Effect of mindfulness meditation on sensory perception and emotional evaluation of mid-air touch on the forearm

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***Abstract*—Sensory perception and emotional evaluation of a stimulus are deeply interconnected with sensory awareness and attention. Mindfulness meditation is a well-established tool for enhancing attention and awareness, but can this heightened awareness influence how we perceive and emotionally evaluate tactile stimuli? In this work, we investigate how mindfulness meditation influences sensory perception and emotional evaluation of gentle stroking stimuli delivered to the forearm using ultrasound-based mid-air haptics, providing tactile sensations without direct skin contact. Two studies were conducted to assess the effects of mindfulness on (1) perceived intensity, confidence, valence, and arousal in response to simple linear strokes and (2) pattern recognition and emotional evaluation of complex mid-air haptic patterns. Our findings suggest that mindfulness enhances perceived intensity, confidence, and valence ratings, but does not influence arousal ratings. Pattern recognition was challenging for the participants on the forearm leading to poor accuracy but mindfulness still enhances the recognition. These findings highlight the potential of mindfulness-enhanced haptic interactions in digital wellbeing and virtual environments. Future research should explore long-term mindfulness training, multi-sensory integration, and adaptive haptic systems to further optimize affective haptic experiences.**

***Index Terms*—affective haptics, pleasant touch, ultrasound-based, tactile perception, sensory awareness, valence-arousal.**

I. INTRODUCTION

Whether it is the comforting stroke of a loved one or the subtle texture of an object, our ability to perceive and interpret touch is fundamental to how we experience the world. Touch provides essential sensory input about our environment, but it also contributes to a continuous awareness of bodily sensations and presence in the moment, often referred to as sensory awareness [1], [2]. Sensory awareness reflects an individual's capacity to attend to and feel their bodily sensations as they unfold, forming a perceptual bridge between the body and emotional experience. This awareness plays a critical role in anchoring individuals during emotionally overwhelming situations, supporting their ability to stay connected to present-moment sensations rather than becoming emotionally dysregulated. Enhancing sensory awareness has been identified as a pathway toward cultivating emotional awareness and self-regulation skills, providing a foundation for recognizing, understanding, and modulating emotional responses [3]. These interconnections highlight the need for technological interventions that can support not only tactile perception but also their role in fostering sensory and emotional wellbeing.

Research suggests that enhancing sensory awareness, with mindfulness meditation [4] as a widely studied approach, has gained increasing attention in both neuroscience [5] and psychology [6]. It can improve attention and maintain awareness of thoughts, feelings, and bodily sensations. Mindfulness meditation is a mental practice that involves focusing on the present moment while calmly acknowledging and accepting one's internal experiences [7]. Despite its well-documented psychological and cognitive benefits [8], [9], mindfulness meditation's impact on sensory perception and emotional experiences remains less explored, especially in the context of affective touch. Investigating this aspect could uncover new ways to enhance sensory and emotional health, particularly in populations experiencing sensory decline. Our prior work demonstrated that mindfulness meditation enhanced participants' ability to recognize complex haptic patterns rendered on the palm using ultrasound-based mid-air haptics and increased their confidence in perceptual tasks [10], suggesting its broader potential for enhancing touch perception. However, the influence of mindfulness meditation on the perception of affective touch and the emotions it evokes remains unexplored.

Affective touch evokes emotional and pleasurable responses, playing a key role in social bonding and emotional wellbeing. It primarily involves gentle, slow stroking of the skin, particularly the hairy skin, such as the forearm [11], [12]. The pleasant sensations of affective touch on the forearm are influenced by contextual factors, including force, site, and notably, the speed of stimulation, with slower strokes often perceived as more pleasant [13]. There are dedicated touch receptors called C-tactile afferents located in hairy skin that specifically respond to affective touch. These specialized fibers transmit the pleasant sensations of affective touch to the brain's emotional centers, reinforcing the link between touch perception and emotional wellbeing [14].

Affective touch technologies [15] have employed various stimulation methods, including vibrotactile devices, human-applied brush strokes, robotic delivery of slow stroking stimuli, and ultrasound-based tactile stimulation (mid-air haptics). Among these, mid-air haptics has emerged as a promising

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technology for delivering contactless touch sensations, enabling new forms of immersive and emotionally engaging experiences [16], [17]. It offers unique opportunities for creating immersive touch experiences [18], [19]. By eliminating direct skin contact, mid-air haptics can mitigate certain practical challenges sometimes encountered with contact-based methods, such as the need for wearable devices, hygiene considerations, or potential confounds from physical pressure and mechanical inertia, making it suitable for diverse interaction contexts.

Although affective touch is traditionally studied in interpersonal contexts, recent research has shown that social familiarity is not essential for affective touch communication. Standardized gestures delivered by trained experimenters can reliably convey emotional meaning, even between strangers [20]. A growing body of work has adopted methods such as vibrotactile arrays [21], rotary stimulators [22], and soft robotics [23] to investigate affective responses in controlled, non-interpersonal settings. These approaches reinforce the idea that while the functional role of affective touch might be inherently social, its emotional qualities can be investigated through carefully parameterized and standardized stimuli. Our work extends this logic into the domain of mid-air haptics.

It is important to clarify that while affective touch is often associated with the activation of C-tactile (CT) afferents in hairy skin, our study does not directly measure CT activation. Instead, we use the term *affective-like touch* to refer to tactile stimuli designed to approximate the physical parameters (e.g., slow stroking speeds, specific directional movements) known to optimally activate CT afferents, based on prior psychophysical and neurophysiological studies [14], [24]. We focus on participants' subjective perception and emotional evaluation of these stimuli, without assuming underlying physiological mechanisms. This distinction is particularly relevant as we explore how mid-air haptic technologies, which deliver contactless tactile sensations, can evoke emotionally meaningful touch experiences without direct skin contact. While our tactile stimuli were designed to match parameters associated with affective touch in prior literature, it remains unknown whether mid-air haptic stimulation directly activates CT afferents; therefore, we adopt the term "affective-like touch" to acknowledge this conceptual nuance.

With the growing interest in mindfulness, which highlights enhanced sensory engagement and a deeper connection to present-moment experiences, this research examines the effects of mindfulness meditation on the sensory perception and emotional evaluation of mid-air affective-like touch stimuli (mid-air ATS). Mid-air ATS refers to tactile sensations designed to evoke affective qualities, created using ultrasound-generated focal points, applied to the hairy skin region of the forearm.

- **[RQ-1]**: How does mindfulness meditation influence sensory perception and emotional evaluation of mid-air affective-like touch stimuli (mid-air ATS), particularly in relation to haptic parameters such as modulation frequency, stroke speed, and direction of stimulation?
- **[RQ-2]**: How does mindfulness meditation influence the emotional evaluation of tactile stimuli, including simple linear strokes and complex patterns rendered using mid-air ATS?

The main contributions of this work are threefold: (1) We present empirical evidence demonstrating that mindfulness meditation enhances sensory perception and emotional evaluation of mid-air ATS, building on our prior work on the effect of mindfulness on touch perception [10]; (2) We investigate how specific haptic parameters such as modulation frequency, stroke speed, and direction of stimulation affect sensory perception and emotional evaluation of mid-air ATS, extending prior research in affective haptics [22], [25], [26]; and (3) We show that mindfulness meditation improves the sensory and emotional evaluation of complex mid-air haptic patterns.

In this research, for the first time, we explore the influence of mindfulness meditation on sensory perception and emotional evaluation in response to mid-air ATS, investigating both low-level sensory perception and corresponding high-level emotional evaluation. Through this exploration, we aim to advance the understanding of how mindfulness influences sensory and emotional experiences in interactive technologies. This research could pave the way for designing adaptive haptic interfaces that integrate mindfulness-based interventions, benefiting populations experiencing sensory decline due to aging or health-related conditions.

II. Related Works

A. Mindfulness meditation: Effects and sensory perception

Mindfulness meditation is a mental training practice originating from Buddhist traditions, emphasizing purposeful, non-judgmental attention to present-moment experiences [7]. It has been widely adopted in psychological and clinical frameworks, such as Mindfulness-Based Stress Reduction (MBSR), to enhance emotional regulation and cognitive flexibility [5]. Neuroscientific studies reveal that mindfulness increases alpha and theta oscillatory power, reflecting relaxed alertness and internally directed attention, while strengthening neural networks like the prefrontal cortex, anterior cingulate cortex, and insula, which govern self-awareness and emotional regulation [27]–[29]. Vago and Silbersweig [27] proposed a comprehensive framework positioning mindfulness as a process that enhances meta-awareness, fosters emotional resilience, and cultivates prosocial behaviors through the modulation of self-related neural networks and adaptive neuroplasticity.

Mindfulness meditation has demonstrated significant physiological and psychological benefits, profoundly influencing stress regulation, emotional processing, and cognitive resilience. Physiologically, mindfulness enhances autonomic regulation, as evidenced by increased heart rate variability (HRV) and breath rate variability (BRV)—markers of parasympathetic activity and adaptive stress response [30]–[32]. Additionally, these benefits extend to hemodynamic responses, with studies showing enhanced oxygenated hemoglobin levels in the dorsolateral prefrontal cortex, indicating improved sustained attention and cognitive efficiency [29], [33]. Psychologically, mindfulness has proven effective in reducing symptoms of anxiety, depression, and stress by enhancing attentional control, reducing emotional reactivity, and fostering nonjudgmental awareness of present-moment experiences [34]–[38]. These findings highlight mindfulness meditation as a robust intervention for promoting psychological wellbeing and physiological resilience.

Mindfulness meditation enhances sensory perception across tactile, visual, and somatosensory domains by improving clarity, sensitivity, and decision-making accuracy. In the visual domain, it enhances sensitivity and discrimination thresholds, supporting moment-to-moment awareness [8]. Brief practices like body-scan meditation reduce sensory misperceptions and enhance sensitivity by refining attention to stimuli [9]. Similarly, mindfulness improves tactile recognition and confidence in recognizing mid-air haptic stimuli, even for subtle sensations [10]. These effects are underpinned by cortical alpha rhythm modulation, which filters sensory input and boosts signal-to-noise ratio in the somatosensory cortex [4]. These effects align with the broader understanding of contemplative practices, which underscore mindfulness as a tool for refining perceptual clarity and fostering embodied awareness across sensory modalities [39]. Together, these findings highlight the broad sensory benefits of mindfulness meditation in enhancing perception and processing across modalities.

B. Affective touch: Definition, physiology, and emotional impact

Affective touch is mediated by a specialized class of unmyelinated, low-threshold mechanoreceptive afferents known as C-tactile (CT) afferents [40], [41]. These fibres are predominantly found in the hairy skin of humans, although recent evidence suggests a sparse presence in glabrous (non-hairy) skin [42]. CT afferents respond optimally to gentle, slow stroking at velocities between 1–10 cm/s, a range consistently associated with peak pleasantness ratings in psychophysical studies [43], [44]. CT afferents project to emotion-related regions of the brain, including the posterior insular cortex, emphasizing their role in processing the emotional valence of touch rather than its discriminative properties [14], [41].

Some researchers have proposed that this cortical activation also implicates CT afferents in interoceptive awareness, though this link remains under discussion [45]–[47]. Experimental evidence from patients with selective deficits in myelinated afferents but intact CT afferents demonstrates their ability to perceive touch as pleasant, despite reduced tactile discrimination, underscoring the independent functionality of the CT system in affective touch perception [41]. This dissociation underscores the independent sensory-emotional pathway underlying affective touch. Importantly, the hedonic properties of CT-mediated touch highlight its potential role in affiliative social interactions, such as nurturing and bonding [48].

The emotional and social impacts of affective touch may extend to physiological pathways, such as a proposed role in modulating oxytocin release, which has been hypothesized to support stress reduction and social bonding [49]. In social contexts, CT-targeted touch elicits consistent preferences for stroking velocities that activate CT afferents, reinforcing its role in promoting emotional wellbeing and interpersonal connection [48]. This dual role of affective touch, as both a sensory and social signal, underscores its significance in human interaction and its potential applications in therapeutic settings to enhance emotional and psychological resilience. While many studies on affective touch focus on interpersonal interaction [20], the broader methodological and theoretical implications of non-interpersonal stimulation are discussed in the following subsection.

C. Affective touch beyond interpersonal contact

Although affective touch is often investigated within interpersonal contexts, its sensory and emotional components can be examined independently of social interaction. Many foundational studies on C-tactile (CT) afferents have deliberately employed non-human, device-mediated stimulation to ensure experimental control and minimize social confounds. For example, Essick et al. and McGlone et al. used custom-built rotary tactile stimulators to deliver consistent stroking velocities across participants [44], [50], allowing researchers to isolate tactile input from contextual cues such as warmth, facial expression, or perceived intent. As Gallace and Spence noted [51], interpersonal touch studies often involve uncontrolled social variables such as gaze, proximity, or expectancy which may bias affective responses and complicate interpretation. To address this, several researchers have advocated for standardized, technology-mediated approaches to investigate the sensory basis of affective touch [13].

Similarly, recent studies have adopted non-interpersonal approaches for studying pleasant touch using rotary tactile stimulators under robotic control, both without [22] and with visual stimulation [52]. Furthermore, soft robotics that mimic stroking gestures without human involvement have also been explored [23]. These systems aim to deliver affective-like stimuli at CT-optimal velocities and forces while eliminating social variables, allowing researchers to explore the sensory and affective consequences of touch in isolation from interpersonal context. Importantly, this paradigm shift has practical relevance. Touch systems that simulate affective qualities without direct interpersonal contact are critical for applications involving remote interactions such as socially assistive robotics or affective communication in virtual environments [53]–[55]. Our study builds on this tradition by employing mid-air haptics as a form of contactless, precisely controlled stimulation to investigate affective-like touch responses outside an interpersonal framework.

D. Affective touch technologies and mid-air haptics

Advancements in affective touch technologies have enabled the simulation and mediation of emotional touch experiences through a variety of devices. Vibrotactile systems, such as wearable gloves and belts, deliver tactile feedback by modulating vibration frequency and amplitude, effectively communicating emotional nuances [15], [21], [56]. Robotic devices have further advanced the field by simulating human-like gestures, including stroking and tapping, through precise control of parameters like velocity, force, and amplitude, enabling communication of valence and arousal [22], [57].

Pneumatic and thermal actuators, which generate pressure or temperature changes, have been employed to simulate comforting or affective touch, enhancing their realism in mediated interactions [58].

Recent advancements in affective haptics have led to the development of innovative systems that replicate emotionally meaningful touch interactions. Devices employing haptic illusions, such as sequential normal indentation, have shown promise in creating continuous stroking sensations that mimic social gestures like caresses, leveraging CT afferents for enhanced affective responses [59], [60]. Similarly, systems like Pinch, Squeeze, and Twist devices simulate localized skin-stretching modalities, offering naturalistic touch sensations with improved emotional resonance compared to vibrotactile feedback [61]. Wearable technologies, such as the PneuSleeve, integrate multimodal actuators capable of delivering sensations like compression, skin stretch, and vibration, providing a diverse range of tactile feedback for emotional expression [62].

Additionally, soft robotic systems employing pneumatic actuation and shape-memory alloys have demonstrated their potential to deliver discreet and lightweight affective haptic feedback, which enhances usability in mediated interactions [61], [63]. Beyond wearable solutions, the importance of contextual grounding in affective haptics has been emphasized, showing that pairing touch stimuli with situational cues significantly amplifies the clarity and emotional impact of mediated social touch [64]. Moreover, tangible user interfaces have emerged as an innovative tool for affective interaction, leveraging embodiment and physical interaction to better engage users and influence their emotional states [65]. While physical contact remains a fundamental aspect of many tactile interfaces, certain practical challenges—such as hygiene considerations, wearer discomfort, and limited adaptability for multi-user scenarios—have motivated exploration of non-contact technologies like mid-air haptics to expand the possibilities of affective touch.

Mid-air haptics represents a novel paradigm in affective touch technology, delivering tactile sensations without the need for physical contact or wearable devices. Using ultrasound phased arrays, mid-air haptics generates focused acoustic radiation forces that create perceivable tactile stimuli in free space [66], offering a non-intrusive alternative for delivering emotional touch [17], [67], [68]. While early applications focused on glabrous skin (e.g., hands and fingers), recent studies have extended its application to hairy skin, tapping into the affective dimension mediated by C-tactile afferents [25]. This transition has paved the way for using mid-air haptics in more expressive and social contexts, emphasizing its potential for affective interactions.

Mid-air haptics offers unique advantages for affective-like touch interactions compared to wearable or contact-based systems. Its ability to simulate gentle stroking and caressing motions with precise control of parameters like spatial summation and acoustic force aligns well with the optimal stimulation range of C-tactile afferents, which are key to affective touch perception [25]. However, the physiological evidence for CT activation is yet to be found. Additionally, its contactless nature can help mitigate practical concerns related to hygiene, device wearability, or user comfort in certain contexts, making it well-suited for scenarios involving multiple users or dynamic touch interactions. By targeting diverse body areas beyond the hands, such as the forearm or face, mid-air haptics enhances user experience, offering a scalable and versatile solution for affective touch delivery [15].

E. Research Gaps

While mindfulness meditation has been extensively studied for its effects on various physical and mental health parameters, its specific impact on touch perception in the context of technologically mediated affective touch remains unexplored. Current research on mindfulness has focused largely on traditional sensory modalities, leaving a gap in understanding its influence on tactile experiences and the corresponding emotions, particularly when using advanced haptic technologies like mid-air haptics.

Additionally, while affective touch technologies have demonstrated their potential for delivering emotional and social touch, most systems rely on physical contact, raising concerns about hygiene and scalability. Mid-air haptics offers a unique, contactless alternative, but its ability to simulate emotionally meaningful touch in conjunction with mindfulness practices is yet to be fully explored. Addressing these gaps could open new possibilities for therapeutic applications, enhancing sensory and emotional experiences.

III. Study 1: Methods and Results

To address our first research question **[RQ-1]**, this study examined the effects of mindfulness meditation on participants' sensory perception and emotional evaluation of mid-air ATS parameters, including modulation frequency, stroke speed, and direction. By focusing on simple linear strokes applied to the forearm, this study aims to establish a foundational understanding of how mindfulness modulates sensory and emotional experiences in response to mid-air ATS.

A. Methods

1) Participants: Thirty participants (13 males and 17 females), aged 18 to 60 years (M = 27.83, SD = 8.94), were recruited for this study. A power analysis using G*Power with a medium effect size (Cohen's f = 0.25), alpha = 0.05, power = 0.8 determined a required sample size of 8 participants. Our final sample of 15 participants exceeded this threshold, ensuring sufficient statistical power to detect the effects of interest. To isolate the effects of the mindfulness intervention, participants with prior experience in mindfulness meditation were excluded from the study. This ensured that the observed effects were not influenced by previous mindfulness practice. The study was approved by the local University Research Ethics Committee, and recruitment was conducted via the UCL Psychology Subject Pool (Sona System). Participants were screened to confirm they had no sensory impairments or medical conditions affecting tactile perception. All participants, except one, were right-handed and provided informed consent prior to the study. The study lasted 90 minutes in total, and participants were compensated with a £15 gift voucher for their time.

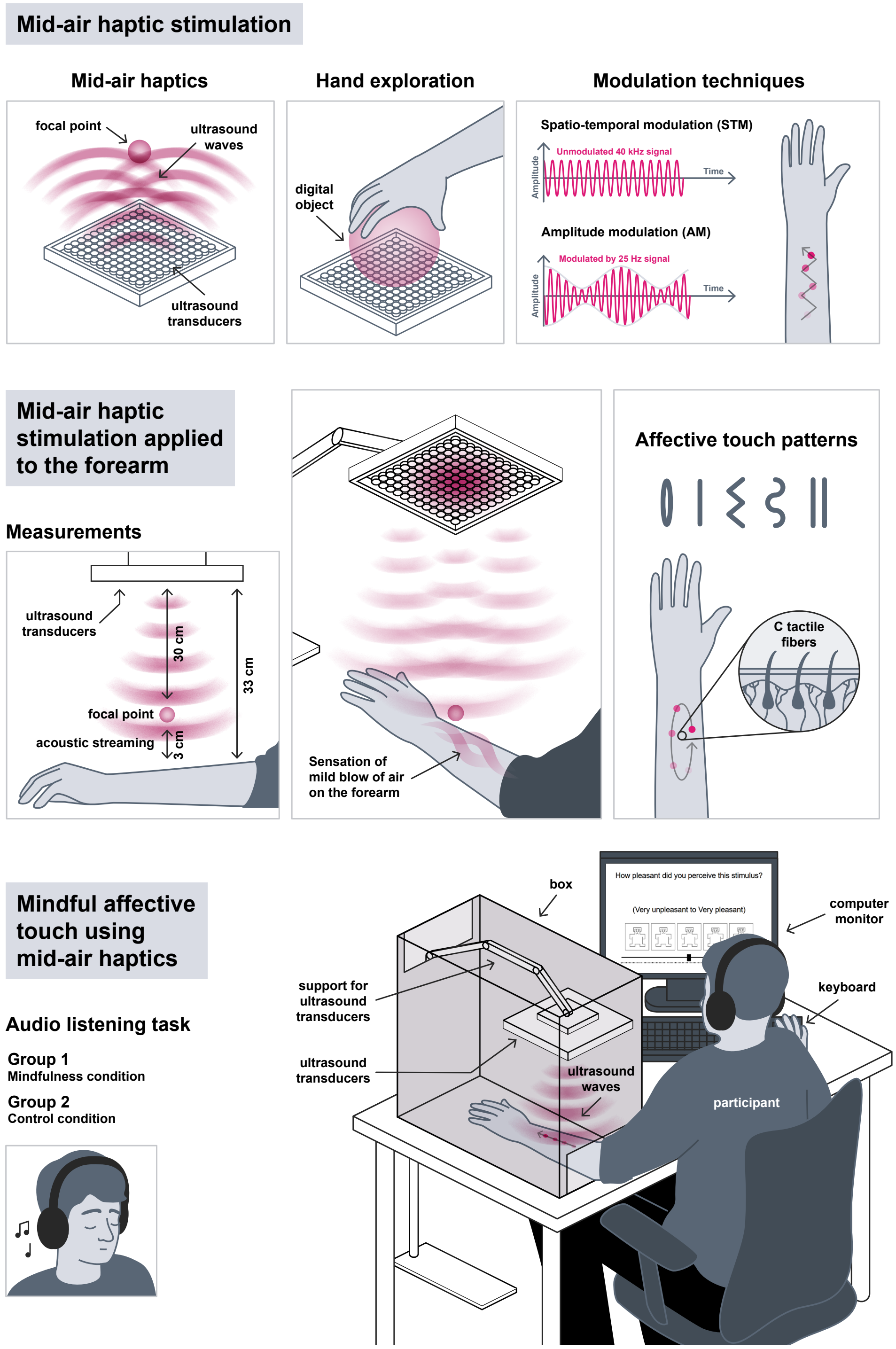

Fig. 1. Illustration of technology, methodology, and studies (1 & 2) setup used in this research, divided into three sections (top, middle, and bottom). *Top (3 parts)*: The first part shows a basic mid-air haptic device with ultrasound transducers generating phase-shifted ultrasound waves that create a focal point in mid-air. The second part demonstrates the same device rendering a digital object in 3D, which is explored by a hand, highlighting its application in creating tangible digital objects. The third part illustrates the two modulation techniques used in this work: amplitude modulation (AM) and spatio-temporal modulation (STM). STM is shown as an unmodulated 40 kHz ultrasound sine wave, while AM is depicted as the same sine wave modulated by a 25 Hz signal, with patterns drawn on a forearm using both techniques. *Middle (3 parts)*: The first part explains the concept of acoustic streaming, showing the mid-air haptic device mounted inverted, with the focal point positioned 3 cm above the forearm [25] to create a sensation akin to a mild blow of air. The second part details the sensation on the forearm, and the third part shows various affective-like touch patterns (oval, back-and-forth, triangular, sinusoidal, and parallel lines) used in the study, including a zoom-in on the forearm to display the location of C-tactile fibers in the hairy skin region. While CT fibers are shown for conceptual completeness, we note that CT activation was not directly measured in this study, and our use of "affective-like touch" refers to stimuli designed to approximate CT-optimal parameters based on prior literature. *Bottom*: Describes the two study conditions (control and mindfulness). The study setup involves participants placing their left arm inside a large black box containing the inverted mid-air haptic device to perceive the haptic stimuli on the forearm. Meanwhile, they use their right arm to respond via a keyboard positioned on the same table. (Displayed on the monitor is a screenshot from the user interface (UI) used by participants to rate valence. The key UI screenshots are shown in the Supplementary Figure 1)

2) Stimuli and setup: We used the UltraLeap Stratos Explore Haptic device (version 2.0) to deliver Mid-air Affective-like Touch Stimuli (mid-air ATS) on the forearm, producing a gentle air-blowing stroke sensation (Figure 1, top and middle section). Setup parameters, including the distance between device transducers and the stimulation site, were adapted from previous work [25]. The device was mounted on a tablet holder stand and held inverted to direct the focal point toward the forearm. The ultrasound focal point was created 30 cm from the transducers, with the forearm positioned 3 cm below the focal point to sense the acoustic streaming (Figure 1, middle section) [25]. The focal point was generated within an 80x40 mm rectangular area using amplitude modulation [16], [69] and spatio-temporal modulation [70]–[72]. The stimuli were single-line stroke sensations with varying modulation frequencies (amplitude modulation at 0, 5, 10, 25, 50, and 100 Hz), stroke speeds (spatiotemporal modulation at 3, 10, and 30 cm/s), and directions (distal-to-proximal and proximal-to-distal [73], [74]). Each combination of modulation frequency, stroke speed, and direction was repeated thrice. The stimuli were randomized using a pseudo-random algorithm to minimize order effects and ensure unbiased presentation across all parameters.

3) Study design and user interface: The study employed a mixed design with mindfulness (mindfulness vs. control) as a between-subjects factor and haptic parameters (modulation frequency, stroke speed, direction) as within-subjects factors. To minimize potential biases, the mindfulness and control conditions were counterbalanced across participants (pseudo-randomly assigned). Noise-canceling headphones ensured a consistent and distraction-free environment.

The user interface (UI) was designed to facilitate seamless interaction and ensure participant comfort throughout the study. The UI began with clear instructions on how participants should position themselves and an overview of the interface. Participants were instructed to focus on the mid-air ATS during the study. For perceived intensity ratings, participants were provided with a text box that allowed only decimal number inputs. They rated on a self-chosen scale from zero to infinity (e.g., 0 to 10 or 1 to 100). This approach allowed participants to internally calibrate their perception of intensity based on their own sensitivity levels, reducing cognitive load and improving response intuitiveness. Given the contactless nature of mid-air haptics and the absence of a predefined reference intensity, a flexible scale ensured that participants could report their subjective experiences without being constrained by an arbitrary fixed scale.

Confidence ratings required participants to select one out of five options ranging from 1 (“not at all confident”) to 5 (“extremely confident”). For valence and arousal ratings, sliders were used with Self-Assessment Manikin (SAM) visuals positioned above the sliders to guide the ratings from very unpleasant to very pleasant and very calming to very exciting. Each of these ratings was presented on a separate screen with a “Next” button located at the bottom right corner. After completing each rating, participants clicked the “Next” button to move to the next screen. For every stimulus, a progress bar was displayed for 2 seconds with a message asking participants to “Please focus” before delivering the next stimulus. Each stimulus was presented twice every time, taking 2 to 6 seconds depending on the stroke speed. Participants were not given a timer for their ratings but typically took 3 to 5 seconds to rate before clicking the “Next” button. To minimize any possible fatigue, the UI prompted participants to take a break every 10 minutes.

4) Procedure: Participants were randomly assigned to either a mindfulness or control condition. Upon arrival, participants read the information sheet, were screened for exclusion criteria, and provided informed consent. They completed demographic and Brief Mood Introspection Scale (BMIS) questionnaires in both studies before starting the following procedure. In the mindfulness condition, participants listened to a 10-minute audio-guided mindfulness meditation session [10], [75]. In the control condition, participants listened to an audio story about the English countryside [75]. Following the audio session, participants were seated comfortably, with their left forearm positioned under the mid-air haptic device to receive the stimuli (Figure 1, bottom section). They received a brief familiarization with the ultrasound tactile stimulation on their forearm. All 36 combinations of the mid-air ATS parameters were randomized and presented three times. After completing perceived intensity, confidence, valence, and arousal ratings for a stimulus, participants clicked the “Next” button to move to the subsequent stimulus.

5) Analysis: The perceived intensity ratings were normalized to a scale of 0 to 1 by dividing each participant’s ratings by the highest value in their individual dataset [70]. Confidence ratings ranged from 1 to 5, while valence and arousal ratings were assigned values from -50 to +50. To analyze the data, we conducted a series of statistical tests. First, the Kolmogorov-Smirnov (KS) test was performed to assess the normality of the distributions for perceived intensity, confidence, valence, and arousal. The results indicated that all four measures deviated significantly from normality. Consequently, non-parametric tests were employed to evaluate differences between conditions. Wilcoxon Signed-Rank Test was used to compare perceived intensity and confidence ratings between the mindfulness and control conditions. Mann-Whitney U Test was employed to assess differences in valence and arousal ratings between the two conditions.

To explore the effects of haptic parameters (modulation frequency, stroke speed, and direction), we applied the Friedman Test, a non-parametric alternative to repeated-measures ANOVA, for perceived intensity, confidence, valence, and arousal ratings. Post-hoc comparisons with Bonferroni correction were conducted to account for multiple comparisons. Additionally, Pearson correlation analysis was performed to investigate potential relationships between sensory (perceived intensity) and emotional (valence, arousal) responses, with confidence analyzed separately as a metacognitive measure. To further model the influence of mindfulness, haptic parameters, and their interactions, linear mixed-effects models were fitted with random intercepts and slopes for participants. Random variability was included to account for individual differences in perception and emotional evaluation, which could influence responses independently of experimental predictors. Fixed effects included modulation frequency, stroke speed, direction, and condition. Likelihood ratio tests were conducted to assess model improvements with random slopes for key predictors, demonstrating the importance of accounting for individual-level variability to improve model fit. All analyses were conducted using MATLAB, and a significance level of 0.05 was adjusted using Bonferroni correction where appropriate.

B. Results

1) Effects of mindfulness meditation: We examined the effects of mindfulness meditation on sensory perception (intensity) and emotional evaluations (valence and arousal) of mid-air ATS. The Wilcoxon Signed-Rank Test revealed a significant increase in perceived intensity ratings in the mindfulness condition compared to the control condition ($W = 525385.5$, $p < 0.001$), as shown in Figure 2. Similarly, confidence ratings were significantly higher in the mindfulness condition ($W = 2488158.5$, $p < 0.001$). These results suggest that mindfulness meditation enhances both the perceived intensity of mid-air haptic stimulation and participants' confidence in their ratings.

For valence ratings, the Mann-Whitney U Test revealed a significant difference between the mindfulness and control conditions ($W = 2419998$, $p < 0.001$), with mindfulness eliciting more positive valence ratings (Figure 3). However, no significant difference was observed in arousal ratings ($W = 2589273.5$, $p = 0.177$), indicating that mindfulness meditation did not significantly affect arousal during mid-air haptic stimulation. Please refer to Table I from the supplementary material.

2) Effects of mid-air ATS parameters: The effects of haptic parameters (modulation frequency, stroke speed, and direction) were analyzed using a Friedman Test, which revealed significant differences across all measures: perceived intensity ($\chi^2(35) = 650.205$, $p < 0.001$), confidence ($\chi^2(35) = 185.762$, $p < 0.001$), valence ($\chi^2(35) = 223.396$, $p < 0.001$), and arousal ($\chi^2(35) = 129.183$, $p < 0.001$). Please refer to Table II from the supplementary material. Post-hoc comparisons with Bonferroni correction showed that lower modulation frequencies (0–25 Hz) and slower stroke speeds (3–10 cm/s) elicited significantly higher valence ratings compared to higher frequencies (50–100 Hz). These findings are consistent with previous research, which suggests that these parameters optimally activate C-tactile afferents, leading to greater pleasantness.

3) Correlation: Pearson correlation analysis revealed weak positive correlations between perceived intensity and valence ($r = 0.2182$) as well as confidence ($r = 0.1512$). A moderate negative correlation was found between valence and arousal ($r = -0.3941$), suggesting that higher pleasantness ratings were linked to lower arousal.

4) Linear mixed-effects: Finally, linear mixed-effects modeling confirmed the influence of mindfulness and haptic parameters on sensory and emotional measures (Tables III-VIII from the supplementary material). Lower modulation frequencies ($\beta = -0.002$, $p < 0.001$), slower stroke speeds ($\beta = -0.696$, $p < 0.001$), and proximal-to-distal direction ($\beta = 0.043$, $p < 0.001$) significantly increased perceived intensity ratings. For valence, lower modulation frequencies ($\beta = -0.020$, $p = 0.002$) and slower stroke speeds ($\beta = -21.602$, $p < 0.001$) were significant predictors. Arousal was significantly influenced by lower modulation frequencies ($\beta = -0.054$, $p = 0.007$) and proximal-to-distal direction ($\beta = 1.648$, $p < 0.001$). These findings underscore the complex interplay between mindfulness, haptic parameters, and participant responses.

Additionally, we examined the effect of mindfulness on touch perception across strokes delivered at 3 cm/s (affective-like) and 30 cm/s (non-affective-like), using a focused linear mixed-effects analysis. We observed (Table IX from the supplementary material) significant Condition $\times$ Speed interactions for valence ($p < 0.001$), perceived intensity ($p = 0.003$), and arousal ($p < 0.001$). The interaction for valence was *negative*, indicating that mindfulness enhanced valence ratings more strongly at the slower, CT-optimal speed. In contrast, the interactions for perceived intensity and arousal were *positive*, suggesting that mindfulness amplified these responses more at the non-affective speed. No significant interaction was found for confidence ($p = 0.630$). These findings suggest that mindfulness modulates sensory and emotional processing, with distinct effects for touch delivered at affective-like and non-affective-like speed.

In summary, mindfulness selectively enhanced the emotional appraisal of affective-like touch, as reflected by increased valence ratings at slower velocities (3 cm/s). At the same time, it appeared to boost sensory intensity and arousal more for non-affective touch (30 cm/s). The observed Condition $\times$ Speed interactions support the interpretation that mindfulness exerts differentiated effects on perception and emotional evaluation, depending on the velocity of stimulation.

5) Reproducibility check: To ensure the reliability of our findings, we conducted a reproducibility check by comparing our results with prior works in affective touch research. Studies involving manual and robotic touch delivery have established that slow stroking velocities between 1–10 cm/s optimally activate C-tactile (CT) afferents, producing the highest pleasantness ratings [22], [26]. Moreover, Pittera et al. [25] demonstrated that slower stroke speeds between 1–10 cm/s in mid-air haptics generated more pleasant sensations due to optimal activation of mechanoreceptors through acoustic streaming (AS) and acoustic radiation force (ARF). Similarly, in vibrotactile stimulation, lower vibration frequencies (140 Hz) were perceived as more pleasant, while higher frequencies (200 Hz) produced more intense but less pleasant sensations due to possible overstimulation [56]. Our results align closely with these findings. We observed that lower stroke speeds (3 cm/s) generated significantly higher pleasantness ratings (valence) compared to faster strokes, consistent with prior work. In addition, we observed that lower modulation frequencies (0–25 Hz) yielded more pleasant perceptions, while higher frequencies (50–100 Hz) were perceived as more intense but less pleasant paralleling the findings of vibrotactile studies. These reproducibility checks validate the reliability of our findings while highlighting the novel exploration of previously

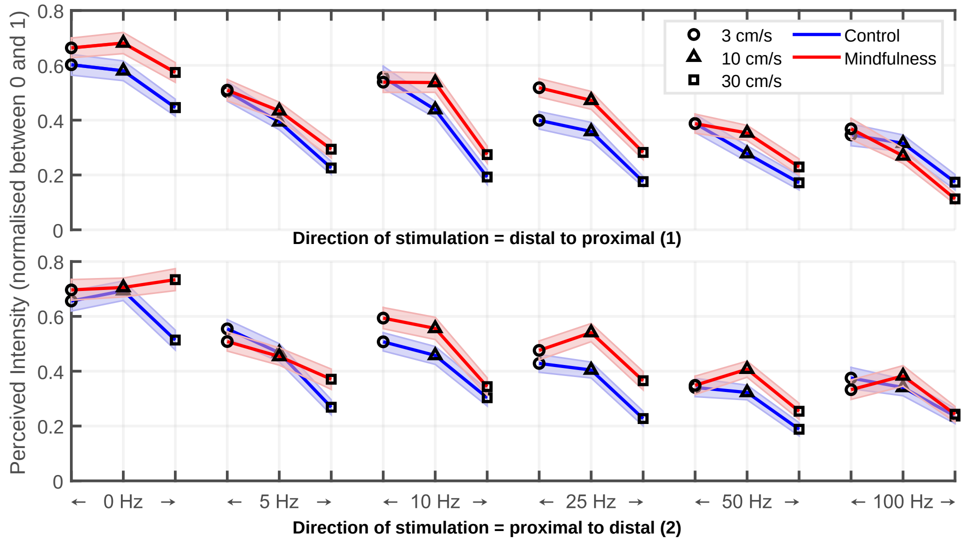

Fig. 2. This figure illustrates the average perceived intensity ratings, normalized between 0 and 1 (shaded area indicates standard error), plotted against four variables: modulation frequency, stroke speed, direction of stimulation, and condition (control and mindfulness). The x-axis represents the modulation frequency, with each frequency value repeated thrice to showcase the variation across three stroke speeds. The top and bottom plots display data for two different directions of stimulation: distal-to-proximal and proximal-to-distal of the forearm. Participants perceived stimuli with a modulation frequency of 0 Hz and slower stroke speeds (3 cm/s, 10 cm/s) as more intense compared to higher frequencies and faster speeds. Additionally, the proximal-to-distal direction was perceived as slightly more intense than the other direction. Statistical analyses confirmed significant effects of modulation frequency ($p < 0.001$), stroke speed ($p < 0.001$), and direction ($p < 0.001$) on perceived intensity, as described in the Results section of Study 1.

underexplored parameters such as modulation frequency and stroke direction in mid-air haptics.

6) Summary (Study 1): In summary, mindfulness significantly enhanced the perceived intensity of mid-air haptic stimulation, as well as participants' confidence in their ratings. It also increased positive valence but did not significantly affect arousal. The effects of haptic parameters, including modulation frequency, stroke speed, and direction, were consistent with previous findings, demonstrating their influence on sensory and emotional responses. Overall, these results highlight the role of mindfulness in modulating sensory perception and emotional evaluations during mid-air haptic stimulation.

IV. Study 2: Methods and Results

To address our second research question **[RQ-2]**, this study investigated how mindfulness meditation influences the emotional evaluation of tactile stimuli, ranging from simple linear strokes to more complex patterns rendered using mid-air ATS. By focusing on pattern complexity, this study builds on the findings of Study 1 and explores higher-level emotional responses to mid-air haptic stimulation.

A. Methods

1) Participants: Twenty-four participants (12 males and 12 females) aged between 18 and 60 years (M = 31.96, SD = 12.13) were recruited for this study. A power analysis using G*Power with a medium effect size (Cohen's f = 0.25), alpha = 0.05, power = 0.8 determined a required sample size of 12 participants. All participants provided informed written consent and were screened to ensure they met the same inclusion criteria as outlined for Study 1 (see section III.A). The study took 90 minutes in total and the participants were compensated with a £15 gift voucher for their time.

2) Stimuli and Setup: The stimuli comprised five distinct patterns delivered to the forearm using the UltraLeap Stratos Explore Haptic device: oval, back-and-forth (two linear strokes along the same path from proximal to distal and back), triangular, sinusoidal, and parallel lines (two adjacent linear strokes spaced 2 cm apart, one moving from proximal to distal and the other in the opposite direction). Each pattern was presented at three stroke speeds (3, 6.5, and 10 cm/s) using unmodulated ultrasound waves (only spatiotemporal modulation). Since a speed of 30 cm/s consistently resulted in lower perceived intensity and valence in Study 1, it was excluded, and 6.5 cm/s was added as a mid-point between the previously tested speeds of 3 and 10 cm/s. Similarly, for simplicity, we selected the frequency that yielded the highest perceived intensity, 0 Hz, indicating that no amplitude modulation was applied. The setup, device configuration, seating position, and randomisation were identical to those described in Study 1.

The use of structured geometric patterns in this study was motivated by the desire to extend affective touch research beyond simple linear strokes and explore how mindfulness may influence the perception and emotional evaluation of more complex tactile forms. Prior affective touch studies have largely focused on single, unidirectional strokes; however, daily tactile experiences often involve more varied and structured tactile inputs. By including distinct patterns with varying geometric complexity, we aimed to investigate whether mindfulness meditation would modulate participants' ability to recognize and emotionally evaluate tactile stimuli that require higher-level sensory processing. This approach allows us to assess not only baseline affective responses but also potential changes in perceptual clarity and emotional meaning as a function of tactile complexity.

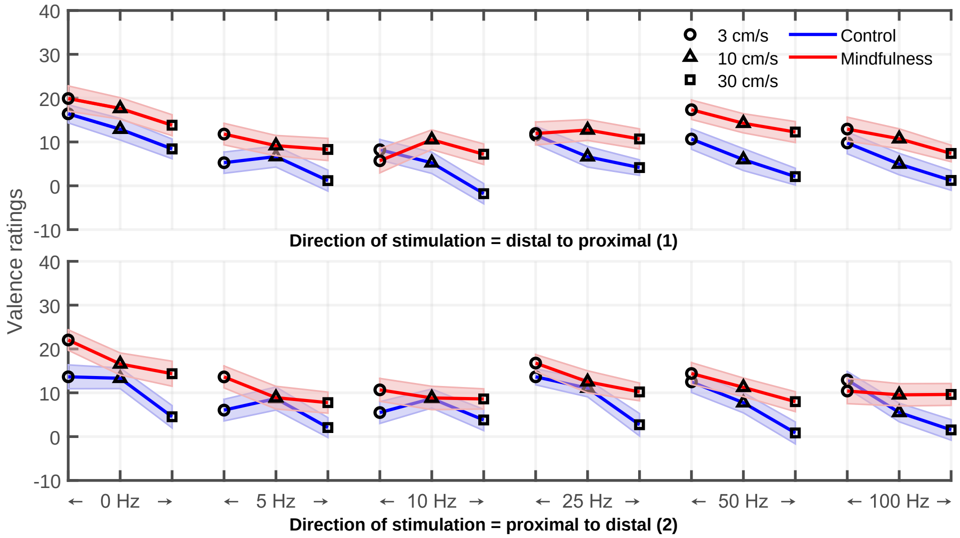

Fig. 3. The figure illustrates the average valence ratings (shaded area indicates standard error), plotted against four variables: modulation frequency, stroke speed, direction of stimulation, and condition (control and mindfulness). Participants rated their emotions on a scale from very unpleasant (-50) to very pleasant (+50). For visualization, only the range covering all ratings is shown. Except for the ordinate (average valence ratings), the other variables are the same as in Fig. 2. The results indicate that lower modulation frequencies and slower stroke speeds are associated with higher perceived valence. No significant differences were found concerning the direction of stimulation. These findings were confirmed through statistical tests.

3) Procedure: Participants were randomly assigned to either a mindfulness or control condition, following the same protocol as Study 1. After the mindfulness or control audio session, participants received a familiarization session with the mid-air ATS patterns. For each stimulus, participants identified the rendered pattern from a list of five options displayed, rated confidence in their pattern identification on a 5-point Likert scale (1 = not at all confident, 5 = extremely confident), and rated emotional evaluation of the stimuli using sliders, as in Study 1, valence (unpleasant to pleasant) and arousal (calming to exciting). Each pattern and stroke speed combination was repeated three times, resulting in 45 stimuli per participant. Breaks were provided every 10 minutes to minimize fatigue.

4) Design and Analysis: The study utilized a between-subjects design with two conditions (mindfulness vs. control) and repeated measures for five patterns and three stroke speeds. The study design and user interface were consistent with Study 1, with one key difference: instead of rating perceived intensity, participants selected the pattern that best matched their perception of the presented stimulus. Confusion matrices were generated to evaluate pattern recognition accuracy for each condition (mindfulness and control) as well as for the combined data. The matrices provide a detailed overview of classification performance, with diagonal entries indicating correct classifications and off-diagonal entries representing misclassifications. Metrics such as accuracy, precision, recall, and F1-scores were computed to assess recognition performance for each pattern. Due to deviations from normality, non-parametric tests were employed for statistical comparisons. A Chi-Square test was conducted to analyze the relationship between pattern recognition and condition. Ordinal logistic regression was used to evaluate the influence of condition, pattern type, and stroke speed on confidence ratings. Additionally, linear mixed-effects models were fitted to investigate the effects of mindfulness, pattern type, and stroke speed on valence and arousal ratings, with interaction terms included to examine potential combined effects.

B. Results

Due to the low density of discriminative mechanoreceptors (i.e., Merkel, Meissner, Ruffini, Pacinian corpuscles) in the hairy skin of the forearm, accurate pattern recognition was more challenging compared to previous findings on the palm [10]. As shown in Figure 4, confusion matrices for mid-air ATS pattern recognition illustrate recognition performance across all data, as well as separately for the mindfulness and control conditions. Overall, pattern recognition accuracy was moderate, with an average F1-score of 40%. The control condition exhibited slightly lower recognition accuracy (38.7%) compared to the mindfulness condition (41.7%). The Sinusoidal (*Sine*) and Triangular (*ZZ*) patterns caused frequent misclassifications across all conditions, likely due to their geometric similarities in wavy and angular strokes. In contrast, the *Oval* and Back-and-Forth (*BAF*) patterns were more distinctive and consistently yielded better recognition performance, reflecting their relative clarity and ease of identification. Each row of the confusion matrices was normalized to highlight recognition performance for each pattern, as described in the figure caption. Detailed metrics for recognition accuracy, precision, recall, and F1-scores are included in the supplementary material (Table 12).

A contingency table (Table X in the supplementary material) was constructed to summarize the frequency of pattern recognition across the control and mindfulness conditions. Based on this table, a Chi-square test of independence was performed, revealing a statistically significant association between pattern choice and condition ($p = 0.028$). This suggests that recognition performance differed significantly between the

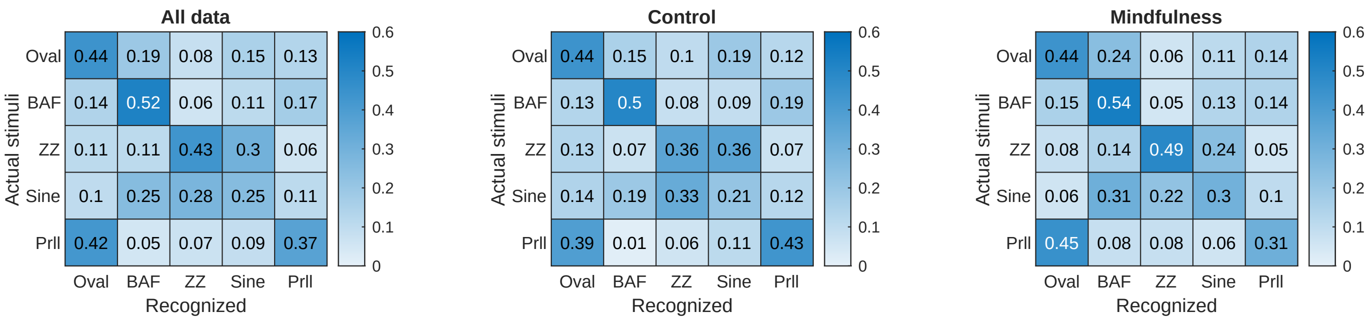

Fig. 4. Confusion matrices for mid-air ATS pattern recognition (Study 2). The left matrix represents all data combined, the middle matrix corresponds to the control condition, and the right matrix corresponds to the mindfulness condition. The patterns include: *Oval* (elliptical stroke), *BAF* (back-and-forth linear stroke), *ZZ* (triangular zig-zag stroke), *Sine* (sinusoidal wave stroke), and *Prll* (two parallel back-and-forth lines). Each cell indicates the proportion of responses for a recognized pattern (column) given an actual stimulus (row), normalized within each row. The diagonal cells reflect correct recognition rates. The color scale for each matrix is set from 0 to 0.6 for consistency and better visualisation. For example, the value 0.44 in the Oval–Oval cell under the Control condition indicates a 44% recognition rate of Oval patterns within control trials.

two groups. Additionally, *ordinal logistic regression analysis* showed that the mindfulness condition significantly enhanced confidence ratings ($p < 0.001$), while greater pattern complexity led to a significant reduction in confidence ($p = 0.031$).

For valence, the mixed-effects model revealed a significant intercept ($\beta = 14.469, p < 0.001$), indicating a strong baseline influence. However, none of the predictors—condition ($p = 0.494$), stroke speed ($p = 0.473$), or pattern ($p > 0.05$)—had a statistically significant effect. Additionally, no interaction terms (e.g., pattern × stroke speed, pattern × condition) were significant ($p > 0.05$). Similarly, for arousal, the mixed-effects model showed a significant intercept ($\beta = -9.297, p = 0.029$), reflecting a baseline effect. However, none of the predictors, including condition ($p = 0.788$), stroke speed ($p = 0.242$), or pattern ($p > 0.05$), were found to significantly influence arousal ratings. Interaction terms were also non-significant ($p > 0.05$).

We found a significant association between pattern choice and condition, with the distribution of pattern choices differing notably between the control and mindfulness groups. Additionally, an ordinal logistic regression showed that condition and pattern significantly influenced confidence ratings, while stroke speed did not.

V. Discussion

This research investigated the influence of mindfulness meditation on sensory perception and emotional evaluation of mid-air ATS, focusing on both simple linear stroke on the forearm with basic haptic parameters and complex tactile patterns. Below, we discuss our findings in relation to previous research, explore their implications for affective touch technologies, and propose directions for future work.

A. Effects of mindfulness meditation on sensory perception and emotional evaluation

Our results suggest that mindfulness meditation may enhance perceived intensity and confidence in mid-air ATS, aligning with prior studies indicating that mindfulness training can increase sensory awareness and attentional focus [9], [10]. Participants in the mindfulness condition tended to rate the stimuli as more intense than those in the control group, which could suggest that mindfulness enhances tactile sensitivity by increasing attention to somatosensory input. This finding is in line with neurophysiological research showing that mindfulness can improve sensory gating mechanisms, potentially leading to heightened perceptual clarity [4]. Additionally, the increase in confidence ratings in the mindfulness condition may indicate a greater certainty in sensory judgments, though further research is needed to confirm this effect across different haptic contexts.

Regarding emotional evaluation, valence ratings were higher in the mindfulness condition, suggesting that participants may have perceived mid-air haptic stimulation as more pleasant. This observation aligns with previous research linking mindfulness to increased positive emotional experiences, potentially through mechanisms such as cognitive reappraisal and reduced emotional reactivity [35], [36]. The consistently positive valence ratings across all conditions reflect the inherently pleasant nature of the stimuli, which were designed to produce soft and gentle sensations resembling a gentle air blow. Given that the stimuli in this research were designed to be gentle and non-intrusive, it is possible that mindfulness enhanced participants' engagement with the tactile sensations, leading to more positive valence ratings. However, this effect could also be influenced by individual differences in emotional processing, which warrants further exploration.

In contrast, mindfulness meditation did not significantly affect arousal ratings. One possible explanation is that the nature of mid-air haptic stimuli—gentle and subtle—did not elicit strong arousal responses, making it difficult to observe a clear modulation effect. Additionally, since mindfulness is often associated with reduced autonomic arousal and relaxation [37], its effects may not be pronounced in contexts where baseline arousal levels are already low. Future research could explore whether more dynamic or intense haptic stimuli elicit different arousal responses under mindfulness conditions.

Our additional analysis comparing responses at 3 cm/s (affective-like speed) and 30 cm/s (non-affective-like speed) revealed a significant Condition × Speed interaction for valence, perceived intensity, and arousal (Supplementary Table IX). The interaction for valence showed that mindfulness enhanced valence ratings more strongly at the slower, affective speed (3 cm/s), while the interactions for perceived intensity and arousal indicated stronger mindfulness effects at the faster, non-affective speed (30 cm/s). These findings suggest that mindfulness modulates tactile perception and emotional responses in a velocity-dependent manner, enhancing affective appraisal at slow touch velocities, and amplifying sensory and arousal responses at faster touch velocities. This highlights a nuanced influence of mindfulness on both affective-like and non-affective-like tactile experiences.

B. Effects of mindfulness on pattern recognition and emotional evaluation

Our findings suggest that mindfulness meditation may influence pattern recognition accuracy and confidence in mid-air ATS. As shown in the confusion matrices (Figure 4), overall pattern recognition accuracy was moderate (F1-score: 40%), with the mindfulness condition exhibiting a slightly higher accuracy (41.7%) compared to the control condition (38.7%). While this difference was small, a Chi-Square test revealed a statistically significant association between pattern choice and condition ($p = 0.028$), indicating that mindfulness meditation may subtly influence haptic recognition processes. However, the underlying mechanisms for this effect remain unclear, and further research is needed to determine whether mindfulness improves tactile discrimination or alters perceptual strategies. Despite the marginal improvement in recognition accuracy, participants in the mindfulness condition reported significantly higher confidence in their pattern identification ($p < 0.001$). However, it remains uncertain whether this increased confidence corresponds to an actual improvement in sensory discrimination or reflects a general tendency toward stronger self-assuredness in mindfulness.

Pattern complexity had a notable impact on recognition accuracy. As seen in Figure 4, more linear patterns like *Back-and-Forth (BAF)* were easier to recognize, the complex geometries of *Sinusoidal* and *Triangular* patterns likely introduced challenges, reflected in higher misclassification rates, likely due to geometric similarities. The moderate recognition accuracy (40%) in pattern recognition may be attributed to the relatively lower mechanoreceptor density on the forearm compared to the palm [24], [41]. While not a direct comparison, palm-based number recognition achieved over 50% accuracy for more complex stimuli like digits (0–9) [10].

In terms of emotional evaluation, pattern complexity appeared to influence valence and arousal ratings. Simpler patterns, such as *BAF* and *Oval*, were associated with slightly higher valence ratings, whereas complex patterns like *ZZ* and *Sine* tended to elicit lower valence scores. However, the mixed-effects model revealed that pattern complexity did not significantly predict valence ($p > 0.05$). Similarly, mindfulness meditation did not significantly influence emotional responses to different patterns. Neither condition ($p = 0.494$) nor pattern complexity ($p > 0.05$) had a significant effect on valence or arousal ratings. Future research could explore whether pairing haptic stimuli with visual or auditory affective content influences mindfulness-related effects on emotional perception.

The mechanisms underlying the observed effects of mindfulness meditation on mid-air ATS perception remain open for further investigation. One possible explanation is that mindfulness enhances tactile perception by increasing attentional focus toward bodily sensations, in line with previous findings that mindfulness improves interoceptive and exteroceptive awareness [76]. Alternatively, mindfulness may modulate mid-air ATS processing through physiological pathways, such as changes in autonomic nervous system activity or modulation of affective neural circuits implicated in touch processing. While our study was not designed to differentiate between attentional and physiological contributions, future research could combine neuroimaging or psychophysiological measures to better disentangle these underlying mechanisms.

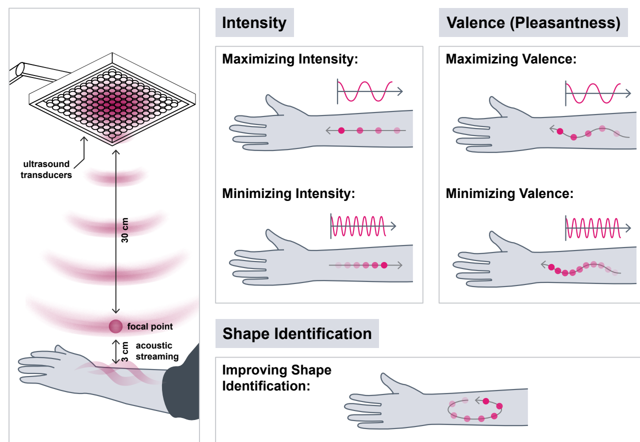

Fig. 5. The figure illustrates the design considerations for affective-like touch using mid-air haptics. The low frequency of stimulation is represented by low-frequency waves, while the slow speed of stimulation is depicted by the number of dots. Focusing on perceived intensity and valence, the figure demonstrates that low-frequency and slow-speed stimulation leads to higher perceived intensity and pleasantness (valence) in affective-like touch. The setup on the left side of the figure shows the optimal physical conditions adhered to for the device setup and stimulus location, as detailed in [25]. These optimal conditions ensure accurate delivery and reception of mid-air haptic stimuli, which is crucial for achieving the desired sensory and emotional perception. The arrows indicate the direction of the tactile stroke, reinforcing the significance of directionality in the perception of affective-like touch. These key parameters and their effects on the tactile experience, provide a comprehensive overview of the experimental design and its implications for enhancing sensory perception and emotional wellbeing through mid-air haptic technology.

C. Influence of haptic parameters on sensory perception and emotional evaluation

Our findings indicate that modulation frequency, stroke speed, and direction significantly influenced sensory perception and emotional responses to mid-air ATS. These results align with prior research demonstrating that variations in haptic parameters can shape the perception of affective-like touch [25], [26]. The relationship between amplitude modulation (AM) and perceived intensity is an important aspect of mid-air ATS perception. Prior studies in mid-air haptics demonstrated that modulation frequency directly impacts tactile acuity and perceived intensity through its interaction with mechanoreceptor channels [77]. Additionally, Raza et al. [78] revealed the non-linear relationship between modulation frequency, input intensity, and perceived output force in ultrasound-based haptic systems. While these studies focus on the hand and fingers, our study targets the forearm, where the density of mechanoreceptors is significantly lower. This difference likely influences the perceptual dynamics of AM. Future research could explore how AM impacts perceptual thresholds across different skin regions, enhancing our understanding of its role in mid-air haptics.

Stroke speed significantly influenced perceived intensity, with slower speeds (3–10 cm/s) leading to higher intensity ratings compared to faster strokes. These results align with prior studies suggesting that slow stroking optimally activates C-tactile (CT) afferents, which are associated with affective and pleasant touch perception [26], [43]. The high-intensity ratings for slower speeds may be attributed to temporal summation, where prolonged mechanoreceptor activation enhances perceived intensity. In contrast, faster strokes (30 cm/s) may not provide sufficient stimulation time for CT afferents to fully engage, leading to reduced intensity perception [79], [80]. The interaction between stroke speed and amplitude modulation should be further explored to determine how temporal and spatial properties of mid-air haptics contribute to the strength and emotional quality of perceived sensations.

Unlike valence ratings, which were not significantly affected by stimulus direction, arousal ratings exhibited a significant directional effect ($p < 0.001$). Stimulation delivered in the proximal-to-distal direction resulted in higher arousal ratings compared to distal-to-proximal strokes. This finding suggests that directional cues in tactile stimulation may influence autonomic and physiological responses, potentially by engaging somatosensory integration mechanisms that influence physiological states. Previous research has suggested that directional stroking on the skin can modulate activation in the somatosensory cortex and limbic regions, potentially contributing to variations in arousal [73], [74].

D. Implications for affective-like touch technologies and mindfulness-based applications

While previous research has focused on mindfulness as a tool for enhancing cognitive and emotional regulation [35], [36], our results suggest that it may also play a role in shaping tactile perception, confidence in sensory evaluation, and valence in response to mid-air ATS. This suggests that it could be systematically incorporated into future affective-like touch studies. One key challenge in haptic research is the variability in subjective perception, which can be influenced by factors such as attention, expectation, and emotional state [4]. By incorporating standardized mindfulness protocols, researchers may be able to reduce perceptual noise and improve the reliability of affective touch studies.

Our findings suggest that mindfulness may enhance users' engagement with haptic feedback, potentially making digital touch experiences more immersive and emotionally meaningful. For instance, in virtual environments or metaverse applications, users could engage in mindfulness-enhanced haptic interactions, where mid-air haptics is used to simulate comforting or emotionally expressive touch during meditation sessions, social VR interactions, or remote therapeutic settings. Additionally, by optimizing haptic parameters such as modulation frequency and stroke speed based on our findings as shown in Figure 5, designers could create more intuitive and emotionally resonant haptic experiences tailored for mindfulness and relaxation applications.

E. Limitations and future work

While this research provides new insights into the interaction between mindfulness meditation and mid-air ATS, several limitations should be considered when interpreting the findings. These limitations also highlight potential directions for future research. One limitation of this research is the use of the forearm as the stimulation site. While the forearm is well-suited for affective touch studies due to the presence of C-tactile afferents [11], [14], it has a lower mechanoreceptor density than the palm, which may have constrained pattern recognition performance. As shown in Figure 4, even slightly complex patterns than linear strokes were frequently misclassified, likely due to the difficulty in distinguishing spatial details on the forearm. Future studies could explore the direct comparison of pattern recognition and emotional evaluation when stimuli are presented on more sensitive regions, such as the palm which have greater spatial acuity.

We acknowledge that while our stimuli were designed to approximate physical parameters associated with CT-afferent activation (e.g., slow stroking speeds, specific directional movements), our study did not directly measure neural responses or CT activation. To date, no microneurography study has confirmed whether mid-air haptic stimulation engages CT afferents. Therefore, while our perceptual and emotional findings align with characteristics of affective touch reported in prior work, the involvement of the CT system in this context remains an open question. Future neurophysiological studies would be necessary to establish a direct link between mid-air tactile stimulation and CT-afferent activation.

While mid-air haptics cannot replicate the full ecological and physiological context of interpersonal skin-to-skin touch, it offers a controlled platform for isolating and investigating participants' subjective affective responses to tactile stimulation without social or relational confounds. We also acknowledge that Study 2 did not include a non-affective (fast-speed) condition for the pattern recognition task. This design choice prioritized consistency in stimulus velocities optimal for pleasant touch perception across patterns, while minimizing complexity in pattern learning. Future studies could incorporate multiple velocity conditions to explore how speed interacts with pattern recognition and emotional responses.

Future research could explore the use of more complex haptic patterns designed to elicit distinct emotions, expanding beyond the sensory and valence-arousal evaluations conducted in this research. Inspired by prior work [17], future studies could investigate how mid-air haptics can be used to map specific emotional states, incorporating dynamic haptic parameters and contextual multi-sensory cues. Examining the effects of mindfulness meditation on emotionally expressive haptic patterns could provide new insights into how attentional states modulate affective touch perception. Additionally, given our findings that mindfulness improves tactile perception and emotional evaluation, future work could investigate how such interventions may benefit populations with age-related sensory decline. Combining mindfulness-based tactile training with mid-air haptics could offer a non-intrusive strategy to support emotional wellbeing and sensory engagement in older adults, particularly in settings where physical contact is limited.

Another limitation is the relatively short mindfulness meditation session (10 minutes), which may not have been sufficient to produce long-term perceptual or emotional changes. While prior research has shown that brief mindfulness sessions can enhance tactile sensitivity [10], longer mindfulness training programs may have a more pronounced effect. Future research could investigate whether extended mindfulness practice leads to greater enhancements in sensory perception, confidence, and emotional responses to haptic stimuli. Future studies should consider using a larger sample size to improve statistical power and generalizability, ensuring that observed effects of mindfulness on tactile perception and emotional evaluation are robust across a broader population. Additionally, investigating expert mindfulness practitioners who have undergone long-term meditation training could provide deeper insights into how sustained mindfulness practice influences sensory awareness, pattern recognition, and emotional responses to mid-air haptics.

Our findings show that mindfulness enhances the clarity and confidence with which users perceive mid-air ATS. This perceptual enhancement may be useful in designing emotionally engaging touch experiences in immersive environments. For instance, combining mid-air haptics with mindfulness-based practices in VR settings could be explored for applications such as stress management, emotional grounding, or body awareness training, especially in therapeutic or wellbeing-focused contexts. Prior research has shown that mid-air haptics can convey emotional nuances [17], and mindfulness training is already used in VR-based relaxation and exposure therapies. Future work can investigate whether combining these modalities offers synergistic benefits.

VI. Conclusion

This research investigated the influence of mindfulness meditation on sensory perception and emotional evaluation of mid-air ATS, focusing on both simple linear strokes and complex tactile patterns. Our findings suggest that mindfulness enhances perceived intensity and confidence in sensory evaluation, while also increasing valence ratings, making haptic interactions feel more pleasant. Our findings have important implications for affective-like haptic technologies and mindfulness-based interventions. By integrating mindfulness training into haptic applications, researchers and designers can enhance sensory awareness, emotional engagement, and confidence in haptic experiences. Future work should explore long-term mindfulness training, multi-sensory integration, and applications in therapeutic and virtual environments to further optimize the design of mindfulness-enhanced affective touch technologies.

Acknowledgments

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