E-Tactile Flow: Exploring A Novel Path of Pain Relief through Interactive Electrotactile Stimulation

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Chronic or recurrent pain significantly impairs quality of life, and conventional pharmacological treatments often produce side effects, motivating the search for non-pharmacological alternatives. This study introduces a novel paradigm — E-Tactile Tactile Flow (E-Tactile Flow)—which integrates electrotactile stimulation with attentional engagement and flow-related task design. Inspired by a bidirectional attention mechanism, the paradigm designed goal-directed task mode and stimulus-driven task mode to examine the role of cognitive engagement in pain modulation. A preliminary study validated the feasibility and safety parameters of an 8×8 electrotactile system. In Experiment 1 (n = 42), both attention modes effectively reduced pain perception, with the goal-directed task mode showing significantly stronger modulation of several physiological measures and a marginal trend toward lower subjective pain ratings than the stimulus-driven task mode. Building on this, Experiment 2 introduced adaptive difficulty modulation to better align task challenge with participant performance. Results showed that dynamic task adjustment significantly enhanced attentional engagement and reduced pain ratings. Overall, this study provides initial empirical support for an electrotactile interaction paradigm for non-pharmacological pain modulation.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**.

Additional Key Words and Phrases: Pain Relief, Electrotactile Stimulation, Human-Computer Interaction, Attention Mechanisms, Flow Experience

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1 INTRODUCTION

Chronic and recurrent pain represent widespread global health challenges that significantly affect patients' quality of life, work productivity, and social participation [1, 26, 83, 88, 106]. Beyond immediate physical distress, such pain is frequently accompanied by psychological complications, including anxiety and depression, which can establish a self-reinforcing cycle between pain and negative affect [40, 66]. Although conventional pharmacological treatments, such as opioid analgesics and nonsteroidal anti-inflammatory drugs, offer short-term relief, prolonged use is associated with risks, including drug tolerance, physiological dependence, and gastrointestinal damage [12, 90]. In particular, the increasing abuse of opioids has evolved into a major public health crisis [66]. These limitations have spurred growing interest in non-pharmacological alternatives that are more physiologically compatible and less prone to adverse side effects.

Among such alternatives, attentional modulation strategies have emerged as a promising avenue for pain management. Virtual reality (VR), in particular, enables immersive multisensory experiences that divert attention away from nociceptive input and consistently yield measurable analgesic effects in clinical contexts including burn care, cancer pain, and postoperative recovery [13, 51, 61, 66, 72, 90, 105, 106]. These effects are believed to arise from the participation of prefrontal–limbic pathways that suppress activity within the pain matrix and activate descending inhibitory networks [12]. The neurocognitive model of pain-related attention provides a theoretical foundation for these VR-based analgesic effects. It distinguishes two complementary mechanisms: top-down (goal-directed) and bottom-up (stimulus-driven), processes that govern the allocation of sensory and cognitive resources during pain experiences [9, 53]. Top-down attention involves deliberate control and cognitive reappraisal, whereas bottom-up attention is triggered by salient sensory events. Recent VR studies adopting this framework demonstrate that immersive environments can leverage both mechanisms: visually salient stimuli capture bottom-up attention, while interactive, goal-directed tasks enhance top-down engagement to suppress pain perception [9].

Although extensive research has focused on audiovisual multimodal integration [29, 44, 64], the potential of the tactile modality in this domain remains underexplored. However, tactile stimulation offers distinctive neurophysiological advantages, engaging the somatosensory system through bottom-up pathways directly linked to nociceptive processing [62, 110]. Unlike vision or audition, tactile input can exert both peripheral and central effects: peripherally, by activating $A\beta$ fibers that inhibit nociceptive transmission [62, 110]; and centrally, by engaging affective and social mechanisms mediated by C-tactile afferents [38, 40]. This dual influence positions touch as an especially potent and versatile channel for non-pharmacological pain relief [73, 110].

The existing tactile interventions, however, are largely based on simple sensory distraction and lack the cognitive depth required to sustain engagement. Vibratory tactile stimulation (VTT) has been shown to reduce pain through spinal gating mechanisms [62, 110], while social and affective touch can elicit central analgesia through oxytocin-mediated pathways [38, 40]. Recent advances, such as robotic or inflatable devices that simulate social grasping, have further demonstrated that the contextual and affective dimensions of touch significantly modulate its analgesic efficacy [73, 110]. Nevertheless, current tactile systems are constrained by limited stimulus diversity, short attention spans, and weak cognitive coupling. Designing multimodal tactile sequences that align with neural encoding and attentional engagement principles remains a key technical and theoretical bottleneck [46, 54, 56, 93].

Building on this rationale, we propose and empirically evaluate an electrotactile interaction paradigm that integrates tactile stimulation with cognitive models of attention and engagement. Advances in high-resolution

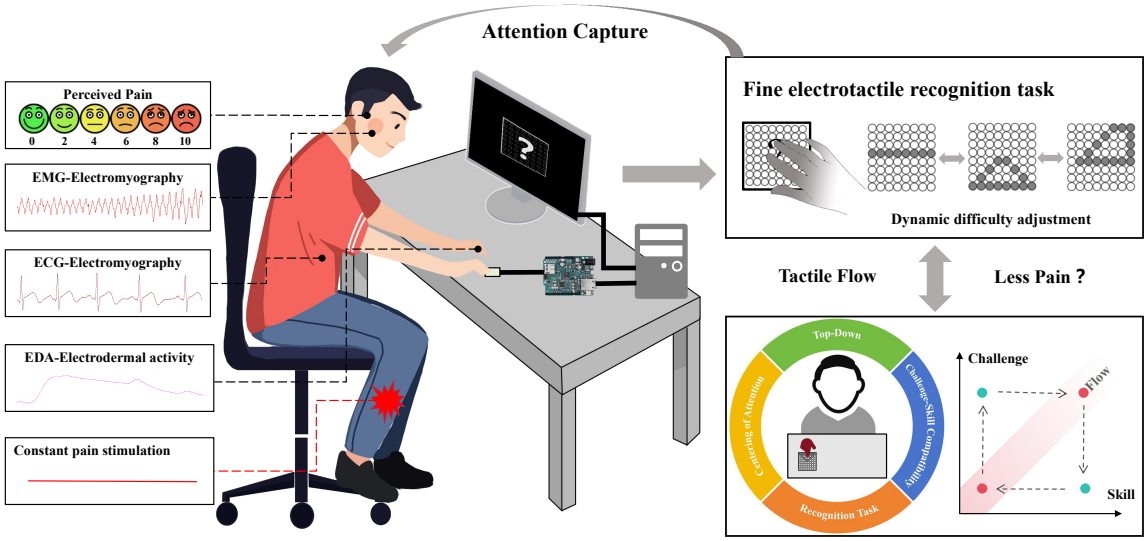

Fig. 1. This figure shows our proposed E-Tactile Flow paradigm, an interactive high-resolution electrotactile approach designed to support sustained task engagement and flow-related experience for pain modulation. The core features of E-Tactile Flow include interactive, high-resolution electrotactile stimulation that presents a variety of electrotactile graphic recognition tasks to fully engage users. It integrates a goal-directed attentional engagement to make users focus on tasks and reduce their attention to pain. By designing tasks with an appropriate level of challenge, E-Tactile Flow aims to support sustained engagement and flow-related experience. The adaptive difficulty mechanism is intended to better align task demands with users' skill levels, thereby providing preliminary support for reducing pain perception through interactive attentional engagement.

electrotactile interfaces now allow precise spatiotemporal control over tactile patterns, enabling the creation of interactive tasks that differentially recruit top-down and bottom-up attentional processes. In parallel, flow theory from cognitive psychology suggests that intense engagement in optimally challenging tasks—characterized by deep focus and reduced awareness of external distractions, which can substantially attenuate pain [100]. Integrating these perspectives, we hypothesize that interactive electrotactile tasks designed to activate goal-directed or stimulus-driven attention may promote sustained engagement and flow-related experiences, thereby reducing pain perception..

Guided by this framework, we tested three hypotheses:

- H1: Both top-down and bottom-up electrotactile tasks reduce subjective pain perception and physiological stress responses compared to a no-intervention control.
- H2: Top-down tasks exhibit superior analgesic efficacy due to deeper cognitive engagement (e.g., pattern matching, memory recall).
- H3: Adaptive difficulty adjustment in top-down tasks improves challenge–skill matching, thereby enhancing attentional engagement and supporting stronger pain inhibition.

To test these hypotheses, we developed two core electrotactile task paradigms: (1) a cognitively demanding top-down task that requires active pattern matching and memory recall, and (2) a bottom-up task that captures attention through novel stimulus variation. Both paradigms were implemented using an electrotactile array of 8×8-channel. We conducted two experiments. In Experiment 1 (n = 42), we compared subjective pain ratings

and physiological indicators, including the masseter electromyogram (EMG), electrodermal activity (EDA), and electrocardiogram (ECG). This comparison was carried out on both paradigms and a no-intervention control condition. We predicted a greater analgesic efficacy in the top-down condition due to higher intentional engagement. Experiment 2 applied an adaptive algorithm to dynamically adjust task difficulty within the top-down paradigm, investigating whether improving challenge–skill matching could enhance flow-related engagement and further suppress pain perception.

By integrating electrotactile stimulation with cognitive models of attention and flow-related engagement, this study provides initial empirical support for an interactive electrotactile approach to pain modulation (Figure 1). The contribution has two layers: first, electrotactile interaction can reduce pain through attentional engagement; second, adaptive task regulation may further enhance analgesic effects by sustaining task engagement.

2 RELATED WORK

2.1 Common Avenues for Pain Relief

The current IASP definition of pain as "An unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage", pain is always subjective [3].

Pain can be classified into acute and chronic types based on characteristics such as duration and nature. Acute pain is typically directly related to noxious stimuli or tissue damage and is of relatively short duration, usually subsiding or disappearing as the wound heals. Chronic pain, on the other hand, persists for a longer period and may be disproportionate to the initial tissue damage or continue even after the injury has healed. It encompasses various types, including neuropathic pain, chronic inflammatory pain, chronic cancer-related pain, and psychogenic pain [48, 68].

Pharmacological treatment is a primary approach for pain management, encompassing nonsteroidal anti-inflammatory drugs (NSAIDs) such as ibuprofen, which reduce inflammation, and opioid analgesics like morphine, which are effective for more severe pain relief. However, frequent use of these medications can lead to side effects. In certain cases, such as psychogenic pain, neuropathic pain, or intermittent acute and chronic pain, it may be possible to avoid pharmacological interventions and explore alternative therapies.

In recent studies, various non-pharmacological pain management methods have been explored, including Transcutaneous Electrical Nerve Stimulation (TENS), hot and cold therapy, acupuncture, physical therapy, cognitive-behavioral therapy, relaxation techniques, hydrotherapy, and other complementary approaches such as music and aromatherapy. These methods offer treatment options beyond pharmacological interventions by addressing different dimensions of pain, including emotional, cognitive, behavioral, and sociocultural factors. They hold potential benefits in alleviating pain, improving functionality, reducing medication side effects, and enhancing quality of life. Although these non-pharmacological interventions have demonstrated some effectiveness in clinical applications, more high-quality research is necessary to further validate their efficacy and appropriateness, ensuring better integration into clinical pain management practices [28].

Distraction as a pain management strategy works by shifting an individual's attention away from the sensation of pain to other non-pain-related stimuli, thereby reducing the perception of pain. Distraction tasks have been shown to alleviate both experimentally induced acute pain and chronic pain. However, research on the effects of different sensory modalities of distraction tasks in pain relief remains limited. Existing studies suggest that auditory, visual, and multimodal distraction tasks can help reduce acute and chronic pain in both adults and children. In contrast, tactile distraction tasks have been less extensively studied, with only one study investigating their effects on pain. This study indicated that tactile distraction could reduce pain perception, but more research is needed to substantiate these findings [5].

2.2 A Neurocognitive Model of Attention to Pain

When constructing a neurocognitive model of pain, the Gate Control Theory of Pain has been the classic framework for understanding how the central nervous system regulates and controls pain signals. It was proposed by Melzack and Wall in 1965 and was first reveals how the "gate" mechanism in the spinal cord controls pain by regulating pain signals entering the central nervous system. This theory emphasizes how the activity of sensory nerve fibers is modulated by the "gate" system in the dorsal horn of the spinal cord, which affects the perception of pain [71]. However, although this theory has significantly advanced the field, it may have limitations in explaining certain complex pain experiences [10].

Building on this foundation, Melzack proposed the Neuromatrix Theory of Pain to further expand the understanding of pain. This theory suggests that pain is not the result of peripheral stimuli alone, but is a holistic experience generated by a complex network of nerves in the brain known as the neuromatrix [70]. The neuromatrix combines genetic, psychological, and emotional factors to generate pain perception through multiple neural pathways, thereby explaining more complex pain phenomena not covered by gating theory.

According to the Neuromatrix Theory of Pain, the perception of pain is the result of a complex dynamic system that codes, transports and processes nociceptive signals, and the relationship between nociceptive information and pain is profoundly affected by affective and cognitive factors [52, 95]. A key role is played by attention, a mechanism by which sensory events are selected and enter awareness. Most literature on attention and pain has been informed by limited-capacity models of human cognition, proposing that sensory signals – including nociceptive ones – exceed processing capacity, and hence require attention to select the signals needed for goal-directed behaviors. Thus, directing attention away from nociceptive information would exclude it from further processing and in this way be analgesic. Legrain et al. [53] developed a neurocognitive model (of attention to pain) which distinguishes between two modes of selection: top-down and bottom-up attention (see Figure 2).

- Top-down selection is an intentional and goal-directed process that prioritizes information relevant for current actions[53]. In this process, the sensitivity of stimulus-specific neural responses is modified by amplifying the activity of stimuli-relevant neurons, and by inhibiting the activity of stimuli-irrelevant ones.
- Bottom-up selection is an unintentional stimulus-driven capture of attention by events themselves [108]. Attentional capture is often imposed by the most salient and novel stimuli in environment, independent of intentional control. Several pre-attentional systems (e.g. Visual and auditory attention) are involved in salience and novelty detection and provide stronger neural activity for these events [35].

2.3 Pain Relief Based on Attention Mechanism

Based on the neurocognitive model, the perception of pain can be relieved through attention selection, which refers to a mechanism of selecting sensory events to enter awareness such as distraction [67]. Utilizing distraction to transform attention of patients into a target can effectively enhance the pain threshold [42, 98]. This could be achieved through multi-sensory approaches.

2.3.1 Pain Relief Based on Visual Distraction. In recent years, pain relief techniques based on visual distraction have gradually become a hot topic in clinical research [78]. This approach reduces pain perception by using visual stimuli (e.g., images, videos, or virtual reality environments) to distract patients from their pain [16]. Visual distraction techniques offer a non-invasive alternative to traditional medications, which is especially important for patients who have adverse reactions to medications or need long-term pain management [11, 78].

The study by Roshanzadeh et al. [84] is one of the important contributions in this field. They compared the effects of auditory and visual distraction on pain and anxiety during extracorporeal shockwave lithotripsy (ESWL). The results of the study showed that visual distraction significantly reduced pain of patients compared to auditory distraction, suggesting that visual stimulation has great potential as an effective pain relief tool during the operation.

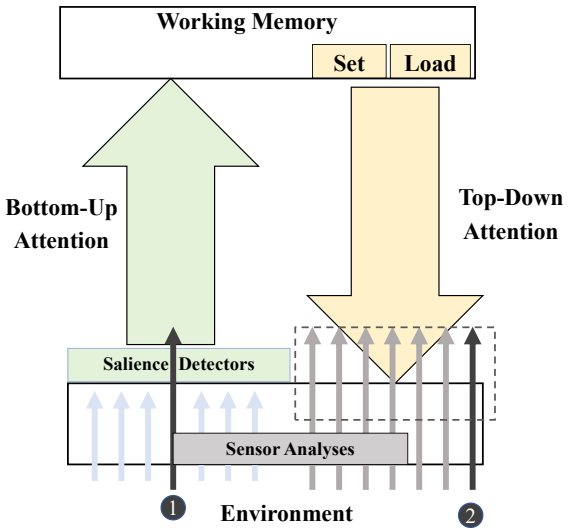

Fig. 2. When confronted with multiple sensory signals (as indicated by the bottom arrows), the brain must select the signals most relevant to current behavior and prioritize them for transmission to working memory for conscious processing. This selection can be achieved through two mechanisms. Bottom-up selection is triggered by sensory stimuli themselves, with attention capture initiated by pre-attentional detectors. These detectors identify salient stimuli (as shown by black arrow 1) and prioritize their processing by eliciting stronger neural responses. Top-down selection, on the other hand, is directed by cognitive goals activated in working memory. These goals define task-relevant stimulus features (the attentional set) and determine the amount of attention allocated to achieve the task (attentional load). Top-down selection enhances neural responses to goal-relevant signals (grey arrows) while inhibiting responses to irrelevant signals (blue arrows) [52, 53].

Visual distraction can relieve pain by influencing mood and relaxation states [7, 92]. Much visual content (e.g., natural landscapes, pleasurable images, or moving videos) reduces activity in stress-related brain regions, especially the amygdala, a fundamental part of the brain that controls emotions, through, for example, positive mindfulness conditioning [92]. A study by Cheraghi et al. [21] explored the use of visual distraction in burn dressing changes in children. They found through a randomized controlled trial that visual distraction was superior to auditory distraction in reducing pain perception in children aged 6 to 12 years. This study not only validated the effectiveness of visual distraction, but also pointed out its particular value in pediatric care because visual stimulation may be more effective than other sensory stimuli for pediatric patients, as children are more easily attracted to vivid visual content.

In addition, a study by Zhang et al. [111] confirmed the effectiveness of visual distraction in adult colonoscopy. They found that visual distraction not only significantly reduced patients' pain, but also lowered the need for analgesic medication, which further supports the clinical value of visual distraction as an effective non-pharmacological intervention.

2.3.2 Pain Relief Based on Tactile Channel. The exploration of pain relief through the manipulation of tactile channels opens a novel avenue for non-pharmacological management of various sensory disorders. Among the innovative approaches, haptic vibrotactile trigger technology (VTT) emerges as a promising tool, offering a non-invasive strategy to modulate neural pathways associated with pain perception [29, 55, 75, 112]. VTT activates skin receptors via vibrotactile stimulation, and these signals are transmitted to the central nervous

system, which in turn affects neural networks in the brain related to cognitive functions, especially by altering alpha and beta band activity in the electroencephalogram (EEG), which may positively affect pain perception, sleep, balance, and stability [44]. A study by Gudin et al. [43] showed that the technique demonstrated significant efficacy in patients with chronic pain, with VTT significantly reducing reliance on pain medication compared to conventional treatments.

However, VTT still has some limitations. A study by Doghramji et al. [31] noted that the use of VTT patches may result in side effects such as itchy skin and irritation due to adhesion. Additionally, as VTT may not objectively control the intensity and duration of pain relief with precision, it lacks room for patient autonomy, leading to inconsistent patient experience.

2.4 Flow Experience and Attention

In the field of psychology, flow refers to a highly pleasurable, fulfilling, and unselfconscious state that an individual experiences when he or she is fully engaged in an activity [24]. The concept was first introduced by psychologist Mihaly Csikszentmihalyi, who described flow as "a complete engagement in an activity in which the individual feels internally focused, loses all sense of time, and concentrates all of his or her attention on the task at hand".

The key to the flow experience is a high level of concentration and deep immersion in the activity. In a state of flow, individuals typically exhibit superior task performance and subjectively feel a great sense of satisfaction and pleasure. A study by Marty-Dugas et al. [65] further revealed the attentional performance of individuals with a high propensity for flow, noting that they have a greater capacity for sustained attention during tasks, suggesting that the flow experience is not merely an unconscious state of flow, but rather relies on intentional attentional focus.

Not only does the flow experience involve a high degree of attentional focus psychologically, it also exhibits unique characteristics physiologically. Ullén et al. [100] examined psychological and physiological indicators of the flow state and found a strong link between the flow experience and certain psychological and physiological states, such as mood and attention.

In recent years, the application of the flow experience in pain management has been gaining attention. Studies have shown that individuals' perception of pain may be attenuated in a state of flow, due to the fact that flow experience can reduce pain perception by enhancing attentional focus and distracting individuals from pain [65, 104], and this provides important support for our exploration of how flow experience affects pain perception.

In this context, tactile experience and tactile tasks have become the focus of relevant research. While haptic experiences typically refer to enhancing a user's perception in a specific situation through haptic technology, such as immersion in virtual reality, haptic tasks go a step further, requiring users not only to feel haptic feedback, but also to maintain a high level of attention while performing a specific task. A study by Saboor et al. [85] showed that the use of haptic feedback in a task can increase spatial presence, which is associated with increased user immersion and concentration in a virtual environment. Söderström et al. [89], by assigning tasks and implementing haptic feedback in first person shooter video games, found that haptic vests and their haptic feedback provided more immersion to the game experience for most participants, thereby enhancing their concentration and perception of the game environment. Although most current studies focus on how to improve user immersion through haptic feedback and tactile experience, the results suggest that haptic technology combined with task orientation may induce flow experience under certain conditions, which is of great significance for future psychological research and application.

Challenge–skill balance has been widely regarded as a central antecedent of flow, and adaptive task difficulty provides a theoretically grounded way to better align task demands with participant skill and facilitate flow-related engagement[25, 34, 36]. Based on the above review, we aimed to examine whether tactile tasks can support flow-related engagement and whether such engagement is associated with reduced pain perception.

3 METHODS

3.1 Experimental Design

Based on general perceptual research and mathematical principles of pattern recognition, we pre-designed a series of electrotactile patterns suitable for the experimental tasks. The patterns were designed to be visually displayable and tactually recognizable, but the visual grid and electrotactile grid were not assumed to have equivalent perceptual resolution. Importantly, the pre-experiment was intended to validate the tactile discriminability of the electrotactile patterns rather than to compare the perceptual resolution of visual and electrotactile displays. Because visual displays were used only to present task targets or response options, a systematic visual-versus-electrotactile resolution comparison was outside the scope of the present study. Therefore, tactile recognizability was treated as an empirical prerequisite rather than a design assumption. The pre-experiment was used to verify that participants could discriminate the 8×8 electrotactile patterns under comfortable stimulation intensities, and recognition accuracy was subsequently used to classify pattern difficulty. To ensure the stimuli were both perceptible and comfortable, the design required determining appropriate pain intensity levels, electrical stimulation parameters, and classifications of pattern difficulty.

During the pre-experiment, we first established a general operating range of electrotactile current and voltage that could elicit clear tactile sensations without inducing finger pain for most participants. Then, in the formal experiments, these parameters were individually fine-tuned according to each participant's subjective feedback on pain tolerance and tactile clarity, ensuring both safety and consistency.

Pattern difficulty levels were determined by statistically analyzing the recognition accuracy of each pattern obtained from the pre-experiment (Figure 3a). Patterns with higher accuracy were categorized as low difficulty, while those with lower accuracy were labeled as high difficulty. This classification enabled the subsequent experiments to systematically adjust the level of task challenge across conditions.

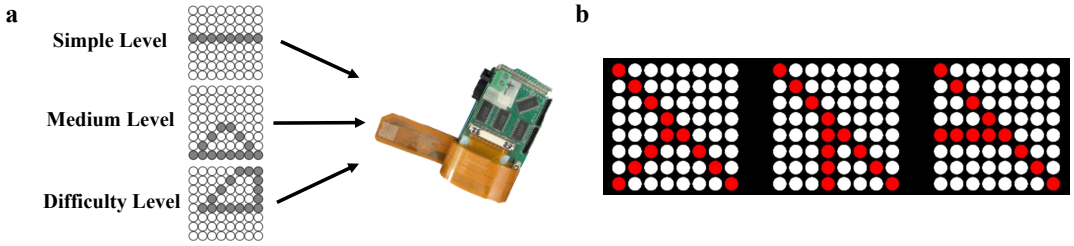

Fig. 3. **a**, 64-channel high-voltage switch module for presenting graphs of varying difficulty levels using current. **b**, Examples of 8 × 8 electrotactile pattern used in the pre-experiment (intersecting lines).

To maintain procedural consistency between the pre-experiment and the formal experiments, both incorporated two electrotactile task structures inspired by the Bottom-Up (B-U) and Top-Down (T-D) attention framework, implemented through similar pattern recognition paradigms:

- B-U mode: A stimulus-driven task mode. In each trial, a randomly selected electrotactile pattern from a set was presented on the electrode array for 15 seconds. After the stimulation ended, three patterns from the same set were shown on the monitor, and participants selected the one that matched the tactile pattern they had just experienced (Figure 4a).
- T-D mode: A goal-directed task mode. At the start of each trial, a target electrotactile pattern was displayed on the screen for 5 seconds and then disappeared before electrotactile stimulation began. Three patterns from the same set were then sequentially presented on the electrode array (15 seconds each) in random

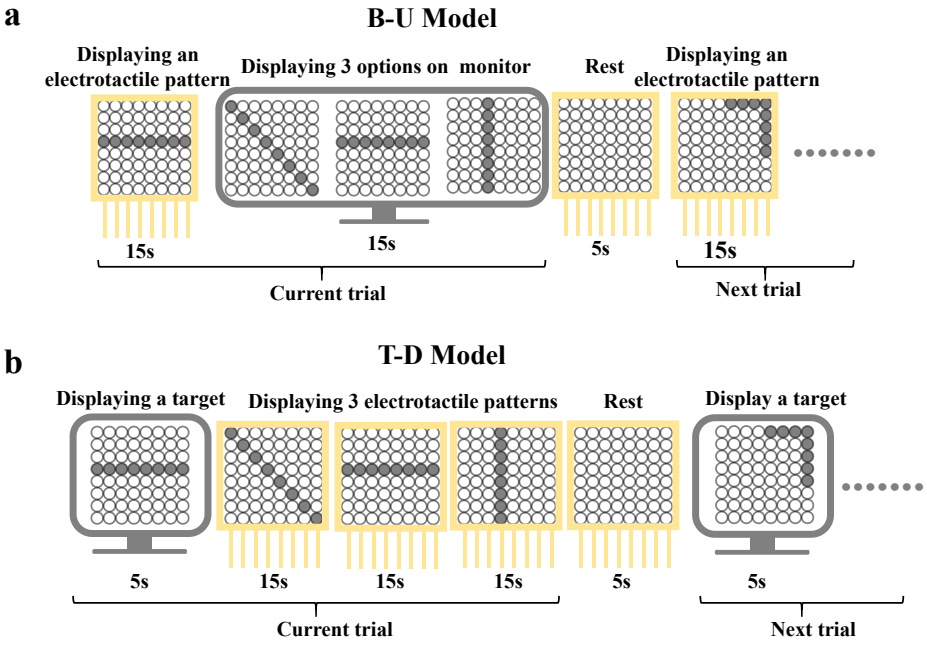

Fig. 4. **Model design. a**, In each B-U trial, electro-tactile patterns of varying difficulty are presented on the electrode array. Three patterns then appear on the screen, and participants select the matching one. **b**, In each T-D trial, a randomly chosen pattern is first shown on the screen. Then, different electro-tactile patterns are presented sequentially on the electrode array. Participants select the pattern that matches the one displayed on the screen.

order. Participants maintained the target representation in working memory and identified which tactile pattern matched the visual target (Figure 4b).

In both modes, electrotactile stimulation was temporally separated from visual information and the recognition judgment itself was merely based on electrotactile pattern perception. The distinction of two modes focused on the perception of the electrotactile stimulation. The visual information was used only to present the target before the perception process (T-D mode) or present response options after the perception process (B-U mode).

In the present study, the T-D/B-U distinction is defined at the process of perceiving the sensory stimulation rather than perceiving the pain level. The paradigm was not designed as a multisensory intervention: visual displays served only as task cues or response options, whereas the formal recognition task relied on electrotactile patterns presented through the tactile modality. Thus, the two conditions should be understood as electrotactile task structures inspired by the T-D/B-U attention framework, differing mainly in target guidance, stimulus timing, and working-memory requirements. This framework provides conceptual guidance for interpreting task engagement [52, 53], rather than a strict mechanistic dissociation of top-down and bottom-up pain-attention modulation.

3.2 Pre-Experiment

3.2.1 Participants. Eighteen participants (11 male, 7 female), aged 18-36 (mean = 21.22; SD = 3.25), took part in the pre-experiment. All participants reported having normal or corrected-to-normal vision and no history of

diseases such as diabetes, hypertension, neurological or mental disorders. They had normal pattern recognition ability and finger tactile ability. None of the participants had experienced alcohol consumption, excessive fatigue, such as drug use or illness before the experiment. Informed consent was obtained from all participants.

3.2.2 Procedure. The pilot study aims to achieve the following objectives, laying the groundwork for subsequent Experiments 1 and 2:

- Evaluate the recognizability of different electrotactile patterns and classify their difficulty levels based on participants' recognition accuracy.
- Calibrate the electrotactile stimulation intensity to ensure that patterns could be clearly perceived without inducing finger pain or discomfort.
- Calibrate the pain-stimulation intensity to ensure that the induced pain was noticeable and tolerable, while allowing participants to complete the subsequent electrotactile recognition tasks.

The overall procedure of the pre-experiment is shown in Figure 5a, before the start of the pre-experiment: (1)Participants complete a pre-experiment questionnaire, which includes basic demographic information such as age. (2)Participants receive a briefing on the task procedures and the requirements of both the Top-Down (T-D) and Bottom-Up (B-U) task modes. (3)Participants experience pain stimulation to determine the pain level they can tolerate. (4)Participants undergo two electrotactile recognition tests to identify the appropriate electrotactile stimulation intensity.

During the pre-experiment: Participants are required to complete tasks in both B-U and T-D modes while receiving the predetermined level of pain stimulation throughout the tasks. Adequate rest is provided during mode-switching phases. Each participant completes 24 trials, with 12 trials in the B-U mode and 12 in the T-D mode. To minimize order effects, the sequence of the 12 trials of patterns in each mode is randomized. Additionally, the order of trials between the two modes is counterbalanced to ensure fairness in experimental conditions. The same counterbalancing principle was applied in the formal experiments, where task order and difficulty/block order were counterbalanced where applicable to reduce order and fatigue effects.

3.2.3 Analysis. Data analyses were conducted to validate the perceptibility of stimulus and to establish hierarchical difficulty levels for electrotactile tasks. Recognition accuracy for each of the 12 pattern sets was calculated across all participants. To define the difficulty tiers (low, medium, and high) for the subsequent experiments, the patterns were ranked based on their mean recognition rates and stratified into tertiles, with four patterns assigned to each level. Descriptive statistics (mean ± SD) were calculated for individual pain tolerance thresholds and electrotactile detection thresholds to ensure that the selected stimulation parameters were within a safe, perceptible, and experimentally valid range.

3.3 EXPERIMENT 1: The Effect of Electrotactile Stimulation on Pain Perception Under Different Attention Capture Mechanisms

3.3.1 Participants. Forty-two participants (29 male, 13 female), aged 18-32 (mean = 21.71; SD = 3.14), participated in Experiment 1. These participants were recruited from a local university and volunteered to take part in the study.

3.3.2 Procedure. The whole process of experiment 1 and 2 as shown in Figure 5, preparatory phase:

- All participants were required to complete a pre-test questionnaire, designed to gather basic personal information and health status.
- Participants were introduced to the Wong-Baker Faces Pain Rating Scale and familiarized with the experimental procedures and rules. This process ensured that participants fully understood the experimental protocol, facilitating smooth progression through subsequent stages.

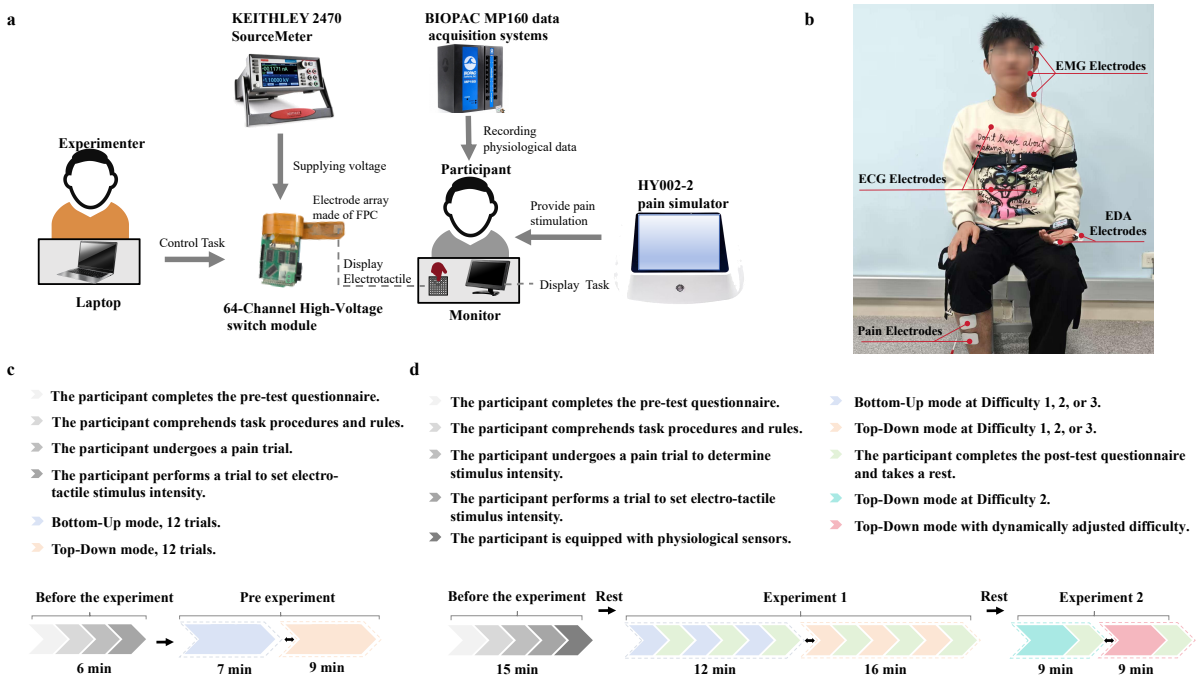

Fig. 5. **Experimental process. a**, Assess the difficulty levels of different electro tactile patterns and establish a classification of difficulty levels. **b**, Participants first calibrated their individual pain thresholds using simulated and electrotactile stimulation. Experiment 1: Three independent trials each of top-down (T-D) and bottom-up (B-U) Modes. Experiment 2: T-D mode only, comparing conditions with versus without difficulty-adjustment mechanisms.

- Based on the results of the pre-experiment, there are significant individual differences in participants' pain perception. Therefore, in the experiment, it is necessary to adjust the intensity of the simulated pain stimulus to a threshold allows at which each participant to clearly perceive the pain at a subjective level of six on the pain scale. This adjustment will ensure that each participant can tolerate the pain while still being able to complete the task, according to their feedback. This individualized intensity should be recorded for use in subsequent experiments.
- Participants experienced 1 to 2 electrotactile patterns to determine the appropriate intensity of electrical stimulation for each individual.
- Participants were fitted with physiological signal electrodes, enabling real-time monitoring of physiological signals during the experiment, and with electrodes for pain stimulation.

Experiment 1: (1) At the beginning of the experiment, participants underwent a one-minute collection of resting baseline data. (2) Subsequently, the pain stimulation was adjusted to the predetermined level, followed by a one-minute baseline measurement of pain without any intervention was recorded. This baseline served as the control condition to test hypothesis H1, evaluating whether T-D (Top-Down) and B-U (Bottom-Up) interventions significantly reduced pain perception. (3) Participants then performed tasks in both B-U and T-D modes, with 3 difficulty levels for each mode. Each difficulty level consisted of 4 rounds of pattern recognition tasks, forming one complete task. A total of 6 tasks were performed, comprising 24 rounds of pattern recognition. The order of B-U and T-D blocks and the order of difficulty levels were counterbalanced across participants. Within each block,

pattern sets were presented in randomized order, and participants were not informed of the total number of pattern sets or the upcoming sequence, which reduced the possibility of explicit memorization or fixed-sequence learning. (4) Before each task, pain stimulation was adjusted to the predetermined level, and after each task, the stimulation was turned off. The participants were then required to complete a post-test questionnaire that evaluated their pain perception. (5) Adequate rest periods were provided between tasks to ensure physical and mental recovery. This arrangement helped maintain consistent psychological and physiological states in tasks, thereby improving data comparability and increasing the reliability of the experimental results.

3.3.3 Analysis. To test Hypotheses H1 and H2, we conducted a paired-samples t-test on physiological stress response indicators including EDA, ECG and EMG collected under T-D, B-U electrotactile task conditions, as well as the no-intervention control condition. Additionally, subjective pain perception scores were analyzed alongside these physiological metrics to confirm differences in analgesic efficacy between task types.

3.4 EXPERIMENT 2: The Effect of E-Tactile Flow on Pain Relief

3.4.1 Participants. The participants recruited for Experiment 2 were the same as those for Experiment 1, and they had been given sufficient rest before conducting the experiment.

3.4.2 Procedure. This experiment aims to examine H3, which posits that the E-Tactile flow condition, compared to the non-flow-modulated condition, significantly enhances flow-related engagement and reduces pain perception. Additionally, it further compares the effects of dynamic task difficulty modulation versus no modulation on participants' flow states and pain perception.

This experiment employed a single-factor within-subject design, with the independent variable being the difficulty regulation mode, consisting of two conditions:

No-Regulation mode: In this mode, tasks were fixed at the medium difficulty level of the T-D mode, and all tasks were completed under this condition.

E-Tactile Flow Mode: Based on flow theory, this mode dynamically adjusted task difficulty. Specifically, the E-Tactile flow mode began at any difficulty level of the T-D mode. If participants correctly identified two consecutive patterns, the task difficulty increased to enhance the challenge. Conversely, if participants incorrectly identified two consecutive patterns, the task difficulty decreased to alleviate frustration. This dynamic regulation mechanism was intended to reduce persistent mismatch between task challenge and participant skill, thereby supporting sustained engagement and flow-related experience. The two-consecutive-response rule was adopted as a practical heuristic inspired by adaptive staircase procedures, in which difficulty is adjusted based on short response sequences rather than after every single trial [109]. We used two consecutive responses because a single correct or incorrect response may reflect chance, momentary inattention, or accidental error, whereas two consecutive responses provide a more stable indication of a possible mismatch between task difficulty and participant skill. It was not intended as an optimized adaptive algorithm, and more principled models remain a direction for future work.

The experiment employed an AB/BA design to alternate between regulation modes, balancing the order of experimental conditions and eliminating potential sequence effects. To further reduce order effects, participants were assigned to counterbalanced condition orders, such as AB/BA, so that the No-Regulation and E-Tactile Flow conditions appeared in different serial positions across participants. Within each condition, pattern presentation was randomized to avoid fixed sequence effects.

The experiment was conducted using the same equipment settings as in Experiment 1, with the objective of eliminating potential result biases that could arise from equipment variability. This approach allowed for a greater focus on differences in participant responses under varying experimental conditions, thereby ensuring the validity and comparability of the data.

3.4.3 Analysis. To test H3: we examined whether adaptive difficulty regulation, intended to improve challenge–skill matching, increased attention and flow-related ratings and reduced subjective and physiological pain indicators.

3.5 Processing of Physiological Signal Data

We processed the physiological signals obtained from the AcqKnowledge software as follows:

For EMG signals, the effective frequency range is typically 20-500 Hz. However, in practical applications, high-frequency noise (such as power-line interference and myoelectric artifacts) needs to be filtered out. A low-pass Butterworth filter with a cut-off frequency of 150 Hz can effectively remove high-frequency noise and retain the main spectral components of EMG signals [8]. High-pass filtering is used to eliminate baseline drift and low-frequency motion artifacts. A cut-off frequency of 50 Hz can remove low-frequency noise (such as interference caused by respiratory movements or electrode displacement) while preserving the effective components of EMG signals [101]. Subsequently, Root-Mean-Square(RMS) processing is carried out on the EMG signals.

EDA signals reflect slow changes in skin conductance, and their main frequency range is 0.05-0.3 Hz [103]. A low pass filter with a cut-off frequency of 0.3 Hz can retain the low-frequency characteristics associated with sympathetic nerve activity (such as skin conductance responses) and suppress high frequency noise (such as muscle movement or environmental interference).

The effective components of the ECG signals are concentrated in the range of 0.05-100 Hz, and the energy of the QRS complex is mainly distributed in 5-30 Hz. A low pass filter with a cut-off frequency of 35 Hz can retain key information from the QRS complex and the T wave while filtering out high-frequency noise (such as myoelectric interference and power line harmonics) [27]. After that, the heart rate(RR) and the RR intervals(RRI) are extracted from the ECG signals.

EEG was not included in the present experiment because the primary objective was to evaluate peripheral physiological responses to pain using EMG, EDA, and ECG-derived indicators, and because EEG recording would require a more controlled recording environment. In addition, simultaneous electrotactile stimulation and EEG recording would introduce additional setup complexity and potential electrical artifacts. To reduce cross-contamination between electrotactile stimulation and physiological recording, stimulation and recording channels were physically separated; physiological signals were recorded using BIOPAC biopotential differential amplifier inputs connected to the MP160 system; shield-drive-based common-mode noise reduction, grounding precautions, and offline filtering were applied to reduce common-mode, power-line, and high-frequency artifacts. The electrodes listed in Table 1 refer to the positive and negative inputs of differential recording channels; no separately amplified active electrodes were used.

3.6 Experimental Device

A pilot study was conducted in a university computer laboratory, with the experimental setup as shown in Figure 5. a, the descriptions are:

Laptop: Responsible for running the task program and physiological signal monitoring software.

Monitor: Used to display task options and targets to participants.

HY002-2 Pain Simulator: This device provided pain stimulation via electrodes, delivering electrical currents of adjustable intensity to nerves beneath the skin.

The 64-channel high-voltage switch module and electrode array made of FPC (flexible printed circuit): The 64-channel high-voltage switch module receives pattern data from the laptop and voltage input from the KEITHLEY 2470 digital source meter, transmitting both to an 8*8 electrode array. This array is used to present 8x8 electrotactile patterns.

KEITHLEY 2470 Digital Source Meter: Provided voltage and current input to the 64-channel high-voltage switch module, allowing for the adjustment of electrotactile intensity on the electrode array.

BIOPAC MP160 Data Acquisition System: A multifunctional platform for recording, monitoring, and analyzing various physiological signals, widely used in biomedical research, psychological experiments, and human-computer interaction studies.

In the pre-experiment, we designed 12 sets of patterns, with each set consisting of three 8*8 dot matrix patterns, totaling 36.

A snapshot of the experimental setup is shown in Figure 5a, in the pre-experiment, we did not use the multichannel physiograph to collect participants' physiological data. It will be utilized in Experiments 1 and 2.

3.7 Measures

Table 1. Schematic Diagram of the Positions of Physiological Signal Electrodes.

Channel	Active Electrode VIN+	Active Electrode VIN-	Reference Electrode GND
EDA	The pulp of the left thumb	The pulp of the left index finger	-
ECG	Below the left rib	Below the right clavicle	Below the right rib
EMG	At the left masseter muscle	At the left temporal muscle	The left rear of the neck
Pain Stimulation	The left calf	The left calf	-

The current methods to evaluate pain experience include subjective indicators, for example, perceived level of pain and objective indicators like physiological indicators. Therefore, we evaluated the pain level from both subjective and objective responses.

The Wong-Baker FACES Pain Rating Scale (FPS) was used to measure the perceived pain of the participants during the Experiment 1 and Experiment 2. The FPS uses a series of facial expression charts, ranging from a happy face to a crying face, to represent different levels of the pain intensity [30]. Numerous studies have shown that FPS have a good reliability and can effectively assess patients' pain levels [4, 39]. Unlike Experiment 1, Experiment 2 additionally introduced two new measures: flow score and attention focus, to validate Hypothesis H3 from a multidimensional perspective.

Flow experience was assessed using an adapted 10-item Flow Short Scale (FSS)[34, 50, 81], which asked participants to evaluate the extent to which each statement matched their actual experience during the preceding task. The items assessed challenge–skill fit, fluency of cognition/action, time distortion, concentration, mental clarity, absorption, automaticity of correct cognition/action, clarity of task goals, sense of control, and reduced awareness of task-irrelevant events. Participants responded on a 7-point Likert-type scale, ranging from 1 = strongly inconsistent with my actual experience to 7 = strongly consistent with my actual experience. Following the structure of the FSS, items 1, 3, 6, and 10 were used to characterize engagement/absorption, while items 2, 4, 5, 7, 8, and 9 were used to characterize fluency of performance. The overall flow score was calculated by summing all 10 items, with higher scores indicating stronger flow-related experience. Attention focus was measured using a single bipolar rating scale ranging from -5 to 5. Negative values indicated that attention was mainly allocated to the pain location, positive values indicated that attention was mainly allocated to the graphical electrotactile recognition task, and 0 indicated no clear attentional bias or approximately equal attention allocation.The full questionnaire items and scoring instructions are provided in Appendix A.

In this experiment, masseter electromyogram (EMG) signals, electrodermal activity (EDA), heart rate (HR), and heart rate variability (RR interval, RRI) were mainly used as physiological indicators for monitoring pain. The reasons are as follows:

Masseter electromyogram(EMG) signals: EMG signals directly reflect the pain responses of participants [41, 99]. During the pain stimulation, the tension and contraction of the masseter muscle become more pronounced. The nature of the pain stimulation in this experiment indicates that masseter EMG is highly sensitive to detecting pain-related electrical changes in muscle activity. Additionally, it is less affected by task demands or emotional fluctuations, providing a clearer and more direct representation of pain perception.

Electrodermal activity (EDA) signals: EDA, also known as the electrodermal skin response (ESR), is an indicator for measuring changes in skin conductivity. These changes are mainly caused by sweat gland activity [49]. EDA is measured in microsiemens (μS) and is typically recorded in areas with a high density of sweat glands, such as the hands. Multiple studies have confirmed that EDA is an effective tool for assessing the arousal state of the sympathetic nervous system (SNS) [6, 33]. The changes in EDA are closely related to sympathetic nerve activity and are widely used in the study of physiological and psychological processes such as emotions, stress, and pain [37].

Electrocardiogram (ECG) signals: Pain stimulation can trigger the activation of the sympathetic nervous system, leading to an increase in heart rate (HR), which can be immediately monitored through ECG signals. At the same time, the shortening of the RR interval (RR-I) reflects the physiological stress response caused by pain. These changes are closely related to pain perception, providing a strong basis for objective assessment of pain [76].

The placement positions of the EMG, EDA, ECG, and simulated pain electrodes are detailed in Table 1.

The experiments were carried out according to the Declaration of Helsinki guidelines and approved by the Ethics Committee of our university. Written consent was obtained from all participants.

4 RESULTS

In two experiments involving 42 participants, we systematically evaluated the effects of bidirectional electrotactile tasks on pain perception and physiological stress responses. The tasks included top-down (T-D) goal-directed and bottom-up (B-U) stimulus-driven approaches. Additionally, we implemented a dynamic difficulty adjustment mechanism in T-D tasks to enhance the flow experience. Both tasks were delivered via an 8*8-channel electrotactile array. In Experiment 1 we compared the analgesic efficacy of T-D and B-U modes against a no-intervention control. Experiment 2 focused on refining T-D tasks through dynamic difficulty modulation to test the impact of challenge–skill matching on pain relief and flow-related engagement. Participants underwent personalized pre-calibration to determine individual pain thresholds and electrotactile parameters, ensuring safe and tolerable stimulation levels during formal testing. In Experiment 1, subjective pain ratings and objective physiological indicators (Masseter Electromyogram, Electrodermal Activity, Electrocardiogram) were recorded under each condition, revealing that both T-D and B-U tasks significantly reduced pain perception compared to the control, with T-D demonstrating stronger suppression of stress-related responses. Experiment 2 further demonstrated that dynamically adjusting the difficulty of the T-D task (increasing complexity after consecutive correct responses and decreasing it after errors) enhanced attentional focus and promoted a trend toward an improved flow experience. These effects were accompanied by physiological changes including reduced masseter electromyographic activity, decreased skin conductance, and increased parasympathetic activation—as indicated by a lower heart rate and increased inter-beat intervals, thereby reflecting a more pronounced analgesic effect. These findings collectively demonstrate that goal-directed electrotactile tasks outperform stimulus-driven approaches in pain relief, with dynamic difficulty adjustment amplifying both cognitive engagement and physiological relaxation for optimized analgesic outcomes.

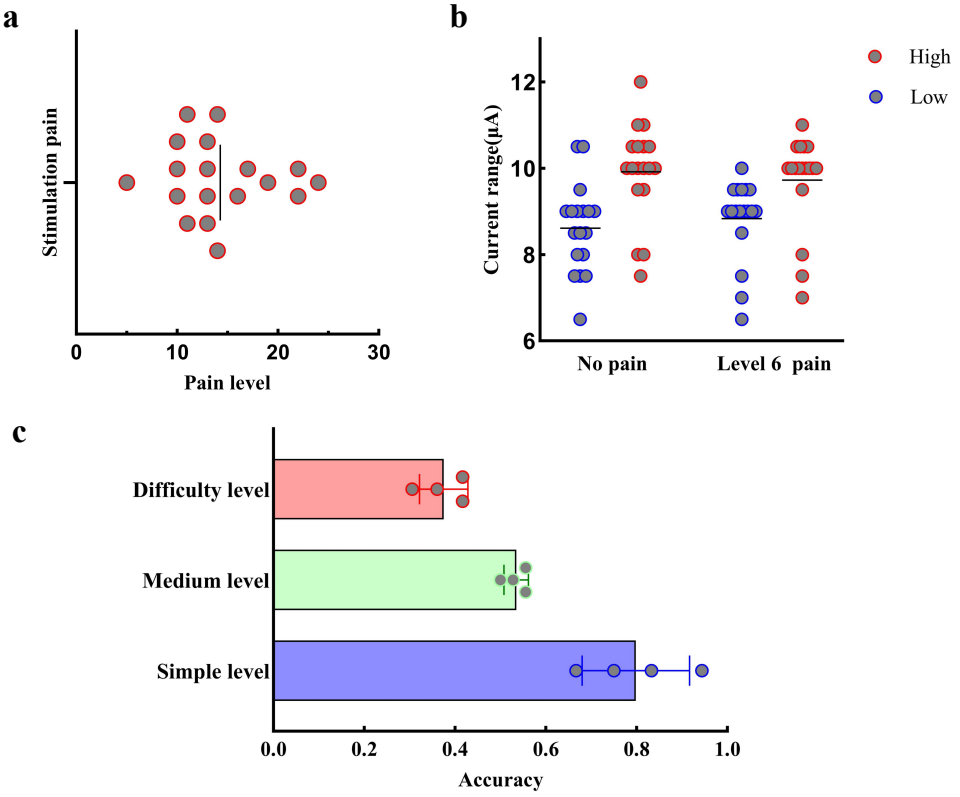

Fig. 6. **Determination of simulated pain, electro-tactile intensity, and pattern difficulty. a**, The simulated pain rating of participants at a subjective pain level of 6. **b**, The current intensities at which participants perceived pain and experienced distinct tingling under the conditions of no simulated pain and subjective level 6 simulated pain. **c**, Electro-tactile patterns were categorized into three difficulty levels based on the correct response rate to standardize experimental parameters and evaluate perceptual thresholds.

4.1 Personalized Electrotactile Calibration Enables Precise Pain Sensitivity Mapping

Before the formal experiment, 18 participants were recruited to determine the simulated pain levels during the main experiment, as well as the current magnitude of electro-tactile stimulation and the allocation of pattern categories. Specifically, Figure 6a details the intensity of simulated pain stimulation determined by the childbirth experience device, Figure 6b documents participant-specific electrical stimulation parameters, and Figure 6c evaluates pattern recognition accuracy across difficulty levels. Results from Figure 6a and Figure 6b demonstrate significant inter-individual variability in pain perception thresholds and electrical stimulation tolerances, necessitating personalized parameter adjustments based on subjective feedback. Specifically, as shown in Figure 6a, the simulated pain stimulation setting corresponding to a subjective pain level of 6 ranged from 5 to 24 device units across participants ($M = 14.28, SD = 4.94$). As shown in Figure 6b, the voltage was fixed at 200 V, while the calibrated electrotactile current intensity ranged from 6.5 to 12.0 μA under the no-simulated-pain condition ($M = 9.26$ μA, $SD = 1.25$ μA) and from 6.5 to 11.0 μA under the level-6 simulated-pain condition ($M = 9.28$ μA, $SD = 1.09$ μA). These results indicate that electrotactile stimulation was maintained within

a comparable perceptible range across pain contexts, while individualized calibration remained necessary to account for participant-specific tactile sensitivity.

Notably, Figure 6c reveals a consistent relationship between pattern complexity and recognition accuracy, with simpler patterns yielding significantly higher success rates. Specifically, the mean recognition accuracy decreased systematically from the simple level ($M = 0.799, SD = 0.118$, range = 0.667 - 0.944) to the medium level ($M = 0.535, SD = 0.027$, range = 0.500 - 0.556) and the difficult level ($M = 0.375, SD = 0.053$, range = 0.306 - 0.417). This graded decrease in recognition accuracy supports the use of recognition performance as the empirical basis for difficulty classification. This stability in performance metrics allows us to establish a hierarchical difficulty classification system for use in the formal experiment. Leveraging these pre-experimental findings, the main study will implement customized pain stimulation levels and electrical parameters tailored to each participant's unique sensory profile, ensuring optimal task engagement while minimizing extraneous variance. Figure 3 illustrates examples of the patterns used in the pre-experiment. Following the completion of the pre-experiment, we classified the 12 sets of patterns into three categories, which are low, medium, and high. This classification was based on the decreasing order of recognition accuracy shown in Figure 6c, with four sets of patterns assigned to each level of difficulty in tasks.

4.2 Electrotactile Attention Capture Significantly Attenuates Pain Responses

In line with expectations, participants ($N = 42$) reported significantly lower subjective pain ratings under both bottom-up (paired samples t-test: $t(41) = 27.835, p < 0.001$, CI = 2.790 to 3.226) and top-down modes (paired samples t-test: $t(41) = 26.727, p < 0.001$, CI = 2.920 to 3.397) compared with the no-intervention condition (simulated pain only)(Figure 7).

Analysis of objective physiological indices revealed that under the bottom-up mode, heart rate (HR; paired samples t-test: $t(41) = 3.210, p = 0.003$, CI = 0.605 to 2.657) and root-mean-square electromyography (RMS EMG; paired samples t-test: $t(41) = 2.681, p = 0.011$, CI = 0.011 to 0.076) decreased significantly, while the RR intervals (RRI; paired samples t-test: $t(41) = -3.099, p = 0.03$, CI = -0.030 to -0.006) increased significantly. Electrodermal activity (EDA; paired samples t-test: $t(41) = 1.887, p = 0.066$, $CI = -0.047 to 1.387$) showed a non-significant downward trend, approaching marginal significance ($p = 0.066$), which may suggest a potential effect of the bottom-up intervention on autonomic nervous activity. Under the top-down mode, EDA (paired samples t-test: $t(41) = 3.580, p < 0.001$, CI = 0.617 to 2.214), HR (paired samples t-test: $t(41) = 3.739, p < 0.001$, CI = 1.110 to 3.716), and RMS EMG (paired samples t-test: $t(41) = 3.001, p = 0.005$, CI = 0.016 to 0.082) all decreased significantly, whereas RRI (paired samples t-test: $t(41) = -3.422, p = 0.001$, CI = -0.038 to -0.010) increased significantly, consistent with the hypothesized attenuation of physiological stress responses.

These findings align with the predictions of H1, suggesting that both bottom-up and top-down task modes can reduce subjective pain perception and modulate physiological stress indicators, thereby providing initial empirical support for the proposed attentional-control account.

4.3 Comparative Between Electrotactile Top-Down and Bottom-Up Modes

Guided by the key inference from attention control theory that "top-down cognitive regulation exerts stronger inhibition on pain processing centers than bottom-up sensory distraction", this study hypothesized that the top-down mode would outperform the bottom-up mode in reducing subjective pain perception and inhibiting stress-related physiological responses. The following analysis empirically tests this hypothesis by comparing subjective and objective data between the two intervention conditions (Figure 7).

Intergroup comparison of subjective pain ratings showed a trend favoring the top-down mode over the bottom-up mode (paired samples t-test: $t(41) = 1.997, p = 0.053$, CI = 0.002 to 0.303). Although this difference narrowly missed conventional statistical significance ($p < 0.05$), the directionality is consistent with our H2

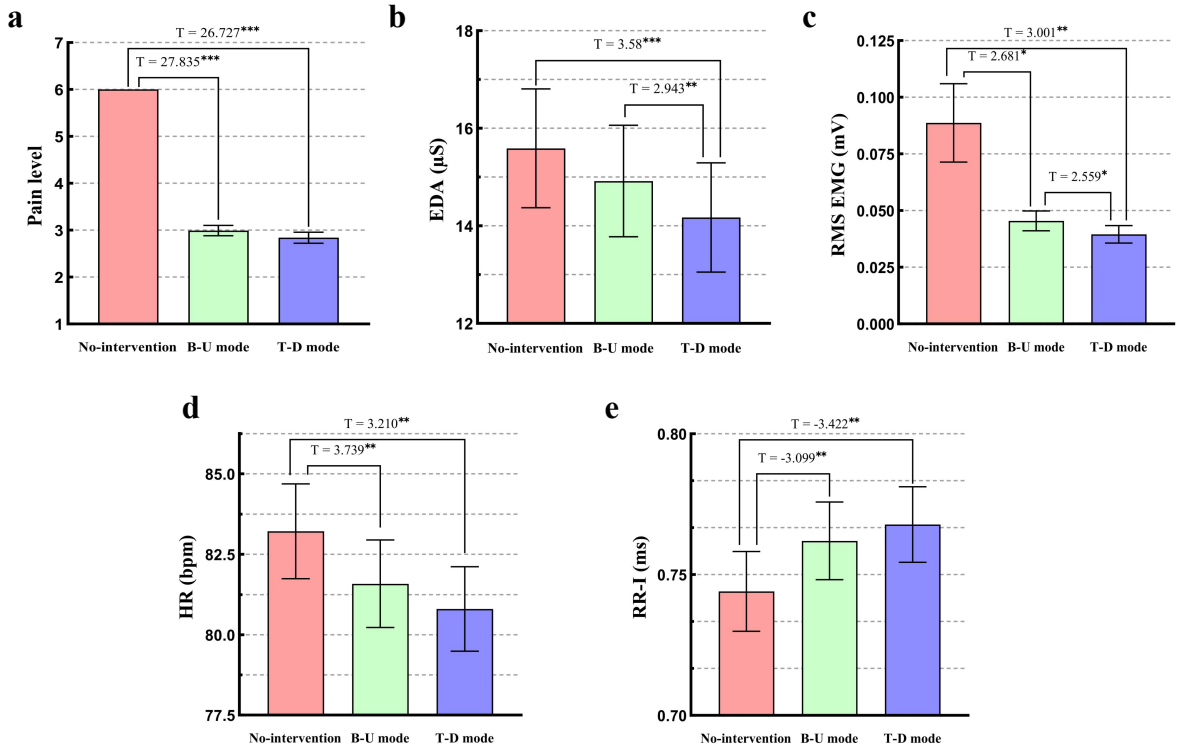

Fig. 7. **Differences in subjective pain ratings and physiological indicators across experimental conditions. a**, Comparison of subjective pain perception across three experimental modes (No-intervention, B-U and T-D). **b-e**, Comparison of objective physiological indicators across three experimental modes.

prediction of stronger cognitive engagement driving greater analgesia. While this result alone is insufficient for definitive conclusions, it aligns with the theoretical prediction of H2: Top-down tasks, by engaging prefrontal cognitive control, exert stronger central inhibition of pain matrices (e.g., insula, anterior cingulate cortex) than passive bottom-up distraction [14, 45, 74, 87].

For objective physiological indices, the bottom-up mode exhibited differentiated effects on somatic stress responses: Electrodermal activity (EDA; paired samples t-test: $t(41) = 2.943, p = 0.005$, CI = -0.234 to 1.256) and root-mean-square electromyography (RMS EMG; paired samples t-test: $t(41) = 2.559, p = 0.014$, CI = 0.001 to 0.011) both showed significant decreases, indicating dual suppression of autonomic nervous excitability and muscular tension; Changes in heart rate (HR; paired samples t-test: $t(41) = 1.699, p = 0.097$, CI = -0.148 to 1.712) and the RR intervals (RRI; paired samples t-test: $t(41) = -1.689, p = 0.099$, CI = -0.013 to 0.001) trended toward stress relief and reach marginally statistical significance ($0.05 < p < 0.1$).

In summary, while physiological indices showed differentiated intergroup effects, the directional decrease in subjective pain ratings (lower in the top-down mode) aligns with theoretical predictions. Anchored in the central inhibition mechanism of attention control theory, These findings provide partial support for a possible advantage

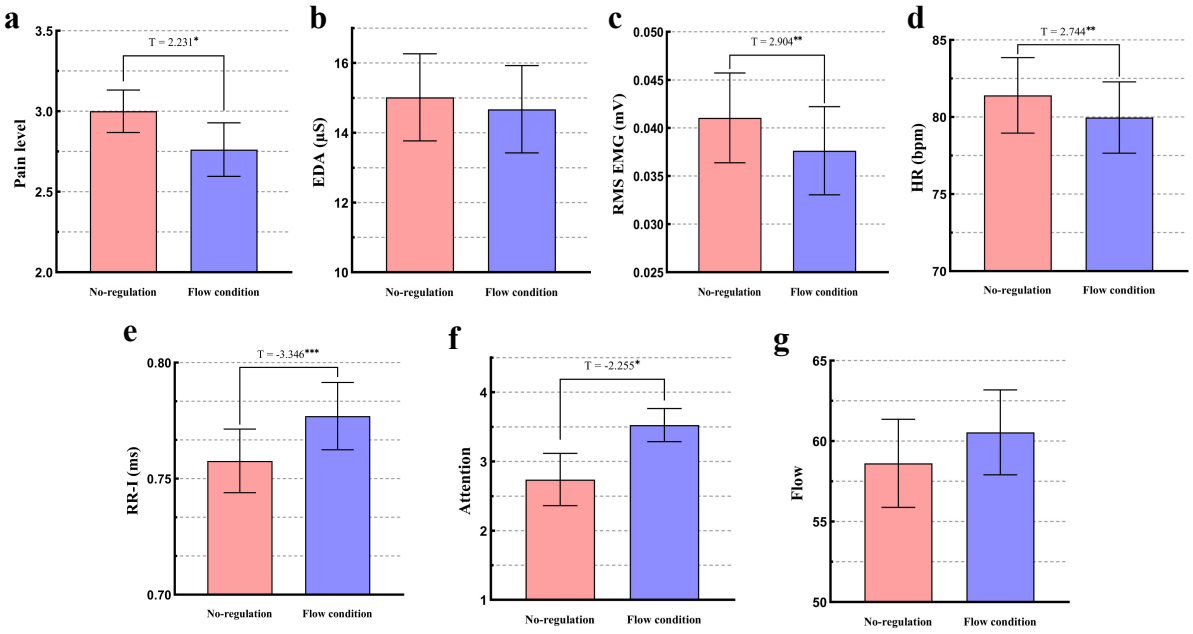

Fig. 8. **Differences in subjective pain ratings and physiological measures under different experimental conditions.** **a**,Subjective pain perception in the two experimental modes (No-Adjustment vs. E-Tactile Flow). **b-e**, Comparison of objective physiological indicators between the two modes. **f-g**, Comparison of attention index and flow state across the two modes.

of the top-down mode, whereas the bottom-up mode's specific modulation of peripheral stress markers provides complementary evidence for personalized pain intervention strategies.

4.4 Dynamic Electrotactile Difficulty Titration Enhances Engagement and Analgesia

Experiment 2 examined the effects of top-down dynamic difficulty adjustment on participants' subjective experiences and physiological stress responses, aiming to provide empirical evidence for the cognitive-physiological mechanisms underlying flow-related engagement and analgesia (Figure 8).

Analysis of subjective and behavioral indices revealed that dynamic difficulty adjustment significantly reduced pain ratings (No-Regulation: $M = 3.00, SD = 0.86$; E-Tactile Flow: $M = 2.76, SD = 1.08$; paired-samples t-test: $t(41) = 2.231, p = 0.031$, CI = 0.023 to 0.454), indicating that adaptive difficulty regulation produced a stronger analgesic effect than the no-regulation condition. Dynamic difficulty adjustment also significantly improved task performance, as reflected by higher recognition accuracy in the E-Tactile Flow condition than in the No-Regulation condition (No-Regulation: $M = 0.71, SD = 0.18$; E-Tactile Flow: $M = 0.80, SD = 0.16$; paired-samples t-test: $t(41) = -3.928, p < 0.001$, CI = -0.129 to -0.041). In addition, dynamic difficulty adjustment significantly increased task-directed attention focus, as measured by the bipolar attention rating scale ranging from −5 to 5, where negative values indicated attention toward the pain location and positive values indicated attention toward the graphical electrotactile recognition task (No-Regulation: $M = 2.74, SD = 2.45$; E-Tactile Flow: $M = 3.52, SD = 1.55$; paired-samples t-test: $t(41) = -2.255, p = 0.030$, CI = -1.489 to -0.082).

For the flow-related measures, dynamic difficulty adjustment significantly enhanced flow-related engagement/absorption, as reflected by the engagement factor of the adapted Flow Short Scale (No-Regulation: $M =$

Table 2. Exploratory correlations among difference scores in Experiment 2. For recognition accuracy, attention focus, engagement/absorption, fluency, and overall flow, difference scores were calculated as E-Tactile Flow minus No-Regulation. Pain reduction was calculated as No-Regulation pain rating minus E-Tactile Flow pain rating.

Variable pair	**Pearson's r**	p	**Spearman's ρ**	p
Pain reduction – ΔRecognition accuracy	0.120	0.448	-0.009	0.957
Pain reduction – ΔAttention focus	-0.248	0.114	-0.010	0.949
Pain reduction – ΔEngagement/absorption	**0.377**	**0.014**	**0.338**	**0.029**
Pain reduction – ΔFluency	0.287	0.065	0.293	0.059
Pain reduction – ΔOverall flow score	**0.338**	**0.028**	**0.333**	**0.031**
ΔRecognition accuracy – ΔAttention focus	0.021	0.897	0.099	0.535
ΔRecognition accuracy – ΔOverall flow score	0.028	0.863	0.180	0.255
ΔAttention focus – ΔEngagement/absorption	0.218	0.165	**0.348**	**0.024**
ΔAttention focus – ΔFluency	**0.317**	**0.041**	**0.490**	**0.001**
ΔAttention focus – ΔOverall flow score	0.291	0.062	**0.464**	**0.002**

Note. Overall flow score was calculated by summing the engagement/absorption and fluency factors. Significant correlations are shown in bold.

22.81, $SD = 4.12$; E-Tactile Flow: $M = 23.93$, $SD = 3.68$; paired-samples t-test: $t(41) = -2.362$, $p = 0.023$, CI = -2.076 to -0.162). The fluency factor was numerically higher in the dynamic difficulty adjustment condition but did not reach statistical significance (No-Regulation: $M = 35.81$, $SD = 5.36$; E-Tactile Flow: $M = 36.62$, $SD = 5.41$; paired-samples t-test: $t(41) = -1.128$, $p = 0.266$, CI = -2.259 to 0.639). The overall flow score, calculated by summing the engagement/absorption and fluency factors, also showed a numerical upward trend in the dynamic difficulty adjustment condition, but this effect was not statistically significant (No-Regulation: $M = 58.62$, $SD = 8.79$; E-Tactile Flow: $M = 60.55$, $SD = 8.46$; paired-samples t-test: $t(41) = -1.696$, $p = 0.097$, CI = -4.225 to 0.368). Although the between-condition difference in the overall flow score did not reach statistical significance, the mean score in the E-Tactile Flow condition exceeded 60 out of 70, indicating that participants reported a high level of flow experience during the adaptive electrotactile task. Therefore, the current data support pain reduction, improved task performance, stronger task-directed attention focus, and enhanced flow-related engagement, but do not provide sufficient evidence to claim reliable induction of a full flow state.

To further examine the relationships among task performance, attentional allocation, flow-related experience, and pain reduction in Experiment 2, we conducted exploratory difference-score correlation analyses. For recognition accuracy, attention focus, engagement/absorption, fluency, and overall flow score, difference scores were calculated by subtracting the No-Regulation condition from the E-Tactile Flow condition. Pain reduction was calculated as the pain rating in the No-Regulation condition minus the pain rating in the E-Tactile Flow condition, such that larger values indicated stronger analgesic effects. As shown in Table 2, pain reduction was significantly associated with increases in engagement/absorption and overall flow score, while its association with fluency showed a marginal trend. However, pain reduction was not significantly associated with changes in recognition accuracy or task-directed attention focus. These results suggest that the analgesic effect of adaptive difficulty regulation may be more closely related to flow-related engagement than to objective task performance alone.

In addition, increases in task-directed attention were positively associated with increases in flow-related fluency. Spearman correlation analyses further showed that increases in task-directed attention were significantly associated with increases in engagement/absorption, fluency of performance, and overall flow score. In contrast, changes in recognition accuracy were not significantly correlated with changes in task-directed attention or overall flow score. These exploratory findings suggest that adaptive difficulty regulation may support analgesia

by enhancing subjective engagement and task-oriented experience, although the present correlational analyses do not establish a causal mediation pathway.

This result did not reach statistical significance, likely due to limitations in the self-report flow scale (e.g., retrospective ratings may not capture moment-to-moment immersion) and restricted task difficulty granularity (only three predefined levels). Future studies could implement real-time feedback mechanisms (e.g., EEG-based attention metrics [36]) to dynamically adjust challenges and validate flow induction. For objective physiological measures, electromyography (EMG;paired samples t-test: $t(41) = 2.904, p = 0.006$, CI = 0.001 to 0.006) and heart rate (HR;paired samples t-test: $t(41) = 2.744, p = 0.009$, CI = 0.379 to 2.493) decreased significantly, indicating reduced somatic tension and sympathetic nervous activation, whereas the RR intervals (RRI;paired samples t-test: $t(41) = -3.346, p = 0.002$, CI = -0.031 to -0.008) increased significantly, suggesting enhanced parasympathetic activity and a shift toward a relaxed autonomic state.

In summary, using a top-down approach to dynamic difficulty adjustment may improve attentional allocation. This leads to reduced pain perception and a directional improvement in flow experience at the subjective level. At the same time, it inhibits somatic stress responses and promotes a beneficial autonomic balance at the physiological level. The alignment between subjective and objective results provides cross-level evidence for the theoretical pathway of "attentional engagement–physiological stress regulation–flow-related experience". These findings provide preliminary cross-level evidence for a possible pathway linking attentional engagement, physiological stress regulation, and flow-related experience.

5 DISCUSSION

In this study, we introduced "E-Tactile Flow," a novel paradigm that integrates high-resolution electrotactile stimulation with adaptive cognitive tasks, aimed at modulating pain perception.The results suggest that interactive tactile engagement can attenuate subjective pain ratings and physiological stress responses. The findings are consistent with an attentional-control account, although the present design cannot fully isolate all possible task-demand contributions associated with the visual cue and response interface. Adaptive difficulty further reduced pain and increased attention ratings, while flow ratings showed a positive but non-significant trend.

5.1 Task-Structure Differences in Electrotactile Analgesia

Our results are broadly consistent with an attentional-engagement account of pain modulation [32, 52, 53] . This model posits that pain processing must compete with executive functions for limited cognitive resources. Although both B-U and T-D modes reduced pain relative to control, the comparison between T-D and B-U showed mixed evidence: subjective pain ratings showed a trend favoring T-D, while several physiological indicators showed stronger modulation under T-D. These findings suggest a possible advantage of goal-directed engagement, but should be interpreted cautiously. This finding aligns with the "Biased Competition" hypothesis: specifically, that goal-directed executive control—mediated by the dorsolateral prefrontal cortex (DLPFC) and anterior cingulate cortex (ACC)—suppresses ascending nociceptive signals more effectively than transient sensory distractors [15, 59, 91, 96, 107].

Unlike previous studies relying solely on passive vibratory stimulation [18, 60] or simple visual distraction [47], our T-D paradigm required participants to engage in active pattern recognition and working memory processing. We propose that this active engagement constructs a "Cognitive Shield": by occupying the limited capacity of the central executive system, the task prevents nociceptive signals from dominating conscious awareness [15, 102]. In contrast, the B-U mode primarily relies on the salience network; while novel tactile patterns initially capture attention, this effect is highly susceptible to habituation [23, 80]. These results suggest that active cognitive engagement may be a valuable component of pain-management interfaces. However, the present study does

not compare electrotactile interaction directly with visual, auditory, or other flow-inducing modalities; such comparisons are needed in future work.

Notably, the present study should be understood as a comparison of electrotactile task structures with different degrees of goal-directed and working-memory engagements, rather than definitely dissociating top-down and bottom-up pain-attention modulation mechanisms. Therefore, the findings provide preliminary evidence for the potentials of interactive electrotactile attentional engagement and adaptive difficulty for pain modulation, but not provide decisive evidence for strictly distinct T-D/B-U mechanisms.

5.2 The Role of Flow and Adaptive Difficulty

A key innovation of this study was the implementation of a dynamic difficulty adjustment algorithm (Experiment 2). We observed that improving challenge–skill matching may be important for enhancing analgesic efficacy. When task difficulty remains constant, participants may experience boredom if the task is too easy or anxiety if it is too difficult, both of which have been shown to lower pain thresholds [82]. By dynamically titrating difficulty, the adaptive condition increased attention engagement and reduced pain ratings, while flow ratings showed an upward but non-significant trend. Thus, the current evidence supports flow-related engagement rather than definitive entry into a flow state [25].

This finding is consistent with recent computational models on priority coding in the visual system [63], suggesting that the brain dynamically reallocates processing resources to stimuli possessing high information value. In our paradigm, the adaptive task becomes the high-priority signal, thereby relegating pain signals to background noise. This is consistent with flow theory [25], which suggests that the "loss of self-consciousness" inherent in flow states may functionally decouple the sensory-discriminative dimension of pain from its affective-motivational aspect [79], thereby blocking the emotional amplification of pain.

5.3 Physiological Correlates of Cognitive Pain Modulation

Subjective reports of pain relief were strongly corroborated by objective physiological indicators, validating the biological basis of E-Tactile Flow. The notable decrease in masseter electromyography (EMG) activity indicates a suppression of reflexive motor responses typically associated with nociception, such as facial tensing or clenching [19]. Furthermore, the simultaneous decrease in electrodermal activity (EDA) and heart rate (HR), along with increased heart rate variability (HRV/RRI), indicates a systemic shift in the balance of the autonomic nervous system [22, 94].

Pain typically triggers sympathetic arousal (fight-or-flight). However, our results indicate that engaging electrotactile tasks can reactivate the parasympathetic nervous system even during painful stimulation. This echoes findings in biofeedback research [69] (as demonstrated in Paper 3), where volitional control over bodily states dampens arousal levels. We argue that high-resolution electrotactile feedback serves as a form of proprioceptive grounding, stabilizes the autonomic nervous system and interrupts the "pain-stress-pain" vicious cycle that often exacerbates chronic pain [20]. Furthermore, this may involve modulation of the locus coeruleus-norepinephrine (LC-NA) system, based on its critical role in regulating arousal and shift attention [2].

5.4 Limitations and Future Directions

While these findings are promising, it's important to acknowledge a few limitations that could provide opportunities for further exploration. First, our sample consisted of healthy young adults induced with acute experimental pain. Chronic pain populations often exhibit maladaptive neuroplasticity and altered attentional biases [53, 86], which may modulate the efficacy of top-down control. In addition, chronic pain populations may differ from healthy participants not only in pain thresholds, but also in attentional bias toward pain, tolerance for task

load, and willingness to engage with high-attention interventions. Future studies should therefore validate the paradigm in population-specific contexts, including patients with neuropathic or musculoskeletal pain.

The present study was not designed to characterize the temporal evolution of flow-related analgesia. It remains unknown whether analgesic effects increase, plateau, or decay during prolonged interaction, and whether perceived task difficulty changes as participants learn the patterns. Because electrotactile pattern recognition requires unfamiliar tactile discrimination through the electrode array rather than ordinary visual recognition, practice effects may emerge more slowly than in visual tasks; nevertheless, learning-related changes in perceived difficulty could influence challenge–skill matching, engagement, and pain reduction over time. Such learning-related changes in perceived difficulty may influence challenge–skill matching and, consequently, the maintenance of flow-related engagement during prolonged use. Future longitudinal or longer-duration studies should analyze task performance, attention, flow-related ratings, and pain ratings over time to clarify how adaptive electrotactile interaction maintains, strengthens, or loses its analgesic effect across extended use.

A further practical limitation is that the current paradigm requires sustained attention, whereas real-world chronic pain episodes may be unpredictable and may occur during activities in which users cannot devote substantial cognitive resources to a task. Future work should explore lower-burden interaction formats, context-aware triggering, and short intervention modules suitable for naturalistic use.

While we utilized peripheral physiological measures, the specific neural pathways involved in "tactile flow" remain inferential, and the physiological markers observed in the present study cannot be regarded as flow-specific because they may also reflect pain-related autonomic responses. Future research should combine neuroimaging techniques such as fMRI or EEG with more flow-specific physiological or neural markers to map the interaction between somatosensory cortex (S1/S2) activation, prefrontal executive control networks, and flow-related engagement during electrotactile tasks [17, 58, 62, 77]. Specifically, investigating whether descending pain inhibitory pathways, such as the periaqueductal gray, PAG, are directly involved in flow-induced analgesia would be of great value [57, 97].

Technical calibration remains a challenge. As noted in our pre-experiment, individual sensitivity to electrotactile stimulation varies widely. Repeated failure or persistent task difficulty may induce frustration and potentially counteract analgesic benefits. Future work should also explicitly examine how feedback availability, perceived failure, and uncertainty about task performance influence frustration, engagement, and pain ratings during prolonged use. Although the current two-response rule was intended to reduce prolonged mismatch, future systems should develop adaptive algorithms based on richer real-time indicators, such as accuracy trajectories, response time, subjective workload, EDA, HRV, or EEG-derived attention metrics.Developing automated, closed-loop calibration systems capable of adjusting not only task difficulty but also stimulation parameters based on real-time physiological feedback (e.g., EDA or EEG peaks) represents a crucial next step toward achieving personalized digital analgesia.

5.5 Conclusion

This study provides initial empirical support and promising non-pharmacological pathway for E-Tactile Flow as an interactive electrotactile approach to pain modulation. By combining goal-directed attentional engagement with adaptive task regulation, the results suggest a promising non-pharmacological pathway for reducing pain perception and regulating autonomic arousal. This contribution should be understood in two layers: electrotactile interaction provides an attentional approach to pain modulation, while adaptive task regulation serves as an additional strategy for sustaining engagement and potentially strengthening analgesic effects.

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A SUBJECTIVE MEASURES USED IN EXPERIMENT 2

Scoring. Participants rated each item on a 7-point Likert-type scale, ranging from 1 = strongly inconsistent with my actual experience to 7 = strongly consistent with my actual experience. Items 1, 3, 6, and 10 were used to characterize engagement/absorption, while Items 2, 4, 5, 7, 8, and 9 were used to characterize fluency of performance. The overall flow score was calculated by summing all 10 items.

Attention focus rating. Participants also rated their attention allocation using a single bipolar scale ranging from −5 to 5. Negative values indicated that attention was mainly allocated to the pain location, positive values indicated that attention was mainly allocated to the graphical electrotactile recognition task, and 0 indicated no clear attentional bias or approximately equal attention allocation.

Table 3. Items of the adapted Flow Short Scale used in Experiment 2.

Item	Statement	Dimension
1	I felt that the task difficulty was just right.	Engagement/Absorption
2	My cognition/actions ran smoothly and fluently.	Fluency of performance
3	I did not notice the passage of time.	Engagement/Absorption
4	I found it easy to concentrate on the task.	Fluency of performance
5	My thoughts were very clear.	Fluency of performance
6	I was fully immersed in the ongoing task.	Engagement/Absorption
7	Correct cognition or actions occurred naturally during the task.	Fluency of performance
8	I knew what I should do at each stage and how to do it.	Fluency of performance
9	I felt that everything was under control.	Fluency of performance
10	I was not aware of things outside the task.	Engagement/Absorption