Affective Touch as Immediate and Passive Wearable Intervention

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We investigated affective touch as a new pathway to passively mitigate in-the-moment anxiety. While existing mobile interventions offer great promises for health and well-being, they typically focus on achieving long-term effects such as shifting behaviors. As such, most mobile interventions are not applicable to provide immediate help in acute conditions – when a user experiences a high anxiety level during ongoing events (e.g., completing high-stake tasks or mitigating interpersonal conflicts). A few works have developed passive interventions that are effective in-the-moment by leveraging breathing regulations and biofeedback. In this paper, we drew on neuroscientific findings on *affective touch*, the slow stroking on hairy skin that can elicit innate pleasantness and evaluated affective touch as a mobile health intervention. To induce affective touch, we first engineered a wearable device that renders a soft stroking sensation on the user's forearm. Then, we conducted a between-group experiment, in which participants underwent high-stress situations with/without receiving affective touch and post-experiment interviews, with 24 participants. Our results showed that participants who received affective touch experienced lower state anxiety and the same physiological stress response level compared to the control group participants. We also found that affective touch facilitated emotion regulation by rendering pleasantness, providing emotional support, and shifting attention. Finally, we discussed the immediate effect of affective touch on anxiety and physiological stress, the benefits of affective touch as a passive intervention, and the implementation considerations to use affective touch in just-in-time systems.

CCS Concepts: • **Human-centered computing**; • **Empirical studies in ubiquitous and mobile computing**;

Additional Key Words and Phrases: anxiety, behavioral health, mental health, health intervention, passive intervention, affective touch, haptics, wearable

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1 INTRODUCTION

The rise of mobile technologies revolutionized personal health and wellness management. Digital interfaces and wearable devices provide insights into the users' health states, such as physical activity [28, 31, 121, 125], calorie intake [119, 130], and social interactions [1, 16, 120]. Moreover, mobile technologies bridge monitoring and intervention. Leveraging the rich data from mobile sensing, intervention systems facilitate self-reflection [10], provide just-in-time support to build healthy behaviors [82], and reduce access barriers to traditional interventions such as psychotherapy [63].

While current mobile intervention technologies are effective in promoting long-term well-being [22], they are limited in handling acute conditions. This is because most interventions require users to *actively* engage in interventions such as processing messages or seeking behaviors (i.e., exercise, meditation). In scenarios such as in high-paced workplaces or during interpersonal conflicts, users might experience a high level of anxiety but cannot withdraw from the ongoing tasks. These scenarios are critical to intervene because acute symptoms such as unmanaged anxiety can lead to detrimental health impacts (i.e., substance usage, anxiety disorders). In such acute moment-of-need, users can benefit from countermeasures that require minimal active participation and mitigate anxiety immediately.

A few researchers have started to explore mobile interventions that mitigate anxiety in-the-moment without active participation from the user. We characterized such an approach to interventions as *passive* interventions. The most prominent solution is biofeedback, which guides or regulates bodily functions using wearable sensors and unobtrusive interactions. For instance, "offset" heart rate feedback can alter the perception of heart rate to down-regulate or up-regulate anxiety [26, 33, 34]. Similarly, breathing regulations delivered through visual [48, 69], audio [48], and haptic patterns [48, 76, 87] can unobtrusively guide slow breathing, a century-old stress countermeasure. These works demonstrated the powerful potential of mobile interventions to immediately and passively mitigate anxiety and/or stress. However, the limited intervention modalities still form a sharp contrast with the abundant active interventions.

We explored a new pathway for anxiety countermeasures: **touch as immediate and passive intervention**. The intervention value of touch has long been explored by both the health community [97] and the HCI community [115]. However, most existing touch-based, behavioral health-benefiting devices are active interventions. We believe touch is also suitable in passive countermeasures because: (1) touch mediates communication of emotions [9, 94, 126, 127, 131], which is effective at regulating anxiety [43] and (2) passive touch typically occupies little cognitive load [39], especially in scenarios when users are engaged in visual- and auditory-occupying tasks. Specifically, we utilize ***affective touch*, the slow-moving, low-force mechanical stimulation on hairy skin** [64, 98]. Affective touch is a tactile processing with a hedonic or emotional component [80]. It codes an innately positive affect [73, 91] beyond the discriminative function of touch. Past work has shown that affective touch can convey positive emotions [7], reduce feelings of social exclusion [117] and increase tolerance to pain [118]. In addition, long-lasting affective touch delivered to participants in a salient state increased the participants' heart rate variability, demonstrating the potential for stress response mitigation [109].

We investigated whether affective touch delivered in a wearable form can function as an immediate and passive anxiety countermeasure. Specifically, we asked two research questions: (1) How effective is wearable affective touch in passively mitigating in-the-moment stress and anxiety? (2) How do users perceive receiving affective touch as an intervention in cognitively demanding, stressful scenarios? To investigate these questions, we first engineered a wearable device that renders affective touch on the user's forearm by creating a soft stroking sensation via a moving brush-like actuator. Then, we stimulated cognitive stress in laboratory and conducted a between-group experiment and post-experiment interviews with 24 participants. We found that affective touch effectively mitigates state anxiety in-the-moment, but not the physiological stress response. We also identified that participants perceived the intervention to be pleasant and minimally distracting. Lastly, we discussed the implementation considerations for future researchers when leveraging affective touch in just-in-time systems.

2 RELATED WORK

Our work builds upon prior work on mobile intervention for anxiety, passive anxiety countermeasure, and affective touch.

2.1 Mobile Intervention to Mitigate Anxiety

Anxiety is an emotional state characterized by a feeling of tension when the human body responds to environmental stressors [100]. While being anxious is a normal state of mind, accumulated and unregulated anxiety can cause or exacerbate physical and mental illness [59]. With the rise of mobile technologies, there is a growing interest in using digital interfaces to increase access to anxiety interventions. There are three main groups of intervention techniques using digital interfaces: (1) mindfulness practices, (2) digitization of traditional therapies, and (3) novel multisensory and multi-modality countermeasures.

Mindfulness is a state of consciousness that focuses on an individual's attention and awareness of the present moment [35, 103]. More than 2500 mindfulness apps have been launched since 2015 [105], with the most popular ones such as *Headspace* [53] and *Calm* [20] being evaluated in clinical and psychiatric settings [40, 70]. Chen et al. [24] proposed a smartphone app that uses sonification of biophysical data to engage users in walking meditation. Cochrane et al. [29] further investigated the first-person walking meditation experience with an interactive soundscape. These mindfulness-based interventions have shown effectiveness in anxiety reduction in long-term deployment [66, 79]. The digitization of traditional therapy is also prevalent. Delivering therapies such as cognitive behavioral therapy through the internet has shown effectiveness in many randomized control trials [79] and in psychotherapy [8]. Moreover, wearable and mobile interfaces allow researchers to create novel practices ranging from gamified social support network [88] to tangible representations of physiological signals [67].

Mobile anxiety interventions undoubtedly flourished but still face one limitation. Most interventions are *active*: they require active participation from the users. However, anxiety can happen in acute, and overwhelming situations (e.g., public speaking, interpersonal conflicts), in which the users might need intervention but cannot withdraw from the ongoing tasks [4]. Therefore, passive interventions that can mitigate anxiety without active engagement are essential to help users in acute situations.

2.2 Passive Anxiety Countermeasure

Only a few researchers have investigated passive countermeasures for anxiety. All current passive interventions leverage biofeedback, which refers to the alternation of physiological functions and emotional experiences by increasing the awareness of physiological signals [12, 112]. There are two main approaches under the broad umbrella of biofeedback: (1) to provide (offset) heart rate feedback and (2) to regulate breathing rate. *EmotionCheck* [33] provided an offset heart rate feedback on the user's wrist through vibration and demonstrated effectiveness in altering heartbeat rate, stress, and anxiety level. *BoostMeUp* [34] further showed that offset heart rate feedback could be delivered to individuals during cognitive tasks and achieved anxiety regulation without distracting the users. *AmbienBeat* [26] reached closed-loop biofeedback via tactile stimulus based on users' heartbeat rate (HR). Besides offset heart rate feedback, researchers also leveraged the bidirectional association between breathing patterns and stress to design interventions [48]. The respiratory system reacts to stress with shallow and fast breathing [23]; voluntary deep and slow breathing can help regulate stress response, hence mitigating anxiety [19]. *Affective Sleeve* regulated breathing through rhythmic sensations of warmth and slight pressure to promote calmness [87]. Choi et al. [25, 27] designed a mobile pneumatic-haptic device to help users regulate their breathing rate via subtle tactile feedback. Many other works leveraged visual [48, 62, 69, 129], audio [48, 62], and haptic [48, 62, 76, 77] cues to guide the user's breathing. Umair et al. engaged users to design personalized haptic patterns to regulate affect [111]. *Just Breath* [89] and *Calm commute* [11] experimented with in-car breathing intervention that leveraged haptic vibration on the driver's seat. They found that such intervention can regulate stress response without affecting driving safety and performance.

While prior research demonstrated the potential of passive interventions in regulating anxiety without explicit user engagement, they mostly leveraged biofeedback. In this work, we explored a new pathway to mitigate anxiety passively.

2.3 Affective Touch

We evaluated affective touch, the slow-moving, low-force mechanical stimulation on hairy skin [64, 98], as a new pathway for mobile anxiety intervention. The sensory perception of touch enables us to interact with the physical environment and communicate emotions with each other. While researchers historically viewed touch as primarily functioning in a discriminative role [81], more works have started to focus on the affective value of touch [74]. Specifically, researchers identified C-Tactile (CT) afferents, existing in the hairy skin of the human body, as the primary pathway for affective touch [86]. The CT afferents respond optimally to light, stroking sensations at a force under 2.5 mN and slow speeds of 1-10 cm/s with a mean activation peak at around 3 cm/s [3, 113]. The CT optimal touch is perceived to be the most pleasant [3, 44, 45, 64, 91]. Such pleasant perception is an innate non-learned process [73] moderated by the reward pathway. Specifically, CT afferents trigger a reward in the brain's opioid system [74, 92]. The brain encodes this reward from with affiliative interactions (i.e., parental care during infancy), which activate the serotonergic systems [74]. Both the opioid and serotonergic systems are strong moderators of the emotion regulation system [21] that can suppress anxiety [49].

Solid cognitive-behavioral evidence supports affective touch's ability to impact both subjective feelings and physiological states. Affective touch is shown to communicate positive emotion [7, 52, 57], reduce the sense of isolation [117], and increase tolerance to pain [118]. Researchers further experimented with long-lasting affective touch delivered to participants when they lay still and showed that affective touch could enhance heart rate variability [38, 109]. To deliver affective touch, the most common approach is to use a soft brush controlled by another person or a robotic arm to stroke the hairy, posterior side of the forearm [110, 117]. Researchers also proposed new engineering solutions, such as using vibrotactile array [54, 85] and pneumatic technique [124].

The abundant prior work demonstrated the potential of affective touch in inducing pleasant affect, easing adverse affect, and regulating physiological responses. However, we are yet to know whether and to what extent affective touch regulates in-the-moment anxiety and whether the same effect can be translated in a wearable form. In addition, receiving touch is innately passive yet intimate. Therefore, we need to understand how users respond to wearable device-delivered affective touch in a high-stress situation. We land the first step in investigating device-delivered affective touch as a passive anxiety intervention in this work.

3 INTERVENTION IMPLEMENTATION

Past work demonstrated various actuation methods to render affective touch, such as brushing one's forearm with a soft brush [91, 109, 117], combining voice coils and haptic illusions [54, 85], or using by pneumatic technique [124]. Among those actuation techniques, the brushing method is the most well-validated one to activate CT afferents [3, 45, 64, 73, 74, 86, 91, 113], the key to affective touch. Most prior studies used human-controlled brushes. We adopted the same design of brushing on the posterior of the forearm in a wearable form factor. This decision was a balance between ensuring the delivery of affective touch (i.e., activating CT afferents, the key of affective touch) and designing a wearable form factor to evaluate affective touch as a mobile

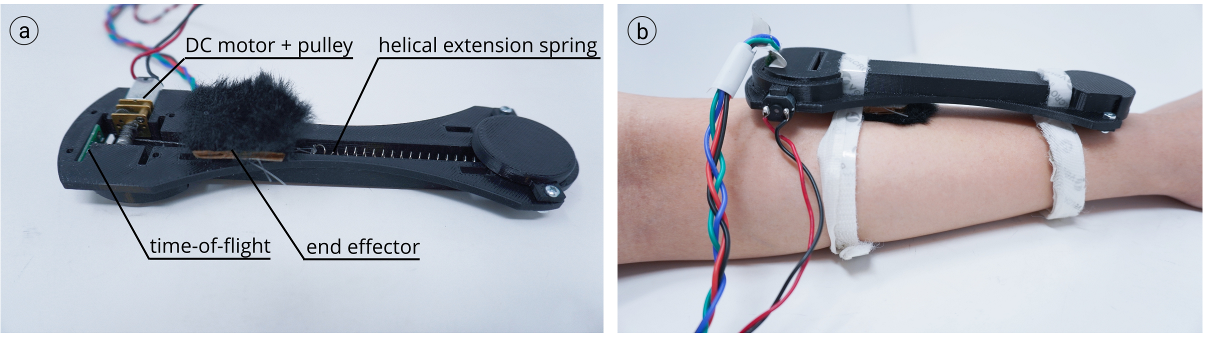

Fig. 1. (a) Key components used to implement our wearable; (b) Our device is mounted to the posterior side of user's forearm and strokes their skin.

intervention. The former took priority; for the latter, we aimed to engineer a device that can be translated to a more wearable-friendly form in the future.

Figure 1 shows the implementation of our wearable device to deliver affective touch. The device has a total dimension of 170L × 50W × 25H mm and weighs 77g. The end effector of our device (i.e., the part that contacts the user's skin) is a 3cm × 2.5cm synthetic fur. We chose this end effector material and size because they best approximated the cross-sectional area and the feel of the brushes used in prior work [109]. To move the end effector back and forth on the user's forearm, we utilized a spring mechanism: we attached an extension spring at one end of the device and attached the other end to the end effector. Our device actuates the end-effector along the forearm using a pulley controlled by a small DC motor (Pololu 250:1 Micro Metal Gearmotor). The total one-way stroking distance of the end effector is 3 cm. To control the end effector's stroking speed and direction, we attached a time-of-flight sensor (Pololu VL6180X) at the end of the device, next to the DC motor. We controlled the end effector to stroke at 3±0.5cm to achieve the most pleasant sensation [64]. We housed all components in a 3D-printed case, following the ergonomics of the forearm. As shown in Figure 1b, we placed the device on the posterior side of the forearm to ensure the end effector brushes on the hairy skin (where CT afferents reside) [74]. We used two Velcro bands to attach the wearable.

4 METHOD

We conducted a between-subject in-laboratory study to evaluate the effectiveness of affective touch in mitigating in-the-moment anxiety. We defined (1) in-the-moment anxiety as the anxiety that the users experience during stress exposure and (2) immediate intervention as the intervention that mitigates physiological stress and anxiety during stress exposure and has immediate effects. To test affective touch's immediate effect on in-the-moment anxiety, we designed an in-laboratory evaluation such that: (1) the intervention is active concurrently with stress exposure, and (2) the effect of the intervention is assessed during stress exposure. We adapted a version of Trier Social Stress Test (TSST) [6], a robust laboratory method to induce stress responses, during which the participants completed a series of stressful cognitive tasks. We assumed that TSST triggered stress responses as soon as participants entered these tasks. One group of participants received the affective touch as intervention once TSST started while the other group did not. We measured momentary physiological stress throughout TSST and measured state anxiety after each cognitive task to best approximate in-the-moment anxiety. We also measured the pleasantness and distraction rating toward affective touch. After the stress-inducing procedures, we conducted semi-structured interviews to understand how participants feel about receiving affective touch during cognitive tasks.

4.1 Conditions

We utilized a two-group, single-blind, between-subjects study design with independent groups who did not have prior knowledge about the intervention or TSST. Both groups underwent the same cognitive tasks (speech preparation, mental arithmetic, speech) adapted from TSST. After cognitive tasks, both groups underwent device tryout. Both groups wore the device during the experiments. The *control* group participants did not receive the stroking sensation during cognitive tasks. The *experimental* group participants received the stroking sensation during cognitive tasks. After cognitive tasks, both groups experience the stroking sensation during the device tryout. Participants in neither group were aware that they were in a controlled experiment during the study, nor did they know which group they were in. All participants were aware of when the device would turn on.

We chose this group design because our goal is to evaluate the effect of wearable affective touch on anxiety. Therefore, the independent variable that impacts anxiety should be whether affective touch is activated from a wearable device. Because affective touch has specific activation criteria that are most dependent on stroking velocity [3, 113], we do not expect affective touch to be activated by wearing a soft actuator; hence the control group will not experience affective touch even though they wear the device.

4.2 Hypotheses

We hypothesized that participants who received affective touch during cognitive tasks would experience lower state anxiety and lower physiological stress responses compared to participants who didn't receive affective touch:

(1) State anxiety:

- **H0**: Participants who received affective touch exhibited **the same level of state anxiety** as participants who didn't receive affective touch during TSST.
- **H1**: Participants who received affective touch exhibited **lower state anxiety** and **lower change in state anxiety** than participants who didn't receive affective touch during TSST.

(2) Physiological stress response:

- **H0**: Participants who received affective touch exhibited **the same level** of the stress response as participants who didn't receive affective touch during TSST.
- **H1**: Participants who received affective touch exhibited **lower change in stress response** than participants who didn't receive affective touch during TSST.

4.3 Experiment Protocol

4.3.1 Apparatus. The study was conducted on campus at a North American institute. The participants and researcher sat facing each other around a table in a windowless room. Before starting the study, participants wore a Polar H10 chest band [95], an off-the-shelf device to collect participants' heart rate data in the following task sessions. Then, the researcher placed the device on the participant's arm that wouldn't use the computer trackpad. This allowed the participants to have a free hand to fill in surveys displayed on the laptop during the study. The participants were told that they could move their device-wearing arms as they liked while watching out for the wires. To block out motor noise, participants wore noise-canceling headphones during the study.

4.3.2 Preparation and Deception. We informed participants that they were recruited to try out a haptic device during/after doing cognitive tasks that they might perform in a professional setting. Researchers first informed the participants that "we will first help you wear the device. Then, you will first watch a short video. After that, we will have you go through a job interview. The video content is not related to the interview". To the control group participants, researchers informed them that "the device will be turned on after you complete the interview". To the experimental group participants, researchers informed them that "the device will be turned on after you watch the video, as soon as we enter the interview section".

We performed multiple layers of deception. To ensure the effectiveness and validity of TSST, we did not disclose that there would be a mental arithmetic task or that the cognitive tasks were intended to induce stress. We also did not disclose that the experiment was a controlled experiment and there were two groups that the participants might be in. We also withheld the true purpose of the haptic sensation from the participants to minimize the expectancy effect at the end of the study.

4.3.3 Procedure. Our study consisted of five sessions adapted from TSST: (1) baseline video watching, (2) speech preparation, (3) mental arithmetic, (4) speech, and (5) device tryout. We monitored the participants' electrocardiography (ECG) throughout the experiment and asked the participants to complete surveys on anxiety levels between each session.

TSST is the golden standard to induce stress responses in-laboratory [6]. Since its original development in 1993, numerous researchers have adapted TSST to fit their research goals. Generally, TSST consists of baseline, anticipatory speech preparation, speech, unanticipated mental arithmetic, and a recovery period [13]. Participants perform the speech and mental arithmetic in front of two or three socially evaluative researchers [13]. The speech is most commonly structured as a job interview to create a natural context for social evaluation [58]. Diverse adaptations of TSST include removing the unanticipated mental arithmetic [33], conducting TSST in VR [46], and conducting TSST in group settings [116].

The two key stressors of TSST are social evaluation and uncontrollability [13, 58, 60]. We adopted our protocol to comply with these two stressors. We followed the widely-used social evaluation protocol by asking participants to perform job interviews and verbally express arithmetic answers to two socially evaluative researchers. To induce a high level of uncontrollability, we placed the unanticipated mental arithmetic task between speech preparation and speech so that participants would also experience uncontrollability during speech. Specifically, we asked the participants to prepare for the speech mentally. Participants need to load their working memory to remember the content they have prepared, then immediately load their working memory again by performing mental arithmetic. When participants perform the speech after the mental arithmetic, they would not only experience the social evaluation, but also face the additional difficulty of recollecting their prepared content.

The detailed study procedure (Fig. 2) is:

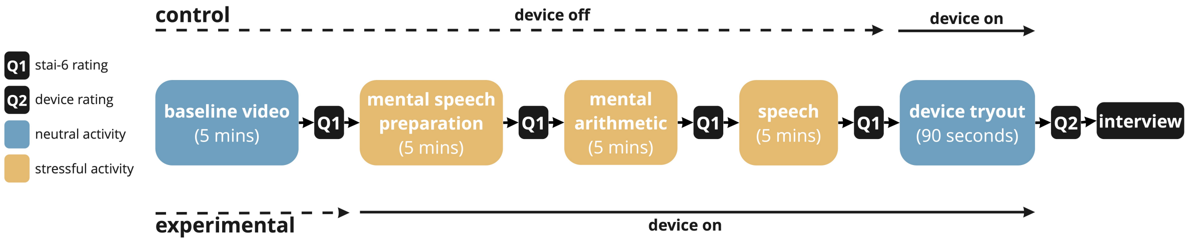

Fig. 2. Study procedure.

Baseline. Participants watched a 5-minute neutral video alone. This step is for collecting baseline physiological data and anxiety levels. After the baseline session, researchers informed the *experimental* group participants that now the device would turn on. After informing the *experimental* group participants, the researchers activated the device. The device kept running for the rest of the study.

Speech preparation. Participants were then instructed to mentally prepare a talk about a 10-year vision for a company or organization they are applying for and elaborate on what their contribution would be. Researchers set a timer for 5 minutes and left the study room. The participant stayed alone in the room to prepare for the talk. This stage was designed to induce anticipatory stress [6].

Mental arithmetic. Researchers entered the room to conduct the next session. Instead of giving the prepared speech, participants were asked to complete a 5-minute mental arithmetic task. They were asked to count the multiples of 37 backward from 5698. The researcher sat in front of the participants and did not express any facial or body language; they only notified the participants when an answer was wrong. This session was designed to serve as a surprise factor.

Speech. After the mental arithmetic task, the participants were asked to give a talk on the topic they had prepared earlier. Similar to the prior session, the researchers did not display any facial expressions to induce social stress. If the participants stopped talking, the researchers would inform them "you still have time" and demand them to "keep going".

Device tryout. Lastly, researchers informed the control group participants that the device would now turn on. Researchers activated the device for control group participants/kept the device running for the experimental group running for another 90 seconds. Participants listened to office noise from the headphone to further block out the motorized noise. After the device tryout, researchers stopped the device and asked participants from both groups to rate the distraction and pleasantness level of the sensation delivered by the device.

4.4 Participants

We conducted the study with 32 participants. Eight samples were excluded in the data analysis due to low ECG quality and interruption during the study. This left us with a total of 24 valid samples, 12 participants from each group. Participants ranged from age 21 and 52 (control: mean = 25.16, SD = 2.26; experimental: mean = 27.42, SD = 6.54). The sample population included 12 participants who identified as male and 12 participants who identified as female (control: six females and six males; experimental: six females and six males). Participants identified their races as seven Caucasian (control: two, experimental: five), 11 Asian (control: seven, experimental: four), 3 Middle Eastern (control: two, experimental: one), one Latin American (control), one African American (experimental), and one multi-ethnic with Caucasian and Asian (experimental). All participants were recruited from the student body of a North American graduate institute and resided in the United States at the time of the study. They received \$15 or \$20 for completing the study. The study was approved by our Institutional Review Board.

4.5 Measures and Data Processing

We performed continuous stress monitoring and per-task state anxiety measurements. This approach is different from conventional TSST, which treated TSST as a *treatment* and measured the stress/anxiety pre- and post-TSST. We didn't follow the convention because we were interested in the in-the-moment anxiety-mitigating effect.

4.5.1 State Anxiety.

We assessed state anxiety with the Six-Item State-Trait Anxiety Inventory (STAI-6) [108]. The original STAI measurements include 40 items, of which 20 items are used to measure state anxiety and 20 items are used to measure trait anxiety. The six-item short version was developed to assess state anxiety in a fast-paced environment by selecting six items with the strongest correlated with 20-item that measures state anxiety [108]. We instrumented STAI-6 to assess the participants' state anxiety at the end of each block.

We computed STAI-6 score such that the three anxiety-present items account for positive scores (1 to 4) and the three anxiety-absent items account for reversed scores (4 to 1) [55]. The possible range of each participant's STAI-6 score ranges from 6 to 24. The higher the STAI-6 score is, the higher level of anxiety the participant experiences. We compared STAI-6 in two ways: (1) we directly compared the STAI-6 score of each task and (2) we computed the **change from baseline** for each task. We calculated the change from the baseline because each participant's baseline anxiety can be different (i.e., due to other life events happening before/after the experiment); therefore, assessing both metrics gives a more comprehensive understanding of the participant's reaction to affective touch.

4.5.2 Stress Response. We assessed in-the-moment stress through heart rate variability (HRV), the variation between consecutive heartbeats and exhibits the activity in the ANS [75]. We collected **raw ECG** signal using Polar H10 throughout the experiment. ECG was sampled at 133Hz. We processed the raw ECG of each participant in the following pipeline [41, 68, 114]: (1) apply a bandpass filter between 0.5Hz to 60Hz; (2) remove baseline wander that is below 0.05Hz; (3) detrend the signal; (4) re-sample the signal to 10x sampling frequency to suppress poor contact artifacts; (5) detect heart rate peaks [114]; (6) remove outliers RR-interval that are less than 300ms or greater than 2000ms; (7) remove ectopic heartbeats using the Malik rule [2]. We then computed HRV metrics from the cleaned RR-intervals for each 5-minute block of our study using Kubios, the most well-recognized HRV processing software. We chose this processing window because 5 minutes is the conventionally used minimum length to compute neurophysiologically meaningful HRV metrics [101].

We took two approaches in choosing HRV features. The first is the neurophysiological approach that considers HRV to be primarily influenced by two systems: (1) the interaction between the parasympathetic branch and the sympathetic branch of the autonomic nervous system (ANS) and (2) the impact of baroreflex and respiratory control [102]. Researchers conventionally use the Root Mean Square of Standard Deviation(RMSSD) and the high-frequency band power (HF) to approximate the parasympathetic activation [101]. RMSSD and HF are correlated, while RMSSD is less influenced by respiration [101]. HF can be reported in absolute value or log-transformed value. We utilized the absolute value following the recommendations from The European Society of Cardiology and The North American Society of Pacing and Electrophysiology [41]. The second approach is the Neuralvesceral Integration approach which emphasizes the role of the central autonomic network (CAN) in HRV regulation. This view considers the role of the brain in HRV regulation and underlines that HRV is also influenced by emotion and cognition [90]. Guided by this theory, many cognitive-behavioral experiments utilize entropy in assessing the regularity of heartbeats during cognitive stress tasks [14, 15, 37, 128]. Lower entropy is correlated with lower brain-heart interaction, lower cognitive adaptability to stressors, and higher sympathetic influence. We utilized Sample Entropy (SampEn) because it is the most robust metric for our recording length (5 minutes) [71, 96, 104].

HRV metrics have large individual variance. For instance, the absolute value of HF can range from $83ms^2$ to $3630ms^2$ [84]. As such, a decrease in HF from $1300ms^2$ to $1000ms^2$ cannot be compared with a decrease in HF from $100ms^2$ to $83ms^2$ unless we normalize these metrics. To enable between-subject comparisons, we baseline-adjusted HF, RMSSD, and SampEn by computing the *percentage of change from baseline* for each subject: we subtract the HRV metric of each task by the corresponding metric of the baseline, divided this difference by the metric of the baseline, and factored this rate of change as a percentage:

$$\Delta\text{HRV}_{\text{metric, task}} = \frac{\text{HRV}_{\text{metric, task}} - \text{HRV}_{\text{metric, baseline}}}{\text{HRV}_{\text{metric, baseline}}} \times 100 \tag{1}$$

4.5.3 Pleasantness and Distraction. To understand participants' perception of the sensation that our device rendered, we asked participants to rate the pleasantness and distraction level of the sensation at the end of the study. Specifically, they rated the pleasantness on a scale of -100 to 100 (-100: 100% unpleasant; 0: neutral, 100: 100% pleasant) and the distraction on a scale of 0 to 100 (0: no distraction, 100: 100% distraction). We chose these numeric scales because (1) they align with how prior research quantified pleasantness in touch [45]; (2) they have sufficient resolution to capture the "exactness of subjective experience" [5], and (3) percentage is commonly understandable.

4.5.4 Interview. We performed a post-experiment semi-conducted interview after the participants completed the device tryout. Each interview lasts for 10-20 minutes. We ask the participants to describe (1) how they felt when performing the tasks (as a form of manipulation check), (2) how they felt about wearing the device and/or being stroked during the tasks, and (3) how they allocated cognitive load to the task, the device, or other sources of attention during the tasks, and (4) how they would describe the sensation rendered by the device. We took observation notes during the interview.

We analyzed our interview recordings, transcripts, and observation notes using affinity diagrams [78]. The co-first, third and fourth authors first open-coded five transcripts to construct the initial version of the codebook. Then, the co-first authors iteratively coded a subset of the interview transcripts until the codes were saturated. We built codebooks with four main codes and 12 sub-codes regarding the pleasantness and unpleasantness, level of distraction, message conveying, and user control over the intervention. These codes were applied to the entire transcript dataset. After coding all textual data, we conducted an affinity process to yield larger themes. All authors reviewed the derived themes together to elaborate and validate the results.

4.5.5 Statistical Analysis. We performed statistical analysis to validate whether *affective touch significantly mitigates physiological stress and anxiety in-the-moment during TSST*. We treated RMSSD as a parametric measurement and STAI-6, HF, and SampEn as non-parametric measurements: the STAI-6 score is ordinal, while HF and SampEn are not normally distributed. To validate that the baseline measurements are not significantly different among groups, we performed Mann-Whitney U Test for non-parametric measures and t-test for the parametric measurement. For in-TSST measurements, we first performed an aligned-rank transform (ART) [123] to non-parametric measurements to allow the use of ANOVA. We performed two-way ANOVA with conditions (control vs. experimental) and tasks (speech preparation, mental arithmetic, and speech) as independent variables. Although we are not interested in how the responses to affective touch differ between each cognitive task, we recognized that the different task impacts the responses. After ANOVA, we conducted contrast tests for the main effects of conditions with Tukey p-value adjustment. Specific to non-parametric measurements, we utilized ART-C [42] to conduct contrast tests because ART-C was developed to perform contrast tests for ART-transformed data. If the main effect of conditions yields significance, we calculated the effect size of the intervention using Cohen's d for parametric measurements and partial η^2 for non-parametric measurements [61]. We consider $d \geq 0.8$ and $\eta^2 \geq 0.14$ as large effect size [30]. If the interaction between tasks and conditions were non-significant, we performed Mann-Whitney U test/t-test to compare the control and experimental responses during each task to understand per-task effectiveness. We utilized Δ to denote the change from baseline, μ to denote mean, and M to denote median.

5 RESULTS

5.1 How Effective is Affective Touch at Mitigating In-the-moment Anxiety Passively

We summarized the ANOVA results in Table 1. In baseline, we did not find significant effect of conditions on STAI-6 ($M_{control}$ = 8.0, M_{exp} = 9.5, p = 0.4645), RMSSD ($\mu_{control}$ = 34.677, μ_{exp} = 37.597, p = 0.7223), HF ($M_{control}$ = 611.150, M_{exp} = 552.112, p = 0.9795), or SampEn ($M_{control}$ = 1.549, M_{exp} = 1.513, p = 0.8566).

5.1.1 State Anxiety. Figure 3 illustrates the trend of state anxiety during the cognitive tasks. For absolute anxiety, we found significant main effect of tasks (p = 0.0004) and conditions (p = 0.0373). The interaction between tasks and conditions was insignificant (p = 0.8675). For the change in anxiety, we found a significant main effect of tasks (p = 0.0003) and conditions (p = 0.0006) on state anxiety. The interaction between tasks and conditions was insignificant (p = 0.8674) (Table. 1).

During all tasks, the control group experienced higher anxiety comparing to the experimental group (Preparation: $\mu_{control}$ = 14.00, μ_{exp} = 12.67; $M_{control}$ = 14, M_{exp} = 12. Mental arithmetic: $\mu_{control}$ = 17.67,μ_{exp} = 16.25;

Table 1. Two-way ANOVA results for state anxiety and HRV measurements

Metric	Interaction	F	p	Metric	Interaction	F	p
Absolute STAI-6	Task	4.5167	0.0004**	RMSSD	Task	0.3190	0.7280
	Condition	8.5907	0.0373*		Condition	0.7044	0.4043
	Task * Condition	0.1547	0.8570		Task * Condition	0.2426	0.7853
Change in STAI-6	Task	9.1654	0.0003**	HF	Task	0.3418	0.7118
	Condition	12.8823	0.0006**		Condition	0.2565	0.6142
	Task * Condition	0.1425	0.8675		Task * Condition	0.6116	0.5455
				SampEn	Task	1.7234	0.1864
					Condition	8.7601	0.0043**
					Task * Condition	0.0433	0.9576

*: p <0,05, **: p <0.01

$M_{control} = 18$, $M_{exp} = 15.5$. Speech: $\mu_{control} = 14.58$, $\mu_{exp} = 13.33$; $M_{control} = 14$, $M_{exp} = 13$). The experimental group reported significantly lower state anxiety during mental arithmetic (p = 0.023).

The experimental group also had lower changes in state anxiety in all tasks (Preparation: $\mu_{control} = 6.00$, $\mu_{exp} = 3.25$; $M_{control} = 5.0$, $M_{exp} = 3.5$. Mental arithmetic: $\mu_{control} = 9.67$,$\mu_{exp} = 6.83$; $M_{control} = 10$, $M_{exp} = 6.5$. Speech: $\mu_{control} = 6.58$, $\mu_{exp} = 3.92$; $M_{control} = 6.5$, $M_{exp} = 3.0$). Such changes in state anxiety was significantly lower in speech preparation (p = 0.0309), mental arithmetic (p = 0.0142), and speech (p = 0.038). The effect size of conditions was large ($\eta^2 = 0.16$). Our results indicated that, while all participants felt more anxious during tasks than during baseline, the experimental group participants were less anxious during the mental arithmetic and had a smaller increase in state anxiety throughout the experiment.

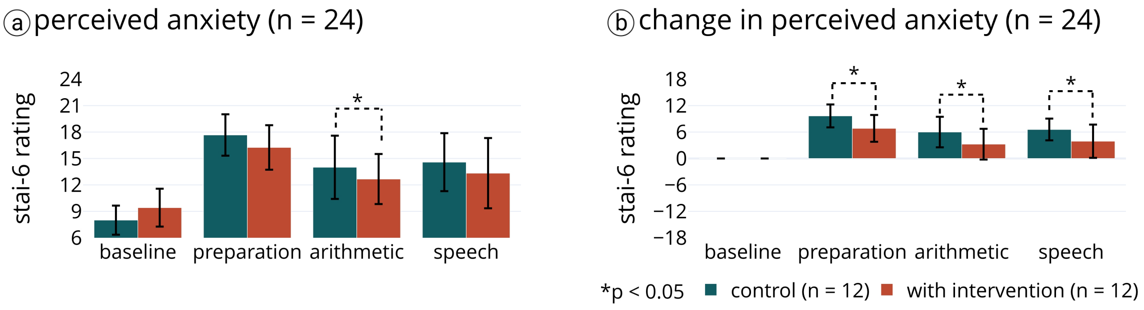

Fig. 3. Effect of intervention on state anxiety.

5.1.2 Heart Rate Variability. Figure 4 illustrates the trend of HRV metrics during the cognitive tasks. We found that both tasks (p = 0.0103) and conditions (p = 0.0088) had a significant effect on SampEn but not on HF or RMSSD (Table. 1). The interaction between tasks and conditions was not significant for either of the three metrics. During each task, we didn't find a significant effect of conditions on either of the three metrics. However, we found that the median percentage of change in SampEn was larger and more negative for the control group than for the experimental group (speech preparation: $\Delta_{control} : -16.24\%$, $\Delta_{experimental} : -0.57\%$; mental arithmetic: $\Delta_{control} : -18.67\%$, $\Delta_{experimental} : -3.28\%$; speech: $\Delta_{control} : -24.80\%$, $\Delta_{experimental} : -3.28\%$). This indicates that the control group might experience lower brain-heart interaction and higher sympathetic influence during tasks than the experimental group.

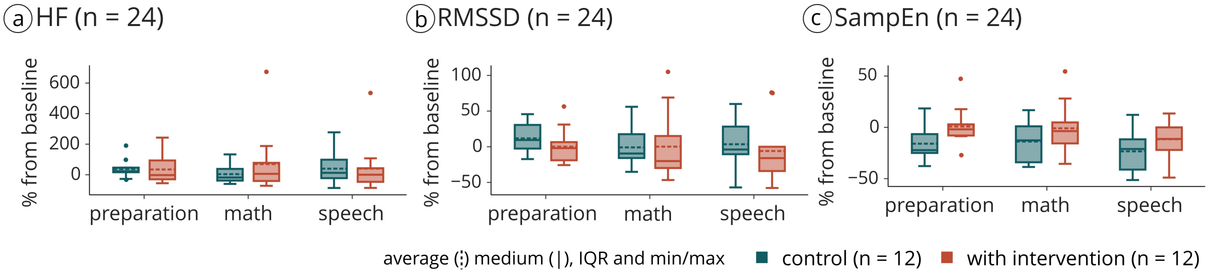

Fig. 4. Effect of intervention on HRV metrics. (a) high-frequency band power (HF), (b) root mean square of successive differences between normal heartbeats (RMSSD), and (c) sample entropy (SampEn)

5.2 How Users Perceive Affective Touch During Stressful Cognitive Tasks

5.2.1 Render Pleasant Sensation. Participants rated the pleasantness of the intervention at 36 ±49 on a scale of -100 to 100 (Figure 5). 20 out of the 24 participants rated positive pleasantness. They attributed the pleasantness to the softness and the slow, steady movement of the end effector. Participants described the sensation as a "*warm, fuzzy feeling*" (P28) and "comfortable" (P17). P25 elaborated that "*[the sensation] is like a feather riding on a surface to make you feel less stressed out and anxious*". P21 connected the sensation to "*the cotton candy*" because the end effector was "*so fluffy*". P13 related the sensation to a "*sweater*" and "*a teddy bear stroking [her] with [its] fingers*". Multiple participants (P04, P13, P17, P28, P27, P30) related the experience of interacting with an animal. P17 thought of "*when [he] rubbed [his] dog's tail on my arm*" during the intervention. P27 also connected the sensation to his dog and described it as "*pet rubs against the side of [his] arm...a loving sensation*". Similarly, P18 described the intervention as "*[the] closest to [her] previous roommate's cat; when [she] was working in meetings, [the cat] would constantly try to seek out attention and just touch [her]". As for the pleasantness in the effector movement, participants described such movement as "a calm heartbeat that's going at a slow rhythm*" (P27) or "*a wave going down your arm*" (P31), which reminded them of "*a very calm feeling... sitting by the sea*" (P03).

Four participants perceived the sensation as unpleasant. All four participants considered the end effector to be "*itchy*" (P26, P29, P32) or "*ticklish*" (P31). P29 also found the periodic stroking motion to be odd and unnatural because "*in [her] daily life, [she] never felt that kind of touch, this kind of periodic motion here*" (P29).

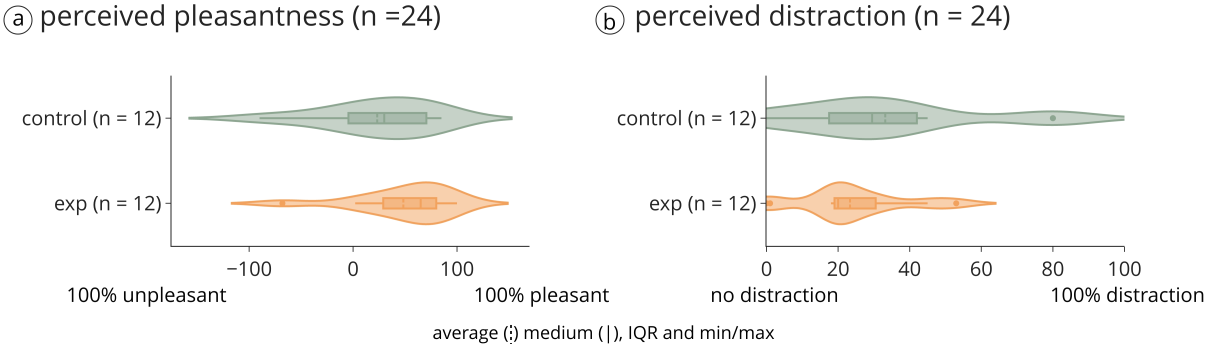

Fig. 5. Subjective rating from participants. (a) pleasantness level and (b) distraction level of the sensation rendered by our device.

5.2.2 Deliver Minimally Distracting Intervention. Participants rated the distraction level of the intervention as 28 ± 20 on a scale of 0 to 100 (Figure 5). During interview, 22 out of the 24 participants reflected that the intervention did not distract them from the cognitive tasks: they became habituated to the sensation and could easily pay attention to the tasks. P13 described the habituation of the sensation as "*it's the kind of sensation you feel... for a while, [then] you will forget it*". P23 commented that she could "*notice it for the first… minute, but then after that, it [got] like a little less noticeable*" because "*[her] skin became like less sensitive to [the sensation]*". Participants also noted that they could easily focus on the cognitive tasks while they were being stroked. P08, for example, described that "*when [the researcher] first put it on, [she] noticed it was there. But as we were doing the other tasks, [she] was more focused on the tasks and less on the device*". P21 added: "*when [she] was doing the task, [she] wasn't really thinking about it*". The cognitive load allocated to the sensation was low. P18 shared that she put on "*lower than 10%*" of cognitive load on the sensation as she "*tried to ignore it*". The steady motion of the effector helped the participants focus on the cognitive tasks because the sensation was "*just repeating*" (P32).

The engineering of the device altered the perception of the distraction. A major engineering byproduct is motorized noise. Despite using noise-canceling headphones, participants could still hear some noise during the intervention. Most participants found the motor noise non-distracting. They reported that they "*didn't really hear the noise very much, to be honest*" (P28), and "*when [they were] doing the task, [they] wasn't really thinking about it*" (P21). P20 even favored the coupling between touch sensation and motorized sound: "*It was easy to either zone out or use it to help me focus because they were coupled*" (P20). However, two participants found the "*noise… disrupted me very much*" (P31) and they became "*was annoyed that noise*" (P31), even described the noise as "*fire alarm*" (P26). The wiring of the device also increased the level of distraction. P18 reported that "*[she was] usually a person with a lot of gestures. But right now, because [she was] doing that experiment with a device on [her] arm, [she] couldn't really move around*". Moreover, the perception of the sensation impacts the distraction level. P26 found the intervention to be distracting because the sensation was "*not comfortable*" and "*feels itchy*" (P26).

5.2.3 Achieve Calming Effect through Emotional Support and Attention Redirection. 23 of the 24 participants perceived the sensation delivered from the device to be calming or soothing. Participants described the sensation as "*soothing*" (P03, P11, P20, P29, P30), as the sensation trying to "*calm me down*" (P09, P13, P21), or "*trying to comfort me*" (P32). The calming effect came from both emotional support and redirection of attention.

Participants connected the calming effect to emotional support. P20 described the sensation as the intimate experience of "somebody's playing [her] hair", while P09 and P06 thought of "*[friends] sitting beside you*" and "*friend comes up to you*". P15 found the sensation similar to "*someone is here to provide moral support*". P08 and P27 interpreted the sensation as "*I'm here for you*". Some participants perceived the sensation to be a consolation, such as being able to "*make someone feel better [when they] might be grieving*" (P28) or comforting someone by saying "*that it's fine. It's okay*" (P04). Participants also described the sensation as "*reassurance*" (P17) and similar to "*from mother to a baby*" (P32).

Participants also felt the calming effect by directing their attention to the pleasant sensations from their negative emotions. P25 described he "*took some of [his] brain energy that's focused on the bad things*", such as "*I'm not prepared for this speech*", and "*I'm not good at math*", and "*put it somewhere else to soothe you*". He thought the device would be suitable for those who work in "*content moderation*", in which "*you're there seeing... all the horrible things... happening in the world*". P23 described the sensation as "white noise" that was "*stimulating [her] enough to... focus on*" performing the tasks instead of being occupied by how difficult the arithmetic task was. P20 even found the steady and cyclic stroking motion to be encouraging: "*because [the movement] was just very consistent. [It] kind of felt like it was saying… you should also be consistent, you can keep going*" (P20). P27 found affective touch suitable for mindfulness practices because "*mindfulness is [about] your ability to focus your attention to a certain thing*" and affective touch can facilitate mindfulness because it directs "*[his] focus [to] shift to this feeling of [his] arm*" (P27).

5.2.4 Seek Control over the Intervention. Participants reflected that they wanted to have more control over when they would receive the intervention. Although participants appreciated the "*I'm here, I can help calm you down*" effort (P18), they wanted the sensation to be "*the physical contact [they] seek out [themselves]*" (P18) and wanted to stop the sensation once they feel they "*don't need this at this moment*" (P18).

Participants also wanted to control what contexts to receive the intervention. Specifically, they questioned if professional settings (simulated by our experiment) were appropriate for affective touch from three angles. First, some participants perceive professional settings to be a naturally intense setting, in which "stress is [natural]... and necessary", therefore "it's not somewhere... you need to calm down [P22]". Second, participants connected affective touch to emotional support and even consolation. As such, receiving affective touch implies that they "*need comfort*", which further implies that they have "*failed the exam*" or "*didn't do well in the interview*" (P22). Such messages were deemed inappropriate for the competitive professional settings. Third, participants questioned if it's ethical to expect people to "*be able to de-stress while [they are] focusing*" and "*be constantly devoting [themselves] to productive tasks*" (P27). Therefore, instead of receiving the intervention while doing work, P27 preferred to have "*distressing activities that are separate from when we're trying to be productive*". P28 also favored a separation between the intervention and stressful tasks and would prefer to use affective to "*[get] ready for something that would normally cause a fair amount of stress*" (P28).

6 DISCUSSION

We presented our exploration in using affective touch as a novel modality for immediate and passive anxiety intervention. Our behavioral experiment and qualitative interview validated that affective touch is powerful at mitigating state anxiety. However, we also found that affective touch did not immediately mitigate the physiological stress response. We discovered that participants mostly perceive affective touch as pleasant, minimally distracting, and calming. As intervention receivers, they seek control over how and when to receive affective touch.

In this section, we discuss the immediate effect of affective touch on state anxiety and physiological stress response. Then, drawing on our findings and emotion regulation theories, we discuss the benefits of affective touch as a passive emotional regulation technique and why it is suitable in just-in-time systems. Finally, we elicit the implementation considerations for affective touch as a wearable intervention in just-in-time systems.

6.1 Immediate Effect on State Anxiety and Non-immediate Effect on Physiological Stress

We conducted the behavioral experiment to validate two hypotheses: *During* stress exposure, (1) participants who received affective touch would experience a lower level of state anxiety and a lower change in state anxiety compared to the control group participants, and (2) participants who received affective touch would experience lower change in physiological stress responses compared to the control group participants. Our results rejected the null hypothesis for state anxiety but not for physiological stress. This indicates that affective touch can serve as an immediate anxiety mitigation intervention.

As for physiological stress response, while we could not reject the null hypothesis, our results did not confront results from prior work. Previous work showed that the impact of affective touch on parasympathetic activation became significant only after participants stayed in a stressor-free environment for more than 16 minutes. Researchers attributed this observation to the "index of safety": parasympathetic activity at the beginning of the experiment was more influenced by participants assessing the safety of the newly entered environment [109]. Our study design was different from the previous study in that we constantly exposed the participants to new stressors in a short, 15-minute set of tasks. Joining the results from prior work and our results, it implies that affective touch either requires a long stroking period to impact the parasympathetic activity, or more threatening stressors such as navigating the environment and cognitive challenges impact the parasympathetic more than affective touch. This observation suggests that affective touch may be effective at non-immediate stress mitigation: intervention systems can utilize affective touch as post-stress-exposure interventions to help users calm down once the users return to a safe, stressor-free environment.

We drew on the Neurovisceral Integration model to explain how affective touch mitigates anxiety without altering physiological stress immediately. The neurovisceral complexity is a separate regulation pathway from the parasympathetic activity captured by the time- and frequency-domain HRV metrics (e.g., HF, RMSSD) [128]. Neurovisceral complexity represents brain-heart interaction: when the autonomic system triggers a stress response, the brain can alter such response by rationalizing the situation or regulating emotion [37, 106]. Such interaction captured by non-linear HRV metrics such as SampEn is critical to consider for cognitive stress [14, 15, 17, 36, 37, 128]. In relation to our results, although we did not find a significant impact of affective touch on SampEn, we did find that participants who received affective touch showed a higher level of SampEn during stressful tasks. This observation indicates those who received affective touch exhibited a higher level of brain-heart interaction, which could infer that the brain networks triggered by affective touch (i.e., the reward response [74, 92]) attempting to regulate the physiological stress response.

In conclusion, we validated that affective touch can serve as an immediate anxiety intervention. However, the benefit of affective touch on stress mitigation may not be immediate because affective touch requires a long stroking period in a stress-free environment to be effective.

6.2 Passive Touch-based Emotion Regulation

Our qualitative findings suggested that wearable affective touch has an emotional regulation effect. Touch can regulate emotion in numerous ways; however, how intervention researchers harness the power of touch is generally through interpersonal emotion regulation: touch communicates emotion and subsequently regulates emotion. Our work opens a new possibility for touch-based intervention: touch is also a neurological process, and invoking the key haptic receptors by wearable devices can passively facilitates emotion regulation.

We drew on the widely used Process Model of Emotion Regulation to characterize how wearable affective touch regulates emotion. This model categorized cognitive emotion regulation into five stages: situation selection, situation modification, attentional deployment, cognitive change, and response modulation [50]. Wearable affective touch contributes to situation modification and attentional deployment. Situation deployment refers to changing aspects of the situation to change emotion, such as “change the music of an environment to lighten up the mood after a conflict” [33, 50]. Behavioral studies and brain network studies have verified that affective touch induces pleasantness both in perception and in neurological activities. Our experiment validated that such pleasant sensation rendered by a wearable form was sensible while participants perform other cognitive tasks. In addition, participants connected affective touch to the emotional support received from other people and animals. The pleasantness and its encoding of emotional support constitute a modification to the situation that counteracts the unpleasant anxiety. Attentional deployment refers to the direction of attention to change emotional response [50]. Participants in our study went through a similar cognitive process: they directed part of their attention to the touch sensation to avoid being drowned by negative thoughts such as not doing well in tasks. This redirection, in return, helped the participants focus on the tasks. They even projected a positive meaning to the touch sensation and used the sensation as encouragement.

The benefit of affective touch-mediated emotion regulation is its passiveness. Similar to breathing regulations and biofeedback, users do not need to devote much attention to the intervention for it to be effective. This makes affective touch suitable for just-in-time interventions: as a monitoring system detects anxiety-inducing contexts, it can automate the intervention delivery without distracting the users. In addition, affective touch has the potential to support passive interpersonal emotion regulation. Touch-based interpersonal emotion regulation is powerful, but it usually requires physical or remote social presence and therefore requires a shift in attention. Moreover, supportive social presence is not always immediately accessible. Affective touch presents an opportunity to render passive and immediately accessible emotional support by eliciting the bodily encoding of affiliative interactions. For instance, a couple going through smoking cessation together could utilize behavioral couple therapy as their primary intervention. During therapy, they may learn to be aware of their responsibility to each other and use such awareness to combat smoking cravings. When they experience elevated cravings when they are at work, wearable affective touch can provide immediate help by delivering anxiety-mitigation affect (because cravings and anxiety often co-activate [72]) as well as rendering a sense of support from each other without taking away their attention. We are not suggesting that wearable affective touch can *replace* interpersonal touch. Instead, we see affective touch as an alternative for users who favors touch-based interventions to receive in-the-moment help to regulate emotions.

6.3 Just-in-time Intervention Considerations

We envision affective touch to be a suitable intervention for just-in-time systems. We identify three key considerations when deploying affective touch as interventions: (1) design minimally obtrusive device, (2) explicitly explain the mechanism of affective touch, and (3) enable control over touch.

6.3.1 Design Minimally Obtrusive Device. The backbone of affective touch is the slow stroking at CT-optimal velocity, a type of tactile feedback that does not rely on the user's action to trigger. As such, devices that deliver affective touch do not need to support interaction. They can be worn at less intractable regions on the body, such as under the clothes, and embody multiple levels of device visibility. Moreover, the human body can easily habituate to affective touch, which allows the intervention to occupy a low cognitive bandwidth. To avoid interference with habituation, the device that deliver affective touch should be minimally obtrusive and easy to wear-and-forget. We engineered a wearable device that used the robust, well-validated brush-stroking mechanism to ensure we could induce CT activation in our in-laboratory study. However, this specific form factor is obtrusive and less suitable for wearable devices. It's technically feasible to deliver slow stroking in a non-obtrusive and wearable form factor, such as using voice coils to render the illusion of soft stroking [54, 85]. When designing devices utilizing affective touch, it's critical to validate if the rendered low-stroking sensation can induce a similar CT activation. One physiological way to perform such validation is through microneurography on the median nerve in the forearm and detecting CT neural activity. For more wearable device-friendly validation, it is worth validating whether the new device's effect on stress/anxiety is comparable with the effect of the traditional brush-stroking technique.

6.3.2 Explicitly Explain the Mechanism and Activation Context of Affective Touch. Affective touch requires an explicit explanation of how the intervention mitigates anxiety. In our study, we observed participants interpreted the message associated with affective touch with large individual differences. While some participants received calming, soothing, and encouraging messages, others viewed affective touch as a consolation. The consolation interpretation projects a negative self-image: some participants thought that because they were receiving affective touch, it indicated that they had failed the tasks they were performing, which was why they needed consolation. It's not uncommon for behavioral health interventions to be hindered by self-image projection. A major contributor to untreated behavioral health conditions is the stigma associated with treatments and the self-image that seeking treatment implies weakness [32]. Such projection may inhibit intervention effectiveness, worsen anxiety, and have a prolonged negative health impact.

Users should have sufficient knowledge to interpret affective touch. Therefore, an affective touch intervention system should explicitly explain the mechanism of affective touch: affective touch mitigates anxiety by rendering pleasantness, providing emotional support, and directing attention. If affective touch is activated automatically, the system should inform the users how it decides when to activate and whether such activation is related to task performance. If the system is designed for performance-driven situations such as the workplace, it can deliberately associate positive messages with affective touch to decouple emotional support and consolation.

6.3.3 Enable Control over Touch. Affective touch intervention system should ensure the users have a sufficient level of control over the intervention. In our study, participants sought multiple levels of control: from wanting to deliberately activate and stop touch, to showing clear preferences on whether a specific context is suitable for affective touch, to whether to receive affective touch as a passive intervention.

Touch is intimate because it directly acts on the body. Wearable device posits uniquely in touch consent: does putting on the wearable device means to consent to receive haptic sensations? Because affective touch imitates the stroking sensation initiated by others, the intervention system should ask for touch consent or let the users start the touch. The system should also allow the users to stop or dismiss the touch effortlessly to lower the user-system friction when the user deems receiving touch to be distracting or inappropriate [33, 56, 99].

We also observed large individual differences in what contexts participants want to receive affective touch. Some participants preferred to use affective touch during stressful tasks to feel better and more focused, while others favored affective touch as preparation for anticipated stress. Some favored affective touch for workplace stress, while others considered stress to be a necessary part of the workplace and that intervention was not necessary. Some even questioned the ethics of passive intervention and whether people should be expected to de-stress while being productive. Instead of using affective touch as a passive intervention, these participants preferred a decoupling between anxiety and anxiety countermeasures – they would rather use affective touch as a dedicated mindfulness practice. To account for individual differences, intervention systems should personalize the touch activation contexts for each user.

We recommend that an affective touch intervention system can adapt and switch between three modes of control to account for individual preferences: (1) A fully device-controlled mode, in which the system asks for touch consent once the users put on the device. Then, the system monitors the bodily signal for stress and user-determined activation contexts. If the user becomes stressed in a user-determined intervention context, the system automatically activates affective touch. This mode takes full advantage of the passiveness of affective touch but limits the level of user control. (2) A consent mode, in which the system still monitors the bodily signal for stress and user-determined activation contexts. In contrast with the fully device-controlled mode, the consent mode subtly asks for touch consent at the moment of activation. This mode respects that the users' consent to touch can vary in each situation. (3) A fully user-controlled mode, in which the user manually starts or stops the affective touch. These three modes represent a spectrum between device control and user control, as well as a balance between intervention passiveness and user preferences. If the device initiates the intervention, the users do not need to allocate cognitive capacity to seek intervention in demanding situations. If the user starts the intervention, they enjoy complete control over the intervention but are on their own in caring for themselves. Engineering systems in consideration of this balance are not only critical to affective touch, but to all passive intervention mechanisms.

6.4 Limitations and Future Work

As we made the first step toward implementing affective touch as an immediate and passive mobile intervention, the limitations of our study opened more questions to be investigated in future work. First, we engineered a proof-of-concept prototype that utilized the same activation mechanism as prior behavior experiments (brush-like end effector on the forearm). We did so to compare our results with prior work, but this activation mechanism was not unobtrusive. Future work could explore how to active affective touch unobtrusively, investigate whether the non-obtrusive slow-stroking devices (e.g., voice coils haptic illusions) have a similar effect as brush-stroking, engineer more compact form factors, and identify other body locations for touch reception that might be more suitable for daily intervention needs. Second, we found an interesting nuance in how affective touch mitigates physiological stress response: non-immediate impact on parasympathetic activity, but some immediate impact on brain-heart interaction. Future work should investigate how and to what extent affective touch influences brain-heart interaction, and how brain-heart interaction mitigates stress induced by both cognitive challenges and physiological distress. Third, our experiments were conducted in a controlled, in-laboratory setting where both stress and intervention were artificially induced. Future work should investigate the effectiveness of affective touch in everyday, in-the-wild contexts.

Beyond affective touch, touch is a crucial sensory that supports humans to interact with the physical environment and communicate interpersonally. As such, the therapeutic value of touch has been a long interest in both health and HCI community [115]. Our paper represents one step toward utilizing haptics as passive interventions. This approach opens many opportunities because the recent development in mixed reality promoted the advancement of haptic devices with small and wearable form factors. We see technical possibilities to render complex geometry [47, 122], textures [107, 122], temperature [18, 93], and even force feedback [51, 65, 83]. These novel sensations, especially temperature, have the potential to impact behavioral health. Future work can take on this opportunity by joining efforts between haptic design and intervention research, investigating more complex haptic rendering devices that can provide immediate benefits to other aspects of behavioral health.

7 CONCLUSION

Affective touch harnesses the power of touch in emotion regulation. In this paper, we validated that affective touch rendered by a wearable device can mitigate anxiety immediately and passively. Our work opens a new possibility – in addition to breathing regulations and biofeedback – for passive mobile interventions to intervene without requiring users to shift attention or activities. Affective touch has the potential to be integrated into just-in-time systems. However, as a touch-based intervention, affective touch pushes intervention researchers to consider the balance between user control and intervention passiveness. Beyond affective touch, we see an exciting opportunity to join effort in novel haptic devices and behavioral health interventions.

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