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Designing Mid-Air Ultrasound Tactons with Spatiotemporal Parameters for Distinguishable Tactile Brushes

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***Abstract*—Mid-air ultrasound technology offers new possibilities for conveying information using spatiotemporal tactile icons (i.e., Tactons) in contactless applications. Although prior work has explored the design space of spatiotemporal parameters, their distinguishability remains underexplored. In this paper, we investigate the perceptual dissimilarity spaces of mid-air ultrasound Tactons by varying five spatiotemporal parameters to support effective tactile brush designs, which serve as the fundamental units for designing various patterns in mid-air ultrasound haptic systems. We created 36, 42, and 54 Tactons and ran three studies with 36 participants to collect similarity ratings. From the collected data, we derived perceptual spaces and analyzed them to identify the dominant parameters in each set. For instance, brush size transition (*open* and *close*) significantly contributed to distinguishability when drawing frequency was fixed but had little impact when drawing frequency was included as a design parameter. Based on the study results, we propose four design guidelines for creating distinguishable spatiotemporal ultrasound Tactons and outline directions for future research.**

***Index Terms*—Mid-air ultrasound technology, Tactile icon, Distinguishability, Spatiotemporal parameter**

I. Introduction

Mid-air ultrasound technology offers contactless interaction opportunities for various real-world and immersive applications. This technology projects ultrasound signals (>20 kHz) into one or more focal points, creating a sense of touch by modulating the signals or moving the focal points [1]. Moreover, the advent of commercial devices like Ultraleap's haptics development kit [2] has enabled researchers to explore contactless applications such as public displays [3], [4], automotive interfaces [5], and virtual reality environments [6], [7].

Prior studies have explored effective methods for rendering spatiotemporal tactile icons (i.e., Tactons) to convey meaning and information, such as system alerts, warnings, or emotions [8]–[11]. One effective form of Tactons is the tactile brush, a fundamental tactile pattern that moves along a path. These brushes serve as building blocks for complex haptic patterns, which are formed by controlling their movement through space [12], [13]. Despite these efforts, creating clear and easy-to-distinguish haptic shapes remains a challenge due to the inherent limitations of human tactile acuity for recognizing shape patterns in mid-air ultrasound vibrations [11] and the relative dominance of temporal parameters over spatiotemporal parameters [14]. In addition, previous studies have investigated user perception and cognition of various spatiotemporal parameters, such as discrimination thresholds between drawing frequencies or intensities [15], [16], as well as identification accuracies for different spatiotemporal patterns or haptic shapes [8], [9], [11]. Other research explored emotional responses to Tactons that varied on spatiotemporal patterns and were combined with temporal parameters, such as amplitude-modulated frequencies [17], [18]. Yet, the relative impact of these spatiotemporal parameters on perceptual distinguishability of mid-air Tactons remains underexplored.

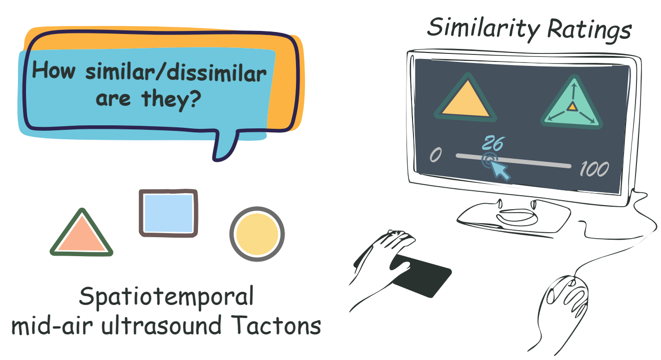

Fig. 1: An overview of our approach for investigating the efficacy of spatiotemporal parameters on distinguishability.

To address this gap, we investigated the distinguishability of mid-air ultrasound Tactons for tactile brushes varying in five spatiotemporal parameters—drawing frequency (how fast the focal point moves), brush shape (the path it follows), brush size (the spatial scale of the pattern), brush size transition (e.g., expanding or contracting over time), and duration—through three user studies with 36 participants. The first study collected similarity ratings for three Tacton sets consisting of 12 static

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brush patterns. These patterns varied on three brush shapes (line, triangle, circle), two brush sizes (3.5, 7 cm), and two drawing frequencies (30, 200 Hz) across three durations (2, 4, 8 seconds). The second study examined two Tacton sets, each with 21 dynamic brush patterns, by varying on three size transition types (*open*, *close*, *none*), three brush sizes (3.5, 7, 10.5 cm), and three durations (1, 2, 4 seconds) across two drawing frequencies (30, 200 Hz). Study 3 tested whether the perceptually salient parameters identified in Studies 1 and 2 remained consistently salient when used together. We created three sets of Tactons with three brush shapes (circle, triangle, square). Each set comprised 18 Tactons, varying on three drawing frequencies (10, 30, 200 Hz), three size transition types (*open*, *close*, *none*), and two durations (1, 4 seconds). In total, we derived eight perceptual spaces in the three studies and identified dominant parameters influencing Tacton similarity perception in each set. For example, brush size transition (*open* and *close*) emerged as a primary parameter when combined with duration and brush size. However, when paired with drawing frequency, the effects of brush size transition on distinguishability diminished significantly, resulting in the lowest perceptual distances. Based on the above studies, we present four design guidelines for creating distinguishable mid-air ultrasound Tactons with spatiotemporal parameters for tactile brushes and discuss future directions of mid-air ultrasound Tacton research. Our contributions include:

- Similarity ratings and perceptual spaces for eight sets of mid-air ultrasound Tactons (total 132 patterns).
- Four guidelines on five spatiotemporal parameters for designing mid-air ultrasound Tactons for distinguishable tactile brushes.

II. Related Work

Mid-air ultrasound technology creates a sense of touch by vibrating the skin from a distance through the focused application of ultrasound waves in mid-air. Previous studies have proposed various methods for generating tactile sensations, including modulating the amplitude of the ultrasound signal [19], moving focal points laterally [20], as well as rapidly moving a single focal point [21] or multiple focal points [22] along arbitrary paths on the skin. These techniques activate mechanoreceptors, allowing users to perceive tactile sensations without physical contact. In our work, we use a single focal point that moves along the boundary of shapes to create Tactons, which serve as "tactile brushes" [12]. These brushes act as the fundamental units (i.e., primitives) for designing complex patterns in mid-air ultrasound haptic systems [13].

One of the key advantages of mid-air ultrasound technology is its ability to create spatial patterns for tactile feedback. Prior research has explored various spatiotemporal parameter spaces to enhance brush shape perception [10], [23] or to enhance perceived intensity [15], [16], [24], [25]. These approaches controlled the speed or drawing frequency of a focal point to achieve the desired effects. Other studies have investigated several spatiotemporal patterns, such as circular, open, close, and random patterns, to explore their impact on user emotions and experience [11], [18]. Recent work proposed adaptive Tactons that respond to external events or states by linking Tactons to external parameters through tactile brushes [13]. When implementing the brushes, it is essential to define their primitive characteristics, such as playback speed and brush size at each keyframe, which result in transitions in brush size over different durations (e.g., open, close, or none). Building on this prior work, we investigate the efficacy of five widely used spatiotemporal parameters—drawing frequency, brush shape, brush size, brush size transition (e.g., open/close patterns), and duration—to inform the design of distinguishable tactile brushes.

In addition to investigating the spatiotemporal parameter spaces of mid-air ultrasound Tactons, researchers have examined the identification of haptic shapes and spatiotemporal patterns, as well as the distinguishability of temporal patterns. Prior studies examined five 3D haptic shapes, such as sphere and pyramid, achieving an accuracy of 61–89% [8]. Korres and Eid investigated four basic 2D haptic shapes—circle, triangle, line, and plus—with participants holding their hands still, leading to an identification accuracy of 44–76% [9]. Other research explored identification abilities for eight 2D haptic shape and spatiotemporal patterns, including open, close, line, circle, and square shapes, with accuracy rates ranging from 26–60% [11]. Recent work explored the distinguishability of temporal ultrasound patterns and identified dominant temporal parameters, such as duration and rhythmic structure [14]. Their findings suggest that temporal parameters may dominate over spatiotemporal parameters in influencing perception. In this paper, we evaluate the distinguishability of 2D haptic shapes and spatiotemporal patterns by combining them with other spatiotemporal parameters. Specifically, we investigate three haptic shapes (line, triangle, and circle) and three brush size transitions (*open*, *close*, and *none*) in Studies 1 and 2, respectively. In Study 3, we assess the relative importance of the salient spatiotemporal parameters identified in Studies 1 and 2 across three haptic shapes (triangle, square, and circle).

III. User Studies

We ran three studies to assess the efficacy of spatiotemporal parameters for ultrasound Tacton design for brushes. We maintained experimental setup and procedure across the studies.

A. Tacton design

We designed 36, 42, and 54 spatiotemporal mid-air ultrasound Tactons for Studies 1–3, respectively (Figure 2). We created all 132 Tactons (distributed across eight sets) using a single focal point that moves along the brush shape. In Study 1, we focused on static brushes that maintained their brush shapes and size during playback. We created 12 spatiotemporal Tactons by varying on three brush shapes (*line*, *triangle*, *circle*), two brush sizes (3.5, 7 cm), and two drawing frequencies (30, 200 Hz). Brush size represents the length of the sides for *line* and *triangle* shapes and the diameter for the *circle* shape. These 12 Tactons were further varied in

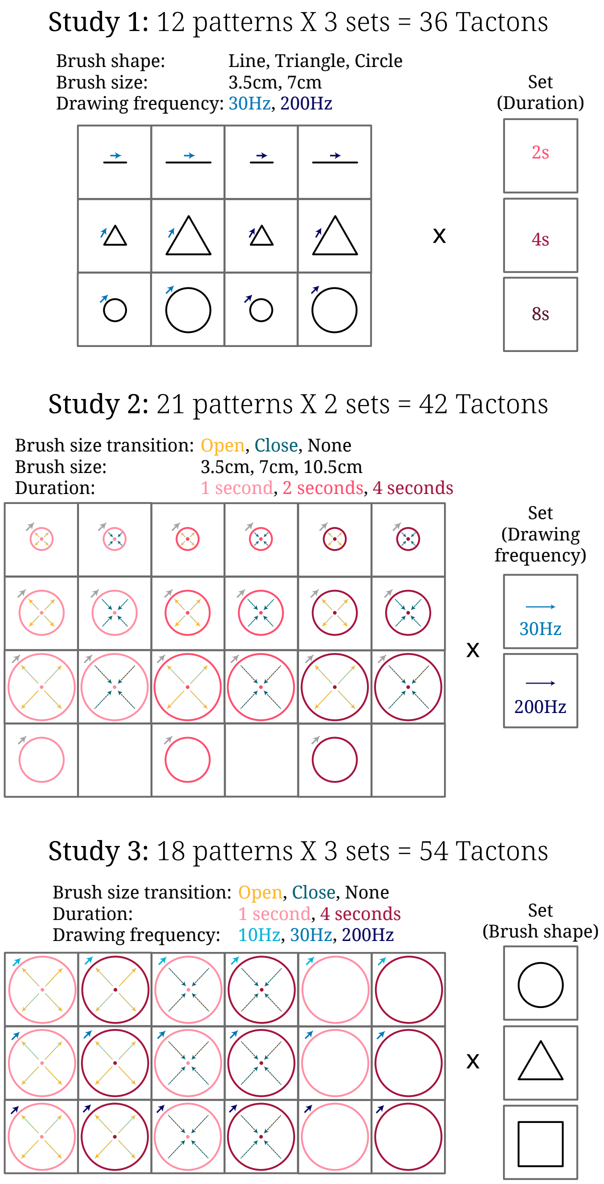


Fig. 2: Mid-air ultrasound Tacton design for Studies 1–3.

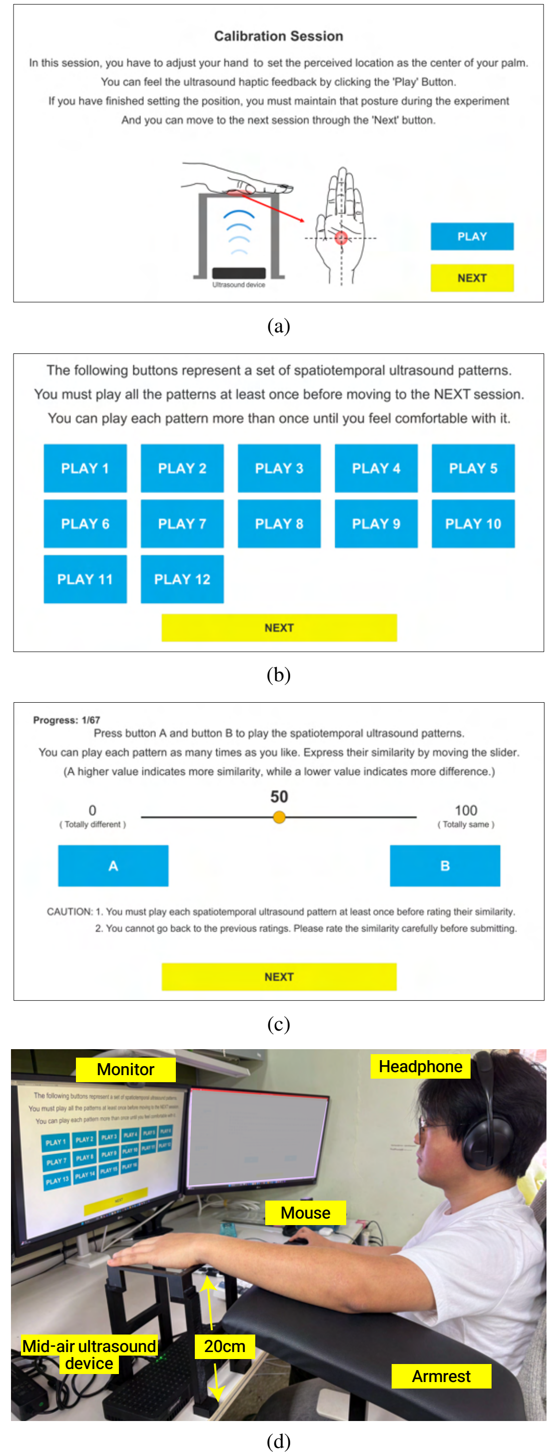


Fig. 3: The GUI for user studies presenting (a) calibration, (b) training, and (c) main sessions, as well as (d) an overview of the experimental setup used.

three durations (2, 4, 8 seconds), resulting in 36 Tactons for Study 1. Study 2 focused on dynamic brushes that transitioned in size during the playback timeline. We created 21 Tactons by varying on three size transition types (*open*, *close*, *none*), three sizes (3.5, 7, 10.5 cm), and three durations (1, 2, 4 seconds). The *open* transition denotes a size change that starts from a single point and expands outward, while the *close* transition reduces the size to a single point over its duration. The *none* transition represents a static brush that maintains a constant size at 7 cm throughout the playback. The 21 Tactons were further varied by two drawing frequencies (30, 200 Hz), resulting in 42 Tactons for Study 2. We used a circle as the brush shape for all 42 Tactons. In Study 3, we varied three drawing frequencies (10, 30, 200 Hz), three size transition types (*open*, *close*, *none*), and two durations (1, 4 seconds) to create 18 Tactons (brush size = 10.5 cm). These Tactons were tested across three brush shapes (*circle*, *triangle*, *square*), resulting in 54 Tactons for Study 3.

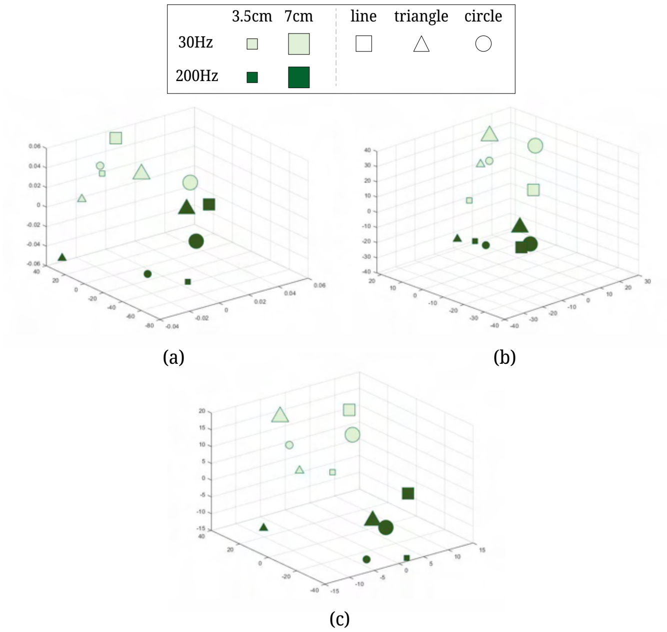


Fig. 4: Three perceptual spaces for Study 1 when duration was (a) 2 seconds, (b) 4 seconds, and (c) 8 seconds. The Kruskal's stress values were lower than 0.1 for all perceptual spaces, suggesting a fair fit.

B. *Participants*

We recruited 40 participants for the three studies (n=12 per study). In each study, 0, 3, and 1 participants failed the attention test, and their data was discarded. The participants included 21 females and 15 males, aged 19–27 years (mean = 21.9, standard deviation = 2.1), with 3 left-handed and 33 right-handed. None of the participants reported any sensory impairments. On average, participants took 60, 120, and 120 minutes to complete Studies 1–3 and received \$14, \$28 and \$28 USD, respectively.

C. *Experiment Setup*

We used the HDK-REC192 device by Ultraleap [2] to render mid-air ultrasound feedback. We placed the device and a 27" monitor on a table in front of the participants (Figure 1). An armrest was used to ensure the participant's palm was positioned 20 cm above the device's center. We collected the participant responses using a graphical user interface (GUI) on a desktop computer. Participants interacted with the GUI programs using their dominant hand while feeling the ultrasound patterns on their non-dominant hand. Additionally, participants wore noise-canceling headphones with white noise to block any environmental sounds.

D. *Experiment Procedure*

The user study consisted of several Tacton sets, each containing three sessions: calibration, training, and main sessions. After completing the consent form, participants received a description of the study from the experimenter. Next, a 27" monitor displayed the GUI program during the study. During the calibration session, participants were guided to place their palm on a handrest and position the center of their palm at the perceived location of the ultrasound vibration, which was focused at a point orthogonal to the device's center (Figure 3a). The handrest measured 12 cm (w) $\times$ 12 cm (d) $\times$ 23.9 cm (h), maintaining the participant's hand at a distance of 20 cm from the device. In the training session, the GUI represented a set of buttons assigned to each block, each randomly corresponding to an ultrasound pattern (Figure 3b). The participants experienced all the Tactons before the main session. In the main session, the participants rated the perceptual similarity for all possible pairs of the Tactons in a set (Figure 3c). The main session displayed each pair once in random order and included an attention test using identical Tactons to ensure focus. The participants rated the perceptual similarity of each pair using a sliding bar ranging from 0 (totally different) to 100 (totally the same). Participants were considered to fail the attention test if their similarity score for the identical pair was below 80, following prior similarity study protocols [14], [26], [27]. The participants could play the Tactons multiple times and take breaks as needed. After completing the main session and before moving to the next set, participants had a mandatory five-minute break. The calibration, training, and main sessions were repeated for each set.

IV. Results

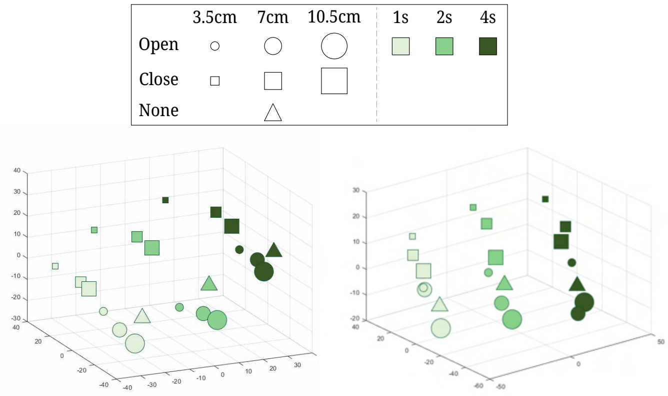
We followed established methods and metrics [14], [28] including non-metric multidimensional scaling (nMDS), Kruskal's stress value, and Spearman's rank correlation to visualize and analyze multiple dissimilarity spaces of Tactons. Using these methods, we derived perceptual dissimilarity spaces from the similarity ratings and compared the corresponding perceptual spaces across the studies (i.e., Study 1: three sets, Study 2: two sets, and Study 3: three sets).

A. *Study 1*

Across all three perceptual spaces, the Tactons were clearly separated by drawing frequency (30, 200 Hz) (Figure 4). For Tacton sets with durations of 2 and 4 seconds, the perceptual spaces indicated that brush size (3.5, 7 cm) influenced perceptual distances as much as drawing frequency, leading to a circular configuration. However, for the Tacton set with durations of 8 seconds, brush size became a secondary factor for distinguishability, disrupting the circular configuration formed by drawing frequency and brush size. Brush shape (*line*, *triangle*, *circle*) showed the closest distances in the perceptual spaces or did not exhibit specific patterns regardless of duration, suggesting it had the lowest impact on distinguishability among the three spatiotemporal parameters. The perceptual dissimilarities among the three sets showed very strong correlations: 2 seconds vs. 4 seconds ($\rho = 0.97$), 2 seconds vs. 8 seconds ($\rho = 0.97$), and 4 seconds vs. 8 seconds ($\rho = 0.98$), all with $p < 0.01$.

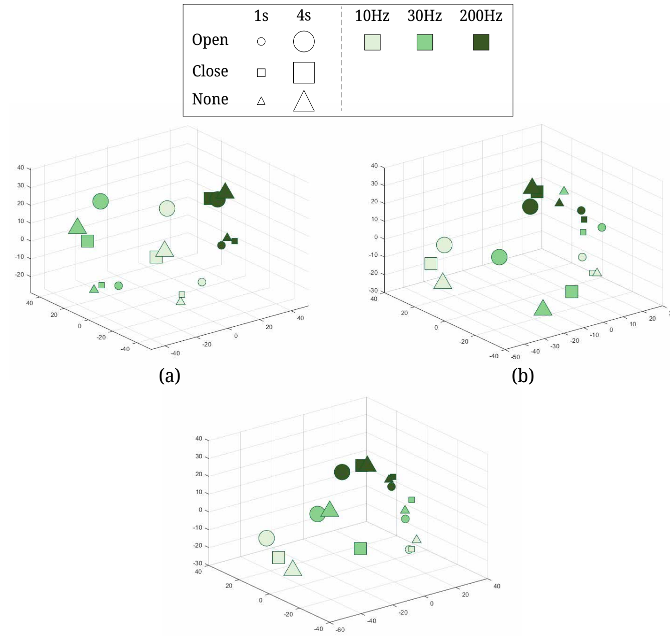
B. *Study 2*

Two perceptual spaces for the two drawing frequencies (30, 200 Hz) showed similar trends in distinguishability of the



(a) (b)

Fig. 5: Two perceptual spaces for Study 2, when drawing frequency was (a) 30 Hz (left) and (b) 200 Hz (right). The Kruskal's stress values were lower than 0.1 for both perceptual spaces.



(a) (b) (c)

Fig. 6: Three perceptual spaces for Study 3 when brush shape was (a) circle, (b) triangle, and (c) square. The Kruskal's stress values were lower than 0.1 for all perceptual spaces, suggesting a fair fit.

three spatiotemporal parameters (Figure 5). The brush size transition (*open*, *close*) and duration (1, 2, and 4 seconds) were the primary parameters, dividing the perceptual spaces into six clusters. Brush size (3.5, 7, 10.5 cm) acted as the second contributor to distinguishability for this set, displaying a similar local distribution trend within each cluster defined by the two brush size transitions and three durations. The brush size transition *none* was positioned outside the two clusters formed by *open* and *close*, resulting in a separate single cluster, while the impact of duration on perceptual distances was still observed within the cluster. The perceptual dissimilarities between the two sets had a very strong correlation ($\rho = 0.86$, $p < 0.01$), indicating that the three parameters maintain their impacts consistently across drawing frequencies.

C. Study 3

For Tactons with the brush shapes of *circle* and *square*, drawing frequency (10, 30, 200 Hz) emerged as the most dominant parameters when used with duration (1, 4 seconds) and brush size transition (*open*, *close*, *none*). For *triangle* Tactons, the effect of drawing frequency remained prominent for the 4-second duration but weakened for the 1-second duration. In other words, the perceptual impact of drawing frequency was less pronounced for Tactons lasting 1 second compared to those lasting 4 seconds. In contrast, brush size transition did not contributed meaningfully to the distinguishability of Tactons when used with duration and drawing frequency. The similarity ratings showed the following correlations: circle vs. triangle - 0.36, circle vs. square - 0.38, and triangle vs. square - 0.84, all with $p < 0.01$.

V. Discussion

In this paper, we created eight Tacton sets comprising 132 patterns and ran three user studies to evaluate the efficacy of spatiotemporal parameters in each set. Through three studies, we investigated five spatiotemporal parameters—drawing frequency, brush shape, brush size, brush size transition, and duration—by varying their combinations and identified their relative dominance in influencing human distinguishability (Table I). Based on our findings, we present four design guidelines for creating distinguishable brushes with spatiotemporal parameters and discuss implications for future research.

TABLE I: Summary of the relative impact of spatiotemporal parameters on distinguishability in each study.

Parameter Contribution	Study 1 (Duration)	Study 2 (Drawing frequency)	Study 3 (Brush shape)
1st	Drawing frequency	Brush size transition & Duration	Drawing frequency
2nd	Brush size	Brush size	Duration
No effect	Brush shape	-	Brush size transition

A. Design Guidelines

We compiled four guidelines to support the design of mid-air ultrasound Tactons for tactile brushes.

1. Duration is an effective design parameter but avoid using excessively short or long durations when using spatiotemporal parameters. Studies 2 and 3 demonstrated that duration was the primary contributor to distinguishability when combined with spatiotemporal parameters. A prior study suggested that temporal factors play a dominant role in Tacton perception [14], and our findings provide additional evidence to support this claim. In Study 1, when duration was constant within each Tacton set, the perceptual impacts of drawing frequency and brush size were comparable for Tactons lasting 2 or 4 seconds. However, for Tactons lasting 8 seconds, this balance diminished, likely due to saturation of mechanoreceptors from prolonged stimulation. Similarly, Tactons lasting only 1 second weakened the perceptual effects of drawing frequency (Study 3), as the duration was too short for users to fully perceive the parameter's influence.

2. Use distinguishable drawing frequency levels with durations longer than 1 second. Drawing frequency was the most prominent parameter in Tacton sets with fixed durations, outperforming brush size and shape in terms of distinguishability (Study 1). Its effects were also evident when combined with duration and brush size transition across three brush shapes but only for durations longer than 1 second (Study 3). Therefore, designers should avoid using drawing frequency with durations shorter than 1 second. Additionally, the effects of duration, brush size, and brush size transition remained consistent regardless of variations in drawing frequency, as Study 2 revealed similar perceptual spaces across two distinct drawing frequencies.

3. Use brush size transition with caution. Study 2 found that brush size transition dominated distinguishability regardless of the two drawing frequencies tested. It resulted in similar perceptual distances between corresponding brush sizes, and this effect remained consistent across three durations (1, 2, and 4 seconds). However, when brush size transition was combined with duration and drawing frequency, its contribution to distinguishability became negligible (Study 3). This suggests that the inclusion of drawing frequency as a design parameter overshadows the effects of brush size transition. Therefore, designers should fix drawing frequency when using brush size transition in Tacton designs to ensure distinguishability.

4. Avoid using brush shape as a parameter for distinguishable Tacton design. Enhancing shape perception remains a challenge in mid-air haptics [10], [11]. Study 1 demonstrated that brush shape had the least impact on distinguishability compared to drawing frequency and brush size. Furthermore, as shown in Study 3, the effects of duration and drawing frequency remained consistent across the three brush shapes of circle, triangle, and square. These findings suggest that, with current hardware and rendering technologies, brush shape contributes minimally to mid-air ultrasound Tacton perception and should not be relied upon as a key design parameter.

B. Implications for Future Work

We highlight how our results can inform future research and haptic design practices in mid-air haptics.

Designers can leverage our findings to create distinguishable spatiotemporal Tactons for diverse applications. Our study provides a comprehensive evaluation of the relative efficacy of five spatiotemporal parameters. Designers can use these findings to map information onto distinguishable Tactons, enabling applications such as alerting system states or enhancing immersive interaction experiences for users. These findings are particularly relevant to scenarios like automotive interfaces and virtual reality environments, where effective haptic feedback can improve safety and user experience.

Researchers can integrate our findings into graphical design tools to enable users to create distinguishable brushes efficiently. Recent studies have proposed GUI tools for effective mid-air ultrasound Tacton design [12], [13], [29], [30]. While these tools visualize Tactons to simplify the design process, especially for transitions in size or shape, perceptual gaps remain between visual and tactile perception. For example, brush size transitions are particularly salient in visual perception, and this effect translates to tactile perception when drawing frequency is held constant. However, when designers vary the drawing frequency, the tactile impact of brush size transitions diminishes to trivial levels. This highlights the importance of incorporating such phenomena into GUI tools to facilitate the effective creation of distinguishable mid-air ultrasound Tactons.

Our study data contribute to developing computational models for predicting similarity perception of spatiotemporal mid-air ultrasound Tactons. The development of computational models to predict Tacton similarity perception requires high-quality, large-scale data for Tactons designed with diverse approaches. For mechanical Tactons, machine learning models have been trained on existing datasets to predict similarity perception [26]. However, no prior work has addressed spatiotemporal mid-air ultrasound Tactons, primarily due to the lack of similarity data for spatiotemporal patterns. Our study provides similarity ratings for eight Tacton sets comprising 132 spatiotemporal patterns, offering valuable data for training computational models. These models can accelerate the design process, enabling more efficient creation of distinguishable mid-air ultrasound Tactons.

VI. Conclusion

Mid-air ultrasound technology presents new possibilities for creating spatiotemporal patterns that enhance user experiences. In this study, we investigated the efficacy of five spatiotemporal parameters on distinguishability to support the design of discernible Tactons for a wide range of applications. We hope that our findings assist designers and practitioners in conveying intuitive and meaningful information through distinguishable Tactons, enabling rich and effective contactless haptic interactions.

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