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

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Abstract

Numerous individuals grapple with chronic or recurrent pain, prompting the exploration for non-pharmacological remedies in human-computer interaction. Redirecting attention from nociceptive signals can effectively alleviate pain, but the path through fine tactile perception is rarely explored. This paper introduce Electronic Tactile Flow, a novel interaction paradigm utilizing an 8*8 electrotactile array to modulate pain through cognitive engagement and Flow theory. We investigated the analgesic effects of top-down (goal-directed) versus bottom-up (stimulus-driven) attention. Results from our user study (N=42) indicate that top-down engagement significantly reduces pain perception compared to passive stimulation. Furthermore, we implemented an adaptive difficulty mechanism that sustains users in an optimal Flow state, which was found to amplify pain relief and immersion. This work presents the first integration of electrotactile interfaces with attentional modulation, offering a promising framework for designing personalized, cognitively interactive pain interventions in HCI.

CCS Concepts

- **Human-centered computing → Empirical studies in HCI**.

Keywords

Pain Relief, Electrotactile Stimulation, Attention Mechanisms, Flow Experience, Human-Computer Interaction

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1 Introduction

Chronic and recurrent pain poses substantial global health challenges, impairing individuals' quality of life, work productivity, and social participation [1, 26, 27, 32]. Beyond immediate physical discomfort, persistent pain is often accompanied by psychological comorbidities such as anxiety and depression, forming a self-reinforcing cycle that exacerbates pain perception [12, 20]. Pharmacological treatments—including opioid analgesics and nonsteroidal anti-inflammatory drugs—offer short-term relief but carry risks such as tolerance, dependence, and gastrointestinal complications

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[6, 29]. The escalating opioid crisis further underscores the need for safe, effective non-pharmacological alternatives [20, 34].

Attentional modulation has emerged as a promising strategy for pain management. Virtual reality (VR), in particular, provides immersive multisensory environments that can divert attention away from nociceptive input and reliably reduce pain across diverse clinical contexts such as burn treatment, cancer care, and postoperative recovery [7, 14, 17, 20, 21, 29, 31, 32]. According to the neurocognitive model of pain-related attention, these effects arise through both top-down (goal-directed) and bottom-up (stimulus-driven) mechanisms that shape the allocation of cognitive resources during painful experiences [2, 15]. VR environments can support both processes by combining salient sensory events with interactive, goal-oriented tasks [2–5].

Despite advances in audiovisual pain modulation [10, 13, 19], the tactile modality remains comparatively underexplored. Yet touch offers unique neurophysiological advantages: tactile input can inhibit nociceptive transmission through peripheral gating mechanisms [18, 33] and activate central affective pathways via C-tactile afferents [11, 12]. These dual effects position tactile stimulation as a potent and versatile channel for non-pharmacological analgesia [22, 33]. However, existing tactile systems rely primarily on simple sensory distraction and often fail to maintain cognitive engagement[8, 24].

To address this gap, we propose an electrotactile framework that integrates tactile stimulation with cognitive models of attention and flow. High-resolution electrotactile interfaces enable precise spatiotemporal control of tactile patterns, creating opportunities to design interactive tasks that selectively evoke top-down or bottom-up attention. Drawing on flow theory, we hypothesize that goal-directed electrotactile tasks—especially when tuned to maintain an optimal challenge–skill balance—may induce deep engagement and stronger pain inhibition [30].

We evaluate this framework through two studies examining subjective pain, physiological responses, and attentional engagement across top-down and bottom-up electrotactile tasks.

2 Related Work

2.1 Non-Pharmacological Pain Modulation

As concerns about opioid dependence grow, non-pharmacological strategies have gained momentum as safer alternatives for pain management [20]. Techniques such as cognitive distraction, sensory modulation, and immersive media have been shown to reduce perceived pain intensity and associated stress responses [1, 27]. VR-based interventions, in particular, leverage immersive environments to divert attention from nociceptive input, producing reliable analgesic effects across clinical settings [7, 14].

2.2 Attention and Pain: Top-Down and Bottom-Up Mechanisms

The neurocognitive model of pain-related attention provides a theoretical basis for understanding how cognitive states influence pain perception [15]. Top-down attention involves intentional, goal-directed processing that competes with pain signals, whereas bottom-up attention is triggered by salient external stimuli. VR research demonstrates that both mechanisms contribute to analgesia: visually salient stimuli elicit bottom-up distraction, while interactive tasks requiring active engagement foster top-down cognitive control [2, 20, 25, 35].

2.3 Tactile Stimulation for Pain Relief

Compared with vision and audition, tactile input offers distinctive advantages in pain modulation. Peripheral tactile stimulation (e.g., vibration) activates $A\beta$ fibers that inhibit nociceptive transmission, consistent with the gate control theory of pain [18, 28, 33]. Meanwhile, social and affective touch—such as holding or stroking—engages C-tactile afferents linked to oxytocin-mediated central analgesia [11, 12]. Recent devices simulating social grasping have demonstrated enhanced analgesic effects when contextual and affective factors are incorporated [22, 33]. However, current tactile systems suffer from limited stimulus diversity and insufficient cognitive coupling, restricting sustained engagement [9, 23].

2.4 Interactive Tactile Interfaces and Cognitive Engagement

Advances in electrotactile technology [16] offer new opportunities for tactile–cognitive integration. High-resolution interfaces enable fine-grained control over spatial and temporal stimulation patterns, supporting the design of interactive tasks that selectively activate attentional mechanisms. Flow theory suggests that tasks with appropriately tuned difficulty can induce deep engagement, reduce awareness of pain, and enhance analgesic outcomes [30]. Nevertheless, few studies have explicitly linked electrotactile interaction design with cognitive and attentional models, highlighting the need for interdisciplinary approaches that bridge tactile stimulation and cognitive engagement.

3 Methods

3.1 Participants

Forty-two healthy volunteers (29 male, 13 female, mean age = 21.71, SD = 3.14) were recruited from a local university. None reported a history of chronic pain, neurological, or psychiatric disorders. All provided informed consent approved by the institutional review board.

3.2 Apparatus and E-Tactile System

High-resolution tactile patterns were delivered via a custom 8×8 flexible printed circuit (FPC) electrode array controlled by a high-voltage switching module and a Keithley 2470 digital source meter. This setup renders spatiotemporal patterns on the user's left forearm. Experimental pain was induced using a commercial stimulator (HY002-2) attached to the left calf. Physiological signals—Masseter Electromyography (EMG), Electrodermal Activity (EDA), and Electrocardiogram (ECG)—were recorded via a BIOPAC MP160 system (see Fig. 1a).

3.3 Task Paradigms and Calibration

We designed two interaction paradigms based on the neurocognitive model of attention. Parameters for pattern difficulty were established in a pilot calibration ($N = 18$), classifying tactile patterns into Low, Medium, and High recognition difficulty.

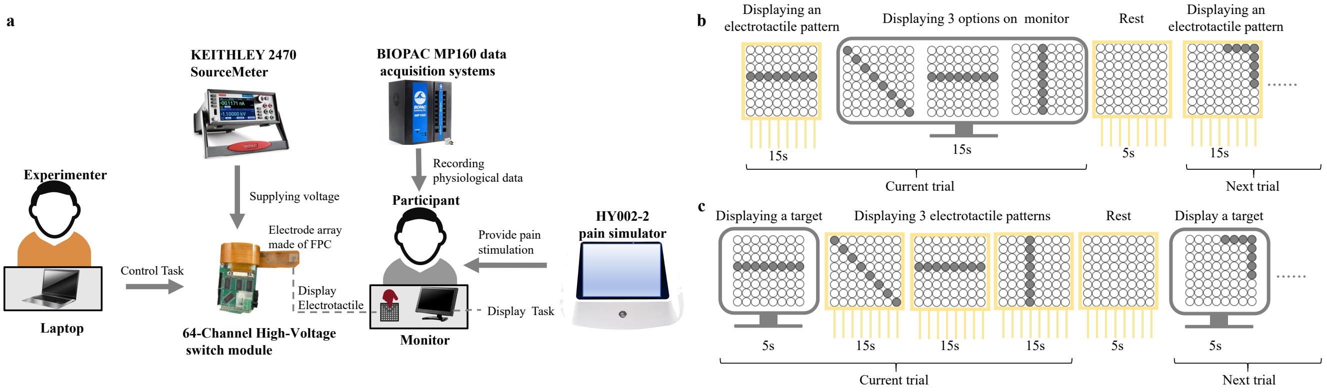

Figure 1: Overview of the experimental settings and task procedure of B-U and T-D mode.

- **Bottom-Up (B-U) Mode:** Designed to test stimulus-driven attention. The user passively perceives a random tactile pattern (15s), then identifies it from three visual options on a screen(see Fig. 1b).
- **Top-Down (T-D) Mode:** Designed to engage goal-directed executive control. A target visual pattern is displayed first (5s). A sequence of tactile patterns follows; the user must actively monitor the somatic input to identify the target(see Fig. 1c).

Adaptive Algorithm (Exp 2): To induce Flow in the T-D mode, we implemented a Dynamic Difficulty Adjustment (DDA) algorithm. The system adjusts difficulty in real-time based on performance: two consecutive correct responses increase difficulty, while two errors decrease it, maintaining an optimal challenge–skill balance.

3.4 Procedure

Calibration: Prior to testing, individual pain thresholds were calibrated to a subjective level of 6/10 (moderate pain) on the Wong-Baker FACES scale. Electrotactile intensity was also calibrated to be clearly perceptible but non-painful.

Experiment 1 (Mechanism): Participants underwent a *No-Intervention Control* (pain only) baseline, followed by *T-D* and *B-U* blocks (counterbalanced). Each block contained 12 trials at fixed difficulty levels.

Experiment 2 (Flow): Participants performed the T-D task under two conditions: *Fixed Difficulty* (medium) versus *Adaptive Flow* (DDA enabled). An ABBA design was used to control for order effects.

4 Results

4.1 Experiment 1: Attention Mechanisms

We evaluated whether goal-directed (T-D) and stimulus-driven (B-U) tasks modulated pain compared to a Control condition.

Subjective Pain: As shown in Fig. 2a, paired t-tests revealed significant reductions in pain ratings for both B-U ($t(41) = 27.83, p < .001$) and T-D ($t(41) = 26.72, p < .001$) modes relative to Control. T-D showed a trend toward greater reduction than B-U ($p = .053$).

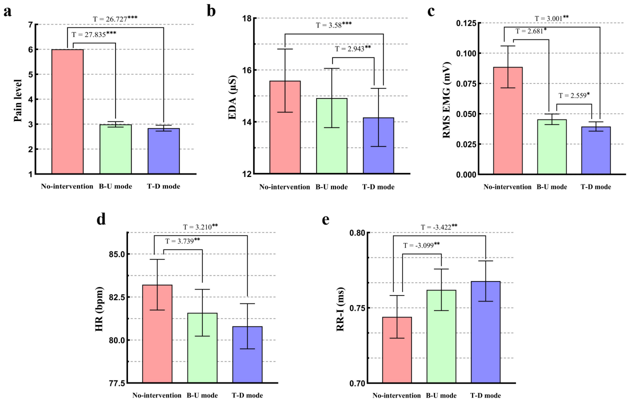

Figure 2: Differences in subjective pain ratings and physiological indicators across experimental conditions. a,Comparison of subjective pain perception across three experimental modes (No-intervention, B-U and T-D). b-e,Comparison of objective physiological indicators across three experimental modes.

Physiological Response: While both modes lowered stress, T-D elicited superior physiological regulation (Fig. 2b-e). Direct comparison revealed that T-D resulted in significantly lower Electrodermal Activity (EDA, $t(41) = 2.94, p = .005$) and Masseter EMG ($t(41) = 2.56, p = .014$) than B-U. Additionally, T-D significantly increased Heart Rate Variability (RRI, $p = .001$), indicating a shift toward parasympathetic dominance—a relaxation response not fully achieved in the B-U mode.

4.2 Experiment 2: Adaptive Flow

We compared the fixed-difficulty T-D task against the adaptive version (E-Tactile Flow) to test the effect of Flow maintenance.

Subjective Experience: The adaptive mode significantly reduced pain ratings ($t(41) = 2.23, p = .031$) compared to the fixed

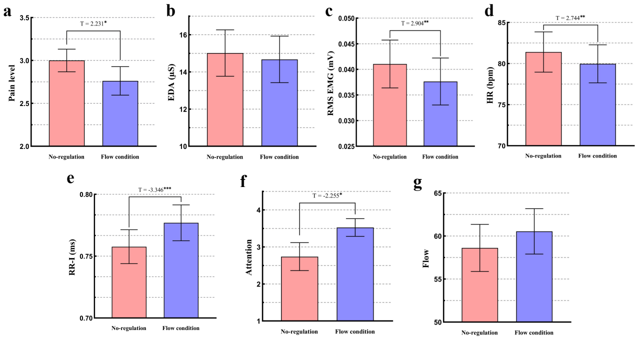

Figure 3: Differences in subjective pain ratings and physiological measures under different experimental conditions. a,Subjective pain perception in the two experimental modes (No-Adjustment vs. E-Tactile Flow). b-e,Comparison of objective physiological indicators between the two modes. f-g,Comparison of attention index and flow state across the two modes.

mode (Fig. 3a). Participants also reported significantly higher attention focus ($p = 0.030$, Fig. 3f), while Flow scores showed a marginal increase ($p = .097$, Fig. 3g).

Physiological State: The adaptive algorithm significantly enhanced physiological relaxation (Fig. 3b-e), evidenced by reduced EMG ($t(41) = 2.90, p = .006$) and Heart Rate ($t(41) = 2.74, p = .009$), and increased RRI ($p = .002$). These results suggest that dynamically matching task challenge to user skill minimizes somatic stress responses more effectively than static tasks.

5 Discussion

Our findings challenge the notion that simple sensory distraction is sufficient for effective pain relief. While bottom-up distraction (B-U) successfully reduced subjective pain, top-down engagement (T-D) produced significantly stronger physiological calming effects. This aligns with the "Biased Competition" hypothesis: active, goal-directed tasks recruit executive resources (DLPFC, ACC) that might otherwise process nociceptive signals, creating a robust "cognitive shield." The physiological data (lower EDA/EMG) confirms that this is not just a reporting bias but a genuine downregulation of autonomic arousal.

Our results reveal that the adaptive difficulty mechanism significantly enhanced analgesic outcomes compared to the fixed difficulty condition. Although subjective Flow scores showed only a marginal increase ($p = .097$), the physiological evidence paints a clearer picture. The significant reduction in EDA and EMG suggests that the adaptive algorithm successfully maintained users in a state of 'optimal cognitive arousal'—preventing the physiological stress associated with frustration (when tasks are too hard) and the disengagement associated with boredom (when tasks are too easy). This indicates that the analgesic benefit of 'E-Tactile Flow' may not strictly depend on the conscious perception of a 'Flow state,' but rather on the system's ability to sustain goal-directed attention without inducing autonomic stress.

Implications for Interaction DesignThe. E-Tactile Flow paradigm offers concrete guidelines for designing next-generation digital analgesics.Beyond Passive Stimulation: Unlike traditional TENS devices that deliver static, passive stimulation, our findings demonstrate that integrating an active cognitive loop significantly amplifies pain relief. Future pain management wearables should incorporate gamified micro-interactions that adapt to the user's performance in real-time.Eyes-Free Pain Management: By leveraging the tactile channel for both input (stimulation) and output (recognition), this approach enables eyes-free interaction. This is particularly valuable for chronic pain patients who need to manage pain while performing daily visual tasks (e.g., working, walking) or for users with visual impairments, offering an inclusive alternative to VR-based distraction.Closed-Loop Adaptation: The success of the DDA algorithm suggests that biometric or performance-based feedback loops are essential. Designers should prioritize systems that can sense the user's cognitive state (via performance metrics or physiological sensors) and autonomously modulate task complexity to prevent habituation over long-term use.

6 Conclusion

This study introduces E-Tactile Flow, a novel paradigm integrating high-resolution electrotactile stimulation with flow theory. We demonstrate that goal-directed attention outperforms passive distraction in regulating physiological stress, and that adaptive difficulty adjustment further amplifies this analgesic benefit. These findings provide a theoretical and methodological framework for designing next-generation, cognitively interactive digital analgesics.

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