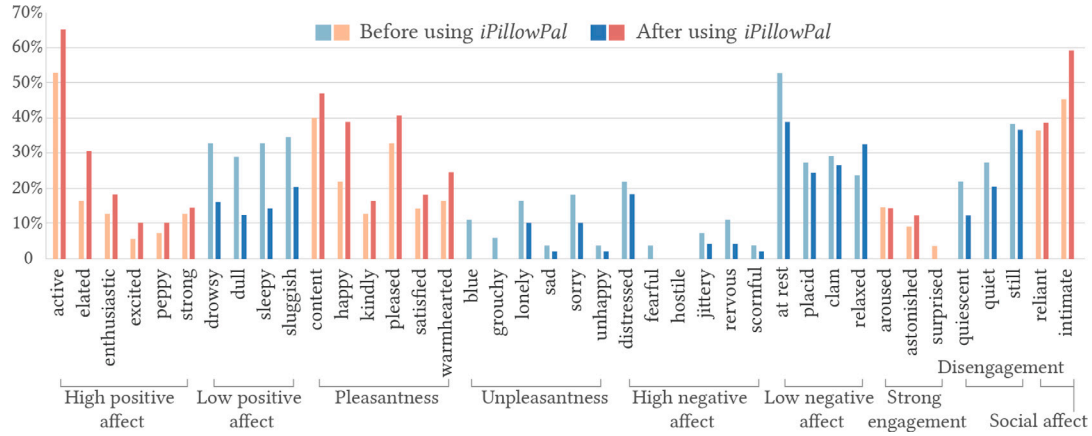

Fig. 13. Distribution of our participants' emotional state before and after using *iPillowPal*. The emotions were classified based on Watson and Tellegen's emotional model.

Table 2
User experience questionnaire results reported by our couples after using the prototype for seven consecutive days.

	Attractiveness	Perspicuity	Efficiency	Dependability	Stimulation	Novelty
Mean	1.375	0.735	0.625	1.075	1.263	1.688
	Positive	Negative	Negative	Positive	Positive	Positive
Variance	1.06	1.74	0.44	1.07	1.33	1.23
Compared to benchmark	Above average	Below Average	Below Average	Above average	Above average	Excellent

2 presents the results of UEQ questionnaires. The UEQ gives insights into six categories: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. The ratings for each category range from −0.6 (Efficiency) to 1.7 (Novelty). The UEQ benchmark comparison showed excellent results for Novelty and above-average for Attractiveness. Our prototype received an average value of 62.9 on the SUS classification scale, which is slightly above the minimum acceptable value (62.6).

5.3.5. User experience with iPillowPal

After using the *iPillowPal* for seven consecutive days in various locations with their partners who are geographically separated from one another, our users expressed their positive comments about the proposed interface, which include:

> *"It is a loving artifact; I can play it all day long, just have to recharge it every night".*

> *"Although the physical distance exists, it was ignored when we were interacting".*

> *"More emotional catharsis can be achieved through Pull gesture interaction".*

> *"I like to Hug it before bedtime, it brought surprise and pleasantness when received vibration from my boyfriend's Hug gesture".*

Users also favoured using the throw-pillow affective-gesture-based textile interface with their friends and family members by commenting the following: *"My mom once asked me if technologies like VR enables her to touch me. With this pillow, I'd like to use it with my mom".* One female user mentioned that she would use this interface with children for fun. She also happily said that her partner agreed that it is meaningful and shows compassion, especially for the left-over kid-parent relationship, by saying *"Children won't get bored of these touches and gestures".* Two

users provided need-to-improve feedback on the set-up and connection procedure of the prototype.

5.4. Summary and discussion of study 3

This study provided statistical evidence and qualitative feedback to support the findings from studies 1 and 2 through *iPillowPal* to perform four types of affective gestures to support emotional communication and interaction for couples in LDR.

The Social Presence results show a significant increase in all four items, particularly improving user connection and making them happy, significantly when they are genuinely distanced from each other when interacting through the prototype. The comparison of the participants' emotions with Watson and Tellegen's model shows a significant increase in positive emotions and a decrease in negative emotions after using the prototype. Our result is consistent with Huisman's 2017 opinion that mediated gestural interaction creates affective responses and enhances social presence for distant relationships. Rognon et al. also indicated similar to direct touch, mediated social touch increased sympathy, empathy, co-presence, and trust towards the interlocutor during communication (Rognon et al., 2022).

Subjective measures on user experience indicate that participants appraise *iPillowPal* for its Novelty, Attractiveness, Dependability, and Stimulation and willingness to use it as a potential emotional communication tool in long-distance relationships.

6. Discussion

This study contributes to the growing body of knowledge on mediated social touch and affective gesture-based interaction for LDRs. Previous studies, such as Hassenzahl et al. (2012), emphasized the importance of mediated touch for emotional connection in LDRs. Our work advances this by incorporating affective gestures (e.g., Hug, Stroke, Poke) into interactive textiles, providing a nuanced approach to exploring how different gestures and real-time emotional feedback can influence emotional connection. Unlike prior research that primarily focused on haptic feedback devices (Price et al., 2022; Wang et al., 2012), our findings demonstrate how gesture types and emotional feedback mechanisms (e.g., vibration, light changes) elicit emotional responses in LDRs. Similarly, our study aligns with previous findings by Jiang et al. (2022) on gesture affordance in textile interfaces, where textures like pleating or quilting afforded specific gestures and elicited emotional responses. We extend this work by showing how dynamic emotional feedback from gestures, such as customized visual cues, further enhances the emotional experience. In addition, this research also resonates with the work of Rognon et al. (2022), which found that mediated touch could evoke empathy and connection in LDRs. While their study focused on online surveys, our work demonstrates that dynamic gestures paired with real-time feedback create more engaging and personalized emotional interactions, enhancing the sense of intimacy and connection in LDRs with both lab experiments and field trials.

6.1. Iterative research-design-research cycle of iPillowPal

In this work, the iterative research-design-research cycle for developing *iPillowPal* involved three key phases: Study 1-understanding user needs in the interview, Study 2-prototyping in the lab experiment, and Study 3-refinement for the field trial. Findings from each phase directly influenced the design choices made in subsequent iterations, see Fig. 14. This iterative design process ensured that *iPillowPal* evolved to meet the emotional and functional needs of LDR couples. By integrating user feedback at each phase, this work demonstrates how user-centred design principles (Abras et al., 2004) can guide the development of mediated affective gestural interaction systems that support an emotional connection in LDRs.

6.2. Design implications

We combine the findings from the above three studies and derive design implications for enabling affective gestural interaction with smart textile interfaces.

6.2.1. Affective gestures for emotional interactions

Prior gesture-based interactive textile studies designed textiles first, then derived or defined interaction gestures on the textile interfaces (Giles and van der Linden, 2014; Wicaksono and Paradiso, 2017; Mlakar and Haller, 2020), which limits the user to propose their preferred gestures on a particular interface. To avoid this issue, we followed a *research-design-research cycle* approach to develop aimed interactive gestures, then realized this gesture sensing with textile texture's gesture affordance design.

Of all proposed affective gestures in this work, Stroke and Hug gestures are highly preferred by both male and female participants in LDR (see Fig. 2b). Our participants mentioned that these two gestures provide comfort and a sense of security they seek from their partners. We also found that Stroke and Hug gestures are almost equally associated with diverse emotions, including negative ones. Price et al. (2022) also believed that Stroke gestures can communicate comfort or relaxed emotions. Participants preferred to use Pull and Poke gestures to express playfulness and as a nudge or reminder, respectively, for emotional communications in LDR. In contrast, the Pull gesture is preferred for expressing playfulness or a reminder. Also, we found that both male and female users follow similar emotional associations for Stroke, Hug, Poke, and Pull gestures in LDR. However, there is a preference for using affective gestures at a particular time of day. We suggest considering the instinctive affective gestures of the interfaces ahead to facilitate natural interaction.

6.2.2. Design textile textures, sensing and feedback mechanisms for affective gestures

We identified and adapted three suitable manipulation methods from `The Art of Manipulating Fabric` textbook (Wolff, 1996) and successfully deployed sensors and electronics underneath the shape-changing surface layer (Jiang et al., 2022). We followed a multiple-layer approach to build our textile interfaces by replacing the standard fabric with conductive fabrics. This method seamlessly integrates visual and haptic feedback mechanisms in the middle layer. We used a creamy-white stretchable scuba-knitted fabric as the base layer for our prototypes. Our participants suggested having ergonomically placed multiple sensing areas around the textile interface. They favoured employing gesture frequency and strength to express emotional intensity for affective-gesture-based textile interfaces. For example, our participants preferred vibration feedback over visual feedback for Hug. We believe this is because Hug involves more haptic sensory input than other gestures. Therefore, we recommend that smart textile interface designers consider the seamless integration of textile aesthetics and interaction or sensing elements to provide users with a positive and playful experience.

6.2.3. Methods to facilitate non-verbal communication for emotional interaction

Understanding gross and fine gestures is essential in studying body language and nonverbal communication because they can convey different levels of meaning and emotion. While gross gestures might be more overt and noticeable (involve large movements using large muscle groups, e.g., trunks, arms, or legs, to move the body, like Hug), fine gestures can communicate more nuanced emotions or intentions (e.g., Poke, Stroke, and Pull). Both types of gestures contribute to the overall nonverbal communication that occurs during social interactions. Prior work showed the benefits of gross gestures (arm gestures) using interactive textiles in emotion regulation (Jiang et al., 2021b,a). In this work, we further explored the emotional attributes of both fine

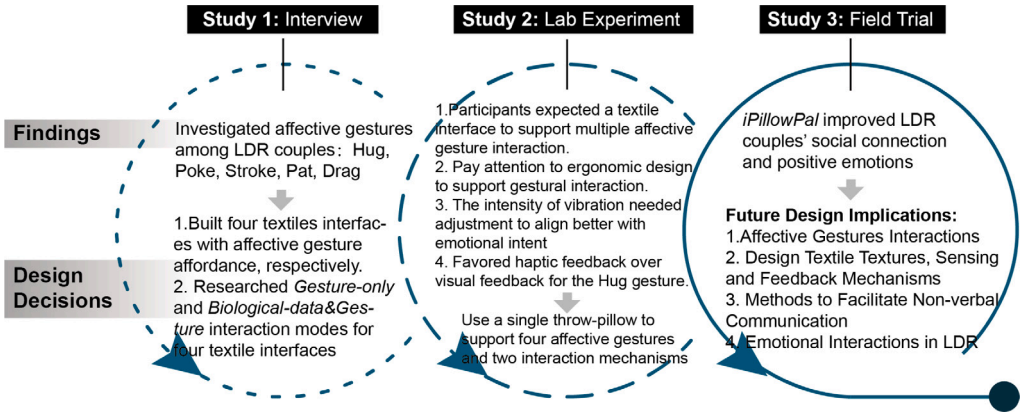

Fig. 14. Iterative Research-Design-Research cycles of three studies.

gestures and gross gestures (Hug) to facilitate smart textile interfaces that regulate user emotions. Similar to the previous work (Jiang et al., 2021b), we also found that gesture type determines the sensing, interaction, and feedback mechanisms. Thus, we recommend visual feedback for off-body textile interfaces requiring subtle finger movements and haptic feedback for gestures involving gross arm movements.

6.2.4. Understand the emotional interactions in LDRs

Emotional interaction is usually intertwined with multiple objectives. It is necessary to clarify the aim of emotion interaction (Ho and Siu, 2012). The emotion interaction objectives involved in this work includes *Emotion Communication*, *Emotion Expression*, *Emotional Effect*, and *Emotion Regulation* (Jiang et al., 2024).

In this work, we first investigated the *Emotional effect* of affective gestures in SDR and LDR in Study 1, then used *Emotional expression* method in Study 2 via gesture and bio-data interaction, and realized *Emotion communication* between couples. This process changed the user's emotional state, realized *Emotion regulation*. So was Study 3, participants realized *Emotion expression* and *Emotion communication* in their real lives via *iPillowPal*, and their *Emotional effect* came along, making the *Emotion expression* and *Emotion communication* a dynamic process, and realized *Emotion regulation* with increased positive emotions and social presence.

The *Emotion expression* and *Emotion communication* always accompany certain *Emotional effect*, but to reach the aim of *Emotion regulation*, proper design strategies and research are needed. For example, which kind of sensory perception leads to what kind of emotion? What is the relationship between affective gestures and emotion? Will the same design lead to different emotions with different long-distance social relationships, for example, friends, parent–children, etc.? These are the factors to think about when designing for LDR emotional interaction.

7. Limitations and future work

While this work demonstrates the potential of mediated gesture-based interaction to enhance emotional connection in long-distance relationships, future research should address several limitations:

Dependence on Custom Mobile App. Currently, the prototype relies on a custom-built Android mobile app to maintain the connection with a cloud server. Thus, two LDR partners must own an Android device and keep it near the *iPillowPal* to ensure a stable connection. The two-second delay in response delivery, while acceptable for initial testing, may impact the perceived immediacy of emotional interaction in real-world use. Future iterations of *iPillowPal* could explore peer-to-peer connection to improve accessibility and responsiveness.

Sample Size and Participant Diversity. The three studies were conducted with a relatively small sample size, primarily consisting of university students in LDRs. This demographic homogeneity limits the generalizability of the findings. Future research will recruit a more diverse participant pool, including varying age groups, cultural backgrounds (Au et al., 2022; Suvilehto et al., 2015), participants with diverse time zones and relationship types. Future research could investigate how *iPillowPal* performs across different demographic contexts.

Focus on Romantic Relationships. The study focused exclusively on romantic couples, which may limit the applicability of the findings to other types of social relationships. Participants also showed interest in how affective gestures can be adapted for different relationship contexts, such as parent–child bonds or friendships, as these relationships may involve different emotions and gesture preferences.

Ethical Considerations and Emotional Risks. Although the study carefully followed ethical protocols, there are some potential emotional risks using the prototype. For example, participants might feel frustrated if the prototype fails to function as expected or if their partner does not reciprocate gestures. Misinterpretations of gestures could potentially lead to misunderstandings or conflicts. To mitigate these risks, we will monitor participants closely in the future study and provide them with a support channel for technical or emotional issues.

8. Conclusion

This research explored the use of smart textile interfaces to enable people in long-distance relationships to experience the perception of touch and emotional communication. We focused on romantic partners who are geographically distanced from each other because they often experience deprivations of somatosensory interaction for intimate communication. To do this, we conducted three studies investigating the usability of smart textile interfaces for sensing affective gestures for LDR couples. The results show that using our prototype (1) increased LDR couples' positive emotions and decreased negative emotions, (2) improved their connections, and (3) made them feel more positive. With the findings from the three studies, we derived design implications for enabling affective gesture-based interactive textile design.

CRediT authorship contribution statement

Mengqi Jiang: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Vijayakumar Nanjappan:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Ziming Li:** Writing – review & editing, Writing – original draft, Visualization, Software, Formal analysis. **Zhen Wu:** Writing – review & editing, Writing – original draft, Software, Methodology, Formal analysis, Data curation. **Ziqian Bai:** Writing – review & editing, Writing – original draft, Supervision, Resources, Methodology, Funding acquisition. **Hai-Ning Liang:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ziqian Bai reports financial support was provided by National Natural Science Foundation of China. Ziqian Bai reports financial support was provided by Guangdong Provincial Natural Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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