MindTouch: Effect of Mindfulness Meditation on Mid-Air Tactile Perception

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ABSTRACT

As we constantly seek to improve and expand upon the capabilities of technology, we frequently wonder whether we use technology to its fullest extent. Studies indicate that increasing our awareness and mindfulness of our senses may lead to a journey of unexplored experiences. In this paper, we focus on the perception of mid-air haptics stimuli and whether it can be improved through mindfulness meditation. We have conducted an experiment with 22 participants given the task to recognize digits 0 to 9 drawn on their palms using a mid-air haptic device under two conditions - with and without prior mindfulness meditation. Results show that for frequencies targeting both Meissner (40 Hz) and Pacinian (200 Hz) receptors, meditation significantly improves performance of the participants, as well as increases their confidence. This suggests that including a short meditation step in haptic user interfaces could lead to improved system performance and user satisfaction.

CCS CONCEPTS

• **Human-centered computing** → **Empirical studies in HCI**; **User studies**; **Empirical studies in interaction design**.

KEYWORDS

Touch, Mid-Air Haptics, Tactile Perception, Mindfulness Meditation, Tactile Experience, Haptics

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1 INTRODUCTION

Studies indicate that increasing our awareness and mindfulness of our senses may lead to a journey of unexplored experiences [18]. Mindful sensory experiences involve the awareness of subtle subjective experiences (e.g., what we touch and how it feels) during our interactions with the environment or technology. With the development of human-centered and multi-sensory technologies, it is essential to ensure that humans are experiencing these technologies to the fullest extent. In the broader perspective of sensory experiences, we hypothesise that becoming more aware and mindful of our sensory experiences will allow humans to better utilise these ever-growing technologies. We tested this hypothesis in the context of tactile experiences and user performance using a mid-air haptic device [11, 28].

Mid-air haptics is a novel, emerging technology that is gaining attention due to its ability to create tactile sensations on users' skin without any physical contact [58]. This contactless tactile stimulation has been studied in a range of application scenarios, from augmented movie experiences [2] to automotive user interfaces [26, 36, 61]. Despite its advantages, a key challenge of using mid-air tactile stimulation in HCI is the subtlety of the sensation. Users previously compared it to blowing on the palm, tingling on the skin, or feeling dry raindrops [52]. We argue that attention and awareness of such subtle sensations have a profound impact on users' performance and subjective experiences and that these can be regulated by simple processes, such as a short meditation.

In this paper, we explore the effect of mindfulness meditation[33] on a tactile recognition task where digits are presented on a user's palm using mid-air haptics. While there has been considerable HCI research on technologies that can support users in mindfulness meditation [15, 33, 57, 60], including external sensory stimulation [65, 71], research has yet to explore using mindfulness meditation as a tool to influence users' interaction with technology, and their sensory experiences.

Human skin contains four major types of mechanoreceptors [9], of which, two are of interest to haptics applications focusing on vibration perception. Meissner corpuscles sense pressure, with its highest sensitivity range from 10 to 50 Hz [20]. On the other hand, Pacinian corpuscles [8] sense vibrations up to a few kHz [7], peaking at around 200 Hz [30]. In our study, we aimed to evaluate and compare the effect of mindfulness meditation on human recognition performance, for both Meissner and Pacinian receptors, separately.

Performance was evaluated through precision and recall metrics calculated from recognition confusion matrices.

Our results show that precision and recall were significantly improved after a short mindfulness meditation session, as compared to the baseline condition. Furthermore, we found that participants responded faster and with more confidence in mindfulness condition. We also found that performance involving Pacinian receptors was significantly better than performance using Meissner receptors.

The contribution of this paper is threefold:

(1) We demonstrate that short meditation can have a significant effect on the perception of mid-air tactile sensations. This offers designers an opportunity to boost system performance (making haptic feedback more recognisable) and enhance user satisfaction and experience through easier, shorter, and more confident interactions.
(2) We build on existing research in the area of basic physiological and emotional responses to mid-air haptic stimuli, establishing its usability in a higher-level cognitive task and pushing the technology into more complex applications involving information transfer.
(3) We consider the suitability of the palm for the tactile recognition task. Our study compares two types of human mechanoreceptors in terms of sensing and facilitating the understanding of mid-air stimuli resembling strokes. This informs the potential designs of mid-air haptic applications, beyond simple digit recognition.

2 RELATED WORK

2.1 Mid-air haptics

Traditionally, tactile sensations are created using actuators that have physical contact with the skin (*e.g.*, electrodes [64], vibration motors or voice coils [63]; and emerging actuators, such as polymers [13] *etc.*). However, recent research has explored contactless alternatives, including stimulation using air jets [23, 68], vortex rings [22], infrared [62], laser [38], electric arcs [67] and ultrasound [14].

In 2010, Hoshi et al. proposed using an array of ultrasound transducers as a tactile display, whereby adjustments to the phase of individual transducers would allow for the generation of a focal point mid-air, with increased radiation pressure that can be felt using mechanoreceptors in the human skin [28]. Carter et al. extended the technique to multiple points, showing that trained users can distinguish between various modulation frequencies [11]. Ultrasound signals (i.e., 40 kHz in most of contemporary mid-air haptic hardware) must be modulated in order to be perceived by human mechanoreceptors. The receptors that can be stimulated in this way are the Meissner corpuscles (10–50 Hz [20]) and Pacinian corpuscles (up to few kHz [7, 75], peaking around 200 Hz [30]). So far, three types of modulation have been described in the literature: amplitude modulation (AM) [43], lateral modulation (LM) [69], and spatiotemporal modulation (STM) modulation [19]. For a survey of ultrasound haptics and their applications, see e.g. [58]. One of the popular applications of ultrasound haptics is an in-car (automotive) user interface which is shown to be less distracting for drivers during interactions by reducing the visual demand [26, 36].

In terms of mid-air 2D shape recognition on users' palms, several studies have been conducted to evaluate users' performance when recognising a few simple shapes: circle, plus sign, line and triangle [31]; circle, square and triangle [25]; circle, square and a point [48]; and 10 combinations of 4 points [55]. Researchers employed several rendering strategies and modulations, with user accuracy ranging from about 43 % [48] to 88 % [55]. Both Hajas [25] and Paneva [55] suggested that rendering the shape all at once (as if it was pressed on a palm) results in significantly worse performance and confidence, as compared to rendering it slowly (as if it was drawn by a finger, or point by point). Our study pushes the boundaries on these recognition tasks by employing a set of complex and similar shapes in the form of digits, extending mid-air stimuli to a broader application scope.

2.2 Mindfulness meditation

Bishop et al. [6] defined mindfulness in terms of two components: (i) the self-regulation of attention, and (ii) an orientation towards the present moment, as characterised by curiosity, openness, and acceptance. In mindfulness meditation, a specific external stimulus or an internal thought is required to focus attention [46]. Intense mindfulness meditation has been shown to improve perceptual sensitivity, the ability to focus for long periods of time and sensory awareness of details [47], and even a brief 10-minute meditation has been shown to effectively reduce stress [41].

In recent years, there has been a steady growth in research exploring the use of HCI technologies in eliciting mindfulness [70]. Many systems have been designed to facilitate mindfulness meditation at a time and place convenient to users, including mobile applications [12, 17, 72], virtual reality systems [21, 32, 60, 65], Internet of Things solutions [56], or tangibles [71, 74]. However, research investigating the converse relationship, that is, how mindfulness meditation can be used to boost task performance or improve user satisfaction, is limited. Bernárdez et al. showed that students who meditated were more efficient at a software modeling task, although the effects on the quality of software models were not significant [5]. Levy et al. found that office workers were just as efficient at multi-tasking with and without meditation. However, those who meditated had better task recall and lower stress levels [40].

On a psychophysical level, Brown et al. found that longer-term practice of mindfulness meditation improved visual sensitivity [10]. Hypersensitivity to light and sound sensation was also recorded by Lindahl et al. [42]. Other effects of mindfulness meditation include altered time perception [16, 34] and better pain thresholds [79]. Finally, Mirams et al. found that healthy participants erroneously reported feeling near-threshold vibrations presented to their fingertip, in the absence of a stimulus. The study used 20 ms contact tactile pulses of 100 Hz on the index finger, which was either accompanied with or without light flashes. This study found that 4 days of 15-minute daily meditation improved the accuracy of somatic perception significantly [50].

A considerable disadvantage of ultrasonic mid-air haptics is the subtle nature of its stimuli [58]. From the above work, it is clear that meditation can have measurable effects on both human performance and lower-level sensory thresholds, including tactile perception. This suggests that meditation could be beneficial in applications involving touch, such as mid-air haptic stimuli. This is a hypothesis that, to the best of our knowledge, has yet to be explored in the existing literature.

3 USER STUDY

In order to investigate the effects of mindfulness meditation on mid-air tactile perception, we designed a controlled user study.

3.1 Experimental design

The experimental design followed a within-subjects design as followed in previous haptic recognition studies [39, 66] and also to account for subjective variability in tactile perception and individual differences in mindfulness meditation. The two main conditions of the experiment are:

- without mindfulness meditation (*baseline condition*) and
- with mindfulness meditation (*mindfulness condition*).

The study was divided into two main sessions, one for each of the two conditions. The two sessions took place on two different days (at least 24 hours in between) following procedures used in prior works applying mindfulness meditation practices [44]. The conditions were counterbalanced to avoid order effects.

The main task consisted of a tactile recognition task, where digits from 0 to 9 (see Fig. 2) were drawn on participants' left palms using two different modulation frequencies (40 Hz and 200 Hz). This was done to evaluate possible differences in sensation from the two mechanoreceptors (Meissner and Pacinian corpuscles [4, 7, 20, 29, 30]). Participants were presented with a total of 60 randomised stimuli in each session (Baseline and Mindfulness). Among the 60 stimuli, every digit (0-9) was repeated 3 times for both modulation frequencies in a randomised sequence that each presented digit was independently sampled from a discrete uniform distribution where possible values in the distribution are 0, 1, 2 . . . 9.

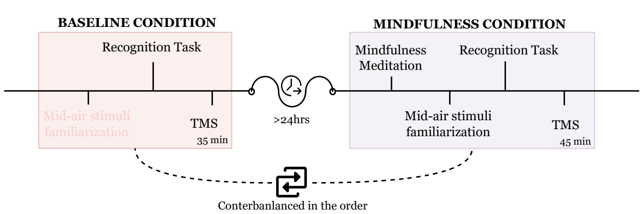


Figure 1: An overview of the study procedure with two counterbalanced conditions: baseline and mindfulness. Both sessions closed with a Toronto Mindfulness Scale (TMS) questionnaire.

3.2 Pilot study

To verify the robustness of the experimental design, we conducted a pilot study with four participants. We initially checked for participants' comfort during mindfulness meditation and experience with the user interface. We also tested for the recognizable drawing speed (1 to 50 cm/s) using an AM focal point at 200 Hz and 40 Hz following the same procedure as the main study. The outcome of this testing yielded 10 cm/s which is the same as reported in prior work [78] as a velocity limit to trace the trajectory in the palm during the mid-air haptic guidance task. During the pilot study, one participant's palm temperature was lower than 34.5 °C. The participant struggled to recognize the characters and sometimes couldn't even perceive the presence of the stimuli; confirming prior works observations [76] that skin temperature influences the tactile threshold. Therefore, we included an additional step in the main study to measure and ensure that the participants' palm skin temperature is between 35 °C and 37 °C.

3.3 Stimuli design

The tactile stimuli were designed so that they mimic the strokes of someone drawing them on someone's hand. However, to ensure the repeatability of the experiment, the digits were described using simple geometry paths (see Fig. 2). The geometry was fitted into 2:1 portrait rectangles scaled to physical dimensions of 6x3 cm, with most of the shapes drawn using single-stroke consisting of simple lines and circles. The notable exception is digit 4, drawn using two separate strokes from the top.

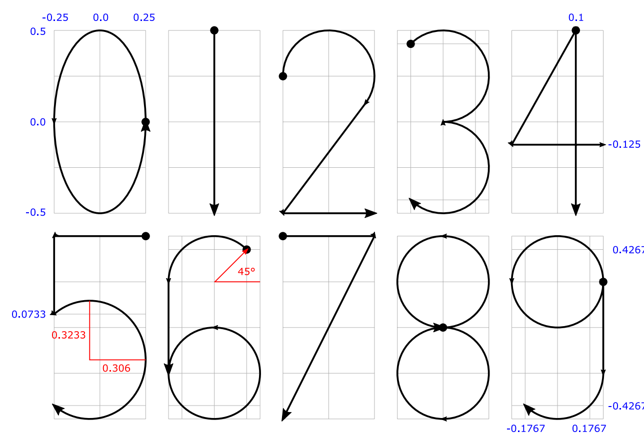


Figure 2: Digit shapes used during the study showing the direction/style. Black circles indicate the start of a stroke, big arrows indicate the end of a stroke.

We originally envisioned using spatio-temporal modulation using high drawing speeds of 5-8 m/s that were perceived as the most intense in the previous work [19]. However, pilot runs of the study showed that these stimuli - akin to pressing the whole digit shape on the palm at once - were extremely difficult to recognize, with the agreement of similar findings in prior work [25, 55]. We, therefore, decided on the slower speed of normal handwriting, 0.1 m/s [78], which allows participants to trace the trajectory in their minds.

At such low speeds, amplitude modulation must be employed for the stimulus to be perceivable by human tactile receptors. We chose to explore two different modulation frequencies: 40 Hz, a frequency used in literature to stimulate the Meissner [4], and 200 Hz, a frequency used to stimulate Pacinian receptors [7, 29].

The stimuli were generated using Ultraleap's STRATOS™ Explore Development Kit, firmware version 2.0.0-beta3, SDK version 3.0.0-beta.10-Research in streaming mode.

(a) (b)

Figure 3: User study setup includes a mid-air haptic device placed inside the black box and a monitor. Participants placed their left arm over the box' aperture (9x10cm) to perceive the stimuli and were wearing the Empatica E4 band on their right wrist to measure their heart rate. (Figure represents the illustration of the user study and not the actual participants.)

3.4 Participants

A total of 22 participants (9 female, aged 19-44, M=28.25, SD=5.77; from 4 continents and 15 countries) were recruited through flyers, university mailing lists, and word of mouth. None of them had any experience in mindfulness meditation, nor they had any sensory or motor disabilities that would affect their perception of mid-air stimuli. Among the participants, 19 were right-handed and 3 were left-handed. Participants were compensated with £15 gift vouchers for their participation. The study was approved by the Institute Research Ethics committee (Approval ID Number: UCLIC_2021_014_ObristPE).

3.5 Study setup and procedure

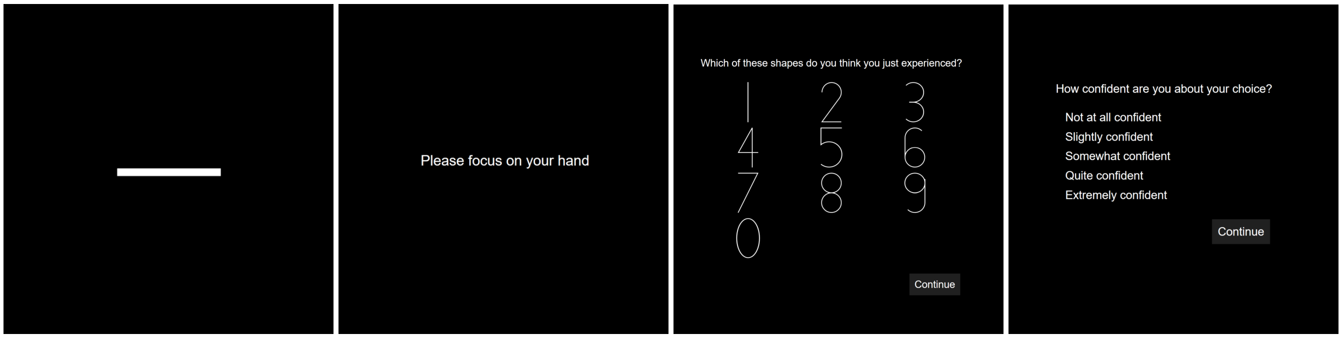
During the experiment, the haptic device was placed on a table facing upwards and covered with a box of 20 cm height, with a rectangular opening of 9x10 cm at the top. Participants were instructed to rest their left arm on the box so that the palm is covering the opening. They were seated on a chair at a comfortable height and followed the study on a screen placed in front of them (see Fig. 3). An Empatica E4 wristband [49] was attached to their right hand which measures skin temperature, skin conductance, and heart rate by default. We used only 'heart rate' data for the analysis in relation to the mindfulness meditation state [80]. The other measures are retained with the intention of future analysis if there is an interest to develop insights into autonomous emotional regulation through mindfulness meditation.

Each trial consisted of a mid-air haptic stimulus drawing a digit from 0 to 9 on participant's palm, participant verbally stating a recognized number while seeing the drawn shapes for all digits on the screen and participant stating how confident they are about their recognition (5 choices ranging from 'Not at all confident' to 'Extremely confident'). Each stimulus was repeated twice with a 1-second delay in between to ensure participants perceived it. In addition, to keep the presentation constant across participants, the onset of the stimulus was aligned showing a visual clue on the screen in the form of a decreasing progress bar for 3 seconds before the stimuli started (see Fig. 4).

The user interface was designed using xamlPsych framework [35] so that participants could navigate it themselves, however, due to the physical constraints of the study setup, both hands of participants being busy (one for tactile stimuli, one for physiological measurements) and possible tactile interference from using keyboard or mouse, we decided for verbal input from the participants recorded by the experimenter. An overview of the study procedure is shown in Fig. 1. Each session included a training phase, during which participants became familiar with the trial structure and tactile stimuli. For training, digits 0 to 9 were presented in order, using 200Hz modulation only.

All participants attended two sessions, one for each condition. The order of the sessions was counterbalanced between participants to avoid any order effects. One of the sessions started with mindfulness meditation, where participants listened to 10-minute audio instructing them to focus on their breathing and become aware of their bodily sensations and thoughts without any judgment. We used the same audio that was used in previous research and shown to be reliable at improving state mindfulness [44]. We played the audio through headphones with Active Noise Cancellation (ANC) turned on. During mindfulness meditation, participants were encouraged to sit on a sofa in a relaxed and comfortable position. After meditation, participants moved to the chair shown in Fig. 3 and proceeded with the experiment.

Participants were randomly assigned to a group to determine whether their first session will be a baseline session or a mindfulness session. We ensured that the two sessions were at least 24 hours apart for each participant. The study sessions lasted for 30 to 45 minutes (without and with meditation respectively), with the first session including additional ten minutes for information sheet and consent forms. After each session, participants were asked to fill



(a) (b) (c) (d)

Figure 4: Screenshots of the user interface flow for each trial. a) the mid-air digits will be drawn on the palm when decreasing progress bar is finished; b) instructions during the drawing: *Please focus on your hand*; c) participants are asked to respond with their recognized digit (orally); d) participants asked to indicate their confidence in the recognition task (orally).

out the Toronto Mindfulness Scale questionnaire [37] to evaluate participants' state of mindfulness.

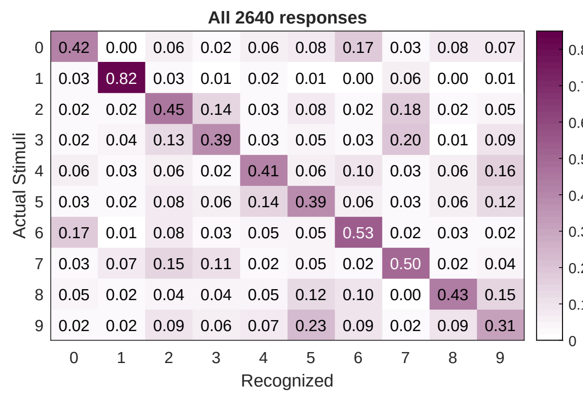
4 RESULTS

Our results include task performance measurements, a state mindfulness questionnaire (TMS), and physiological measurements (i.e., heart rate). The task performance indicators are the confusion matrices, true positive rate (TPR or recall), participants' recognition confidence, and both median and IQR of their response time. We used descriptive statistics and data visualisations to show our findings and gain more insight into the data collected from both conditions.

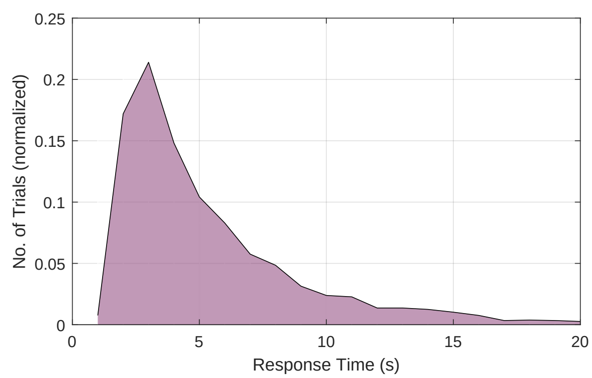
4.1 Recognition Task Performance

A total of 2,640 responses from 22 participants were analysed and mapped onto confusion matrices shown in Fig. 5a. Each row corresponds to the digit rendered on participants' palms using the mid-air haptics device, while each column corresponds to the digit indicated by participants (values show the respective proportion of responses for given combination of digits, adding to 1.0 in each row and column). The main diagonal contains responses where participants correctly recognized the stimuli (true positives). Each row, apart from the main diagonal cell, contains false negatives; and each column, apart from the main diagonal cell, contains false positives for that particular stimulus.

4.1.1 Overall results. The overall digit recognition accuracy across all conditions was 46.4% (precision (PPV) = 46.8%, recall (TPR) = 46.4%). Participants took 5.3 seconds on average (4.0 for correct answers, 5.5 for incorrect) to indicate their response, with an average reported confidence of 29% (53.31% for correct answers, 26.42% for incorrect answers). Performance for individual digits can be seen in Fig. 5a. A histogram of response durations is shown in Fig. 5b (responses lasting longer than 15 seconds are considered breaks and excluded from all timing analysis; time is measured between prompt being shown on screen and researcher recording the answer).



(a)

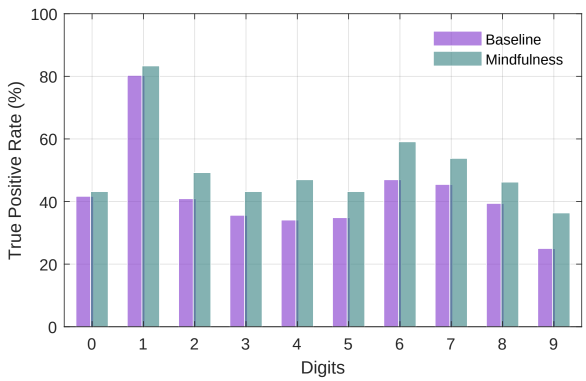


(b)

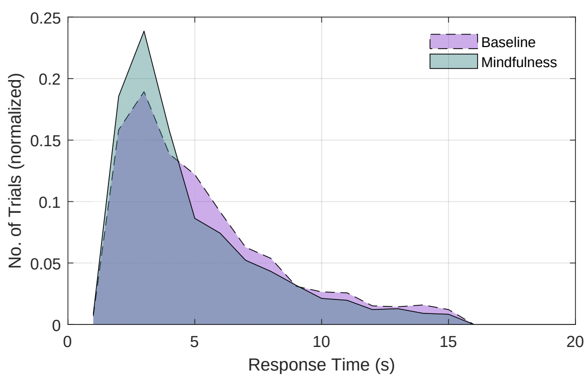
Figure 5: a) Confusion matrix for overall digit recognition across all conditions; b) Histogram of durations participants took to give their response on the digit recognition.

4.1.2 Effects of meditation. Accuracy for digit recognition in the *baseline condition* was 42.42%(PPV = 42.53%, TPR = 42.42%). Participants took 4.04 seconds (median) to indicate their response (4.43 s for correct answers, 5.52 s for incorrect), with an average reported confidence of 30.55% (51.05% for correct answers, 28.21% for incorrect answers).

Accuracy for digit recognition in the *mindfulness condition* was 50.45% (PPV = 51.05%, TPR = 50.45%). Participants took 3.38 seconds (median) to indicate their response (3.72 s for correct answers, 5.31 s for incorrect), with an average reported confidence of 28.87% (55.58% for correct answers, 25.67% for incorrect answers).



(a)

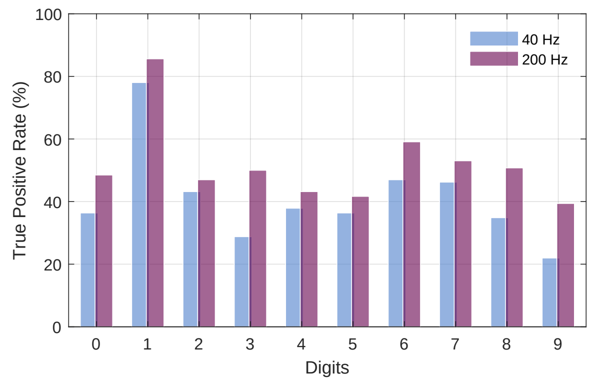


(b)

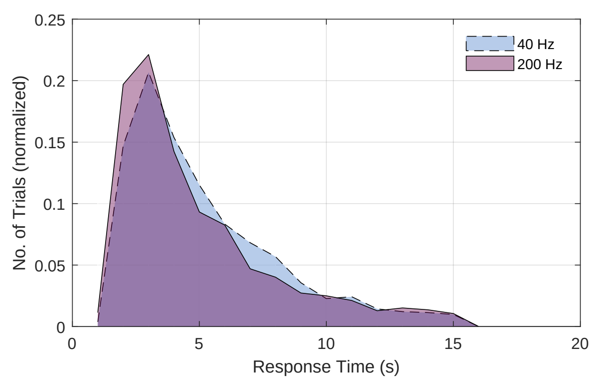
Figure 6: a) Per-digit true positive rate comparing baseline and mindfulness conditions; b) Comparison of response duration histograms between trials from the baseline and the mindfulness sessions.

A non-parametric Friedman test showed that mindfulness meditation has a significant effect on the precision ($Q = 6.39$, $p = 0.012$) and recall ($Q = 10.79$, $p = 0.012$) of digit recognition, as well as on the confidence ratings ($Q = 4.17$, $p = 0.041$) and response duration ($Q = 10.78$, $p = 0.001$). The difference in true positive rate between baseline and mindfulness conditions for individual digits can be seen in Fig. 6a. The difference in response duration is visualized using a histogram in Fig. 6b.

4.1.3 Effects of modulation frequency. Accuracy for digit recognition using the *40 Hz modulation* regardless of meditation was 41.06% (PPV = 41.02%, TPR = 41.06%). Participants took 3.92 seconds (median) to indicate their response (4.62 s for correct answers, 5.43 s for incorrect), with an average reported confidence of 25% (46.45% for correct answers, 22.63% for incorrect answers).



(a)



(b)

Figure 7: Per-digit true positive rate comparing 40 Hz and 200 Hz modulations; b) Comparison of response duration histograms between trials using the 40 Hz and 200 Hz modulation.

Accuracy for digit recognition using the *200 Hz modulation* regardless of meditation was 51.82% (PPV = 52.74%, TPR = 51.82%). Participants took 3.45 seconds (median) to indicate their response (3.91 s for correct answers, 5.23 s for incorrect), with an average reported confidence of 36.4% (59.15% for correct answers, 33.52% for incorrect answers).

A non-parametric Friedman test showed that the modulation frequency has a significant effect on the precision ($Q = 10.79$, p =0.001) and recall ($Q = 15.57$, $p < 0.001$) of digit recognition, as well as on the confidence ratings ($Q = 185.5$, $p < 0.001$) and response duration ($Q = 11.73$, $p < 0.001$). The difference in true positive rate between 40 Hz and 200 Hz modulation for individual digits can be seen in Fig. 7a. The difference in response duration is visualized using a histogram in Fig. 7b.

Table 1: Measures of recognition task performance: Precision, Recall, and Response Time (RT). PPV and TPR indicate positive predictive value and true positive rate, respectively. RT is represented in terms of median and Inter-Quartile Range (IQR).

Conditions	Accuracy	Precision (PPV)	Recall (TPR)	RT (median)	RT (IQR)	Confidence
Baseline	42.42%	42.53%	42.42%	4.04 s	4.12 s	51.05%
Mindfulness	50.45%	51.05%	50.45%	3.38 s	3.81 s	55.58%

4.2 Mid-air digit recognition and different regions of tactile sensitivity in palm

In general, most participants were able to perform the digit recognition task well above chance, as shown in Fig. 8. While we expected some participants to perform better than others, the results did not indicate any outliers either way (cf. true positive rate of individual participants in Fig. 8), despite the performance spanning a surprisingly large range. For comparison with previous work, the overall TPR for recognizing circles, triangles, lines, and plus signs in the case of Korres et al. [31] was 59.44 %, while the overall TPR in our study was 46.4 %, suggesting a comparable performance despite the increased number of shapes.

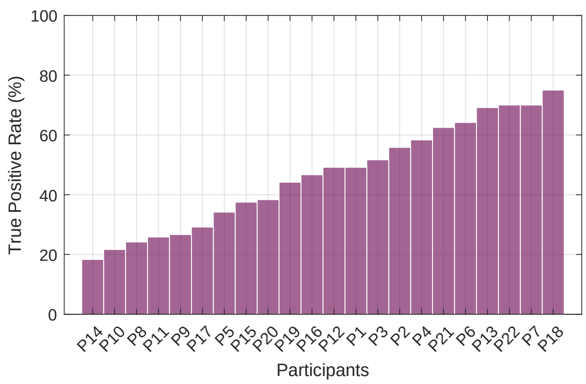


Figure 8: Recognition task performance of individual participants in terms of true positive rates from low to high.

The most confusing pair of digits were 5 and 9 (17.8%), 0 and 6 (17.0%), and 2 and 7 (16.7%), which can be glanced from high non-diagonal values in the confusion matrix (cf. Fig. 5a). This is most likely due to the high similarity of strokes used in drawing the digits in these pairs. For example, digit 5 was drawn as a single stroke from the top right to the bottom left and so was digit 9, with a sharp angle starting the last arc in both cases. Similarly, both 0 and 6 were drawn counter-clockwise starting on the right side (the strokes and their direction for all digits can be seen in Fig. 2). Contrast this with 0 and 9, where despite the shapes of 6 and 9 being identical except for rotation, the confusion rate is very low (4.5%). This suggests that it is considerably easier to perceive stroke directions and changes in directions during drawing rather than the absolute positioning of stimuli. As a result, we speculate that preferring direction and angle diversity when designing the stimuli (for example, using two strokes - one downward and one rightward - to draw the digit 5) as opposed to its geometrical simplicity might lead to an increase in performance metrics.

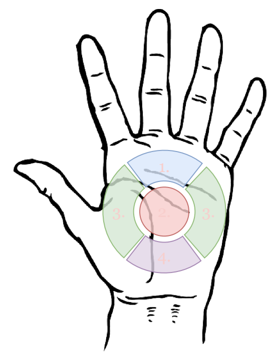


Figure 9: Regions of palm ordered by reported sensitivity (1. highest, 4. lowest, inferred from informal discussion).

Another factor contributing to the confusion might be the different sensitivity in different regions of a human palm. During pilot runs of the study, participants raised the fact that it was more difficult to perceive the stimuli in the lower part of their palms (closer to the arm). Based on this observation, we informally asked all participants at the end of each session to comment on the sensation, which region of the palm they felt was the most sensitive, and if they had to rate them, how would they order them based on sensitivity. All participants considered the top or middle (or both) parts as the most sensitive ones and suggested the order of top, middle, sides, and bottom parts of the palm (see Fig. 9). This could further explain some of the misrecognized digits. For example, while 2 and 7 were confused in 16.7% trials, 3 and 7 were very close with 15.5% confusion. Similarly, the 0 and 6 pair confusability could be attributed to their main differences being in the lower part of the palm. This agrees with previous results on varying palm sensitivity in contact haptics applications (see, e.g., [3]) and should be taken into account when designing stimuli, however, further research into palm sensitivity regions with regards to and using mid-air stimuli would beneficial due to its superior spatial resolution.

4.3 Further findings

The *curiosity* score yielded by the Toronto Mindfulness Scale (TMS) questionnaire was 2.23 on average (SD 1.16) in the baseline condition and 2.19 on average (SD 1.17) in the mindfulness condition. A non-parametric Friedman did not indicate a significant difference between the two conditions ($Q = 0.474$, $p = 0.491$). The *de-centering* score was 2.10 on average (SD 0.93) in the baseline condition and 2.08 on average (SD 1.11) in the mindfulness condition. A non-parametric Friedman did not indicate a significant difference in de-centering between the two conditions ($Q = 0.2$, $p = 0.655$) either.

The average heart rate of participants in baseline sessions was 77.5, while the average heart rate of participants after mindfulness meditation was 78.5. A non-parametric Friedman test did not find any significant difference in the average heart rate between the baseline and mindfulness conditions ($Q = 0.429$, $p = 0.513$).

5 DISCUSSION AND DESIGN CONSIDERATIONS

In this section, we discuss the implications, design suggestions and potential future works related to mid-air tactile recognition. Additionally, we share our experiences working on this study to understand the effects of mindfulness meditation on tactile recognition, and also reflect on our findings. We believe that this might be of interest to the researchers and designers using mid-air haptic technology, and to those who are exploring the subjective experiences involved in tactile and other sensory modalities.

5.1 Is it sensation or recognition?

Although meditation effects are not evident from the TMS questionnaire and heart rate measurements, recognition performance for stimulation at each frequency (40 and 200 Hz) was significantly improved. Perhaps meditation effects are not noticeable physiologically (HR) and consciously (TMS), however, they are noticeable perceptually. This could demonstrate the possibility that the meditation influences various levels of cognition/neural processing and physiological responses. In the literature, the reported effects of meditation on physiological responses were for long-term meditation (minimum four weeks) [45, 73]. Here, we consider (following the definition of mindfulness) meditation a quick way to regulate our attention [51]. The improvement in recognition performance may indicate two possibilities as follows: Either (1) perception of the stimuli is improved, meaning that information from the peripheral receptors has been perceived better, or (2) perception is unaffected, but recognition, which is a higher order cognitive processing, is increased. The first possibility may lead to a statement that the tactile threshold has been reduced, which enhanced sensation and further improved recognition. The second possibility may lead to a statement that the threshold has remained the same, but recognition is improved. These two statements lead us to a research question "Is the improvement in the mid-air tactile recognition performance due to the influence of mindfulness meditation on low-level neural processing or high-level neural processing?". Furthermore, the research hypothesis for future work can be framed as "The improvement in the mid-air tactile recognition performance due to the mindfulness meditation is due to improvement in the tactile threshold."

5.2 Performance in baseline and mindfulness conditions

As briefly described in the section 4, our results show that recognition performance and response confidence are significantly improved for the condition with prior meditation, as shown in Fig. 6. It is interesting to see the significant effects of a brief 10-minute meditation. We believe that this is mainly due to the attention regulation elicited by the meditation session. This is supported by the findings of Norris et al. [51], which reported improved attention for those who performed 10 minutes of mindfulness meditation. However, we still do not know if there are any other effects involved in this improvement. A prolonged meditation effect could shed more light on our understanding of these initial findings. As we know, the audio that we played for the meditation session instructs participants to gently observe their breathing and senses without any judgment. Maybe this observation was powerful enough for participants to regulate their attention, which is reflected in their subsequent tactile recognition performance. Other aspects of recognition performance, such as their confidence ratings and response times, also improved. In other words, they responded quickly and with more confidence in the mindfulness condition than in the reference condition. This constitutes possible evidence for the effects of mindfulness meditation on tactile recognition performance.

5.3 Improved recognition performance in both Meissner and Pacinian frequency ranges

Irrespective of the condition that participants were in, we also observed a significant difference between the 40 Hz and 200 Hz frequencies (see fig. 7), which are in the Meissner and Pacinian corpuscles ranges. To verify the effect of frequencies, we compared the confusion matrices of 40 Hz and 200 Hz separately, irrespective of condition. We observed that the true positives for digits such as "4, 6, and 9", which are considered difficult to recognise, are higher for 200 Hz than 40 Hz. Furthermore, this difference is statistically significant. In terms of conditions, the performance in both Meissner and Pacinian range frequencies was enhanced in the condition with prior meditation. Additionally, this effect is significant in terms of participants' confidence ratings. Therefore, it is evident that stimulation frequency (modulating frequency for AM) is important for the design of mid-air tactile applications, especially where recognition performance is crucial. From the existing literature [7, 8], it is well-known that the Pacinian corpuscle is a crucial receptor for the perception of stimuli in the range of vibrotactile frequency from 10 Hz to 1000 Hz, with its peak frequency lying between 200 and 250 Hz. In our experiment, the mid-air haptic sensation threshold (AM focal point) [59] is also very low in the Pacinian range of frequencies compared to the Meissner range of frequencies (40 Hz). These results suggest that the frequency in the Pacinian range is more suitable for tactile recognition. However further studies are needed to verify this assumption.

5.4 Factors influencing mid-air tactile perception

5.4.1 Recognition influenced by style of writing. Another factor that we observed during the study is the idiosyncrasy related to the rendered style of writing. Although we made sure that the numbers were rendered at a speed that is optimal for human perception [78], there are other factors such as the direction of writing and starting point for a character. One left-handed participant (among the three in our study) was experiencing difficulty in recognising the style of the characters since the participant believed that their way of writing was much different from what was rendered on the palm. We therefore separately analysed the drawing/writing style of this particular participant and a few other participants. We asked them to write the characters on a piece of paper. We specifically observed their style of writing in terms of direction, shape, starting point, and edges. We visually observed that there were some idiosyncrasies associated with their style of writing, which may affect recognition performance. Therefore, we believe that considering the style of writing when designing tactile stimuli is crucial. Furthermore, in our study, the numbers were automatically drawn using AM focal point. In the future, we plan to study the effects of recognition performance on three conditions: (1) auto-drawn numbers, (2) self-drawn numbers, and (3) numbers drawn by others. The first condition will be the same as our current stimuli, the second condition is where the participants will be asked to recognise their own style of writing, and in the third, participants will be asked to recognise the writing of a stranger. This could give us a preliminary understanding of the effects of writing style on recognition, and possibly lead to various applications related to communicating messages through one’s palm.

5.4.2 Recognition influenced by the skin temperature. Skin temperature of the palm region has been observed to influence recognition performance, though we did not exclusively study these temperature effects. It is well known from the literature [1] that skin temperature has an effect on tactile sensation thresholds which follows our observation from the pilot study. We believe that it is due to the fact that the sensation is affected before the recognition. In our study, we made sure that skin temperature is always between 35 °C and 37 °C by measuring the skin temperature of the left palm at the start, breaks, and end of the recognition task, in both baseline and mindfulness conditions. We, therefore, suggest that the palm’s skin temperature should be considered before rendering the mid-air tactile patterns for recognition.

5.5 Limitations, Future Works, and Potential Applications

We highlighted a few limitations of our current work on recognition performance, and how it is influenced by mindfulness meditation. We start by highlighting the meditation duration and our choice of study design. Although we conducted our study using 10 minutes of meditation and observed significant effects, we did not consider the effects of meditation duration on recognition performance. The prolonged meditation may have effects that could shed more light on our understanding of subjective experiences. Moreover, future work could apply a between-subjects design approach to validate the effect of mindfulness meditation, reducing any possible learning effects. We used a within-subjects design, predominantly used within HCI [27, 39, 66], to account for subjective variability, both with regard to the haptic perception and mindfulness meditation experiences. Using a within-subjects design, it is difficult to state with complete certainty that mindfulness was the key factor since there could be potential carry-over effects, and the fact that the TMS showed no significant differences in mindfulness between groups. In addition, skin temperature appears to be influencing recognition performance, which we did not study exclusively except for making sure, during the study, that one’s skin temperature was between 35 °C and 37 °C. If one’s sensation is poor in the low-temperature range [1], then the influence of mindfulness meditation on low skin temperature could be investigated, potentially through consideration of different temperature ranges.

In this work, we considered only auto-drawn numbers, however, in the future, we could test participants’ performance with hand-written numbers or characters. Furthermore, we considered only numbers which were single digits. In the future, we could use a combination of numbers, characters, and shapes, and possibly render more than one character at a time to investigate the effect of mindfulness in the context of increased complexity. In doing so, we need to consider the influence of writing style, as explained in the section 5.4.1. We need to verify the influence of mindfulness meditation on other aspects of neural processing, such as sensation threshold, agency, and emotions. The influence of meditation on emotions and perception would give us more insight into the area of subjective experiences. Additionally, we could explore this effect in other sensory modalities such as taste, smell, and vision and their associated subjective experiences. We had 24 hours gap between the sessions as a washout period to account for meditation effects. However, the aftereffects of meditation still need exploration to verify the washout period corresponding to the duration of meditation [77].

The experimental task used is one of many options for future explorations, however, we believe that haptic ‘recognition tasks’ are widely used within the HCI community to demonstrate new ideas and interaction concepts. For example, in the context of touchless/gesture-based interaction, we can imagine a simple interaction with an ATM screen where we need to be accurate about the digits entered using our findings as verification. More complex, in remote social interaction, we can share non-verbal cues between friends or partners. Most HCI research has shown interest in supporting long-distance relationships enriching verbal with non-verbal cues. We can build on the shown research where we can communicate emotions in midair [53], but valence was often a challenge in these interactions, and adding mindfulness can make a difference. But even beyond this prior research, mindfulness meditation could be a tool to, for example, ‘listen through touch’ where a story is told through a combination of shapes [24, 54], letters, and digits. This would open new avenues for multimodal interaction and accessibility research and design.

6 CONCLUSION

Our study’s long-term goal is to enhance the subjective experiences associated with human-computer interactions by being more aware and mindful of stimulation to our sensory modalities. To begin, we studied the subjective experiences associated with mid-air haptics, specifically, tactile recognition performance. We found that there is a significant effect of mindfulness meditation on tactile recognition performance and we believe that the same effect could be verified with other sensory modalities. In all sensory modalities, neural processing consists of low-level and high-level components. We still do not know precisely where in the neural processing the influence of mindfulness meditation lies - it could be in the high-level or low-level components, or both. From our study, we determined that there is an effect on recognition, which is a high-level component of the tactile sensory modality. Our research shows the possibility of a wide variety of hypotheses that can be tested to gain a better understanding of how to maximize our subjective experiences associated with a sensory modality.

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