# Illusory-UMH: A Systematic Comparison of Tactile Illusions and Modulation Techniques in Ultrasonic Mid-air Haptics

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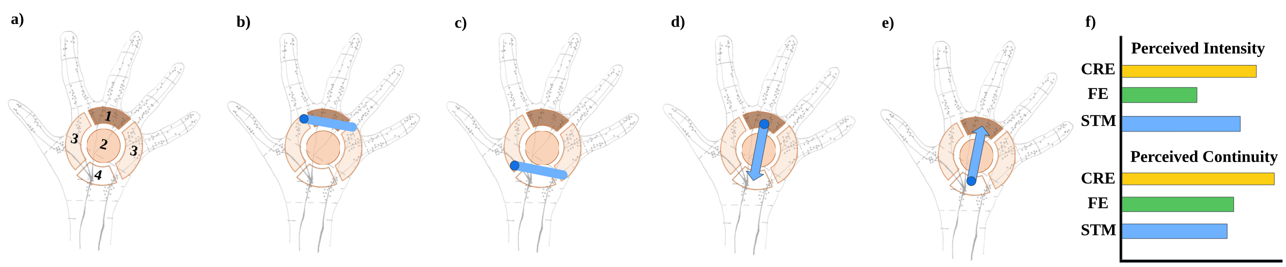


**Figure 1: a) Different sensitivity areas across the hand overlaid with pacinian receptors (dots). We create tactile shapes at low (c) and high (b) sensitivity areas, as well as across areas (d and e), comparing their perceived intensity and continuity when using spatiotemporal modulation (STM) and tactile illusions (funneling effect (FE) and cutaneous rabbit effect (CRE) ) (f).**

## ABSTRACT

Spatiotemporal modulation (STM) is the current de facto standard technique for generating continuous tactile sensations in Ultrasonic Mid-Air Haptics (UMH). However, like other techniques, it assumes a uniform sensitivity distribution across the hand. Tactile illusions, such as the funneling effect (FE) and cutaneous rabbit effect (CRE) create continuous sensations by stimulating only a few points along the shape, which could be strategically selected at highly sensitive points in the hand for stronger effects, but such effects remain unexplored in UMH. This paper investigates tactile illusions (FE, CRE) as potential alternatives for STM, comparing their ability to produce continuous and intense shapes at regions on the palm with different skin sensitivity. Our results reveal significantly superior performance for CRE, when compared to FE and STM in the tested parameter range. FE in turn provides slightly higher continuity, even across sensitivity regions, while STM provides higher intensity.


*UIST '25, September 28-October 1, 2025, Busan, Republic of Korea*

ACM ISBN 979-8-4007-2037-6/2025/09
https://doi.org/10.1145/3746059.3747661

## CCS CONCEPTS

• **Human-centered computing** → **Haptic devices**; **User studies**.

## KEYWORDS

Mid-air haptics, Perception, Tactile illusions

**ACM Reference Format:**
Zhouyang Shen, Joanna Bergström, Madhan Kumar Vasudevan, Marianna Obrist, and Diego Martínez Plasencia. 2025. Illusory-UMH: A Systematic Comparison of Tactile Illusions and Modulation Techniques in Ultrasonic Mid-air Haptics. In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28-October 1, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3746059.3747661

## 1 INTRODUCTION

Ultrasonic mid-air haptics (UMH) operates by creating high-pressure focal points via the additive interference of acoustic radiation waves emitted from transducers [26], with various modulation techniques such as amplitude modulation (AM) [26], lateral modulation (LM) [63], and spatiotemporal modulation (STM) [17, 59], enabling users to perceive these focal points.

LM and STM are often favored for their efficiency and enhanced perceived intensity [63]. However, they generate continuous tactile shapes by moving focal points of equal intensity along the shape trajectory, overlooking the non-uniform sensitivity distribution of human skin [28] (see Figure 1a).

Tactile illusions, such as the cutaneous rabbit effect (CRE) [19] or funneling effect (FE) [5, 32] present a promising alternative to generate continuous tactile shapes. These techniques only stimulate a few discrete points, but they create the illusion of continuous tactile stimuli between the stimulation points [2, 4, 48, 50, 72]. This would allow for more selective rendering of the tactile shapes (e.g., stimulation points only on highly sensitive areas, with the illusory sensation spanning across the low sensitivity ones).

This paper explores this potential, by providing a systematic comparison between tactile illusions (i.e., CRE, and FE) and STM (i.e., conventional shape rendering technique). More specifically, we compare perceived shape continuity and intensity for tactile shapes rendered across areas of the hand with varying sensitivities, or even across sensitivity areas (see Figure 1b-e). We did this through a two part experiment: in the first part, participants determined the optimal rendering settings for achieving continuous and intense sensations for each independent stimulus (i.e., a given tactile shape with a given technique/illusion). In the second, the participants rated the perceived intensity and continuity of the shapes rendered with the settings they had selected.

Our results (see Figure 1e) confirm that both illusions (CRE and FE) work in UMH but, more importantly, allow us to assess how their intensity and continuity compare against that of conventional techniques (STM). Overall, CRE provides superior continuity and intensity than FE and STM, suggesting its applicability towards rendering more intense and continuous shapes. FE emerges as a comparable or slightly better method for generating continuous tactile shapes, particularly in low-sensitivity areas, while STM provides high perceived intensity. Our findings confirm that tactile illusions work in UMH, derive usable parameter values to use them, and put their intensity and continuity in perspective against common shape rendering techniques (STM). This paves the way for further exploring the use of these techniques to create continuous tactile shapes.

## 2 RELATED WORK

Rendering haptic sensations with Ultrasonic mid-air haptics (UMH) has been studied in numerous works. Here, we first review its working principles and current UMH modulation techniques aimed at achieving continuous and intense shapes. We, however, argue that uniform shape rendering employed by these techniques may not be optimal for inducing continuous and intense sensations, given the non-uniform of sensitivity of different areas of the hand. Second, we focus on the non-uniform sensitivity of the palm and then describe how tactile illusions could provide a feasible alternative for continuous and intense UMH sensations across the skin regions with varying sensitivity.

### 2.1 Ultrasonic Mid-air Haptics, Affected by Skin Sensitivity

Ultrasonic mid-air haptics (UMH) uses Phased Arrays of Transducers (PATs) to generate haptic sensations. Each transducer is driven to focus the acoustic waves from all transducers at the same position, resulting in a high-pressure focal point [9]. Modulation techniques make such focal points perceivable [59] through temporal and spatial variations.

There are three main modulation techniques to create haptic shapes in UMH: Amplitude Modulation (AM), Lateral Modulation (LM), and Spatiotemporal Modulation (STM). AM discretizes the shape into several focal points, presenting them all simultaneously but varying the pressure of each point over time at a given modulation frequency [23] (Figure 2c). LM and STM work on a different principle, retaining the pressure of the points constant, but changing their location. LM uses a similar number and distribution of points to AM, but moves them laterally along the shape to evoke sensations [63] (Figure 2d). STM (Figure 2e) uses a single focal point quickly moving along a densely sampled shape trajectory at a specific drawing frequency $f_d$ [17, 31].

All three techniques have been extensively studied for rendering continuous tactile shapes [18, 34, 36, 64]. AM supports shape rendering [34, 36], but the temporal modulation of multiple points does not constantly use the maximum power the UMH device can deliver [17]. On the other hand, LM and STM offer higher intensity [63] as points are always active, and continuity as the distance [18] between such sampled focal point's placement along the trajectory is small enough [24] to create the sense of continuity.

However, all these techniques ignore hand sensitivity, delivering the same amount of power to each point in the shape, irrespective of the sensitivity of the point it stimulates (see Figure 2c-e, below), which could cause weak stimulation and discontinuities in perception, especially at low sensitivity region. This was, for instance, observed by Vasudevan et al. [69], where tactile shapes '7' and '2' were frequently confused, particularly due to the horizontal line of the '2', which spans across a low-sensitivity area of the hand (see Figure 2b). Moreover, discontinuous tactile feedback can increase cognitive load as the brain works harder to process and "reconnect" each sensation, which can lead to mental fatigue or confusion, especially in tasks requiring fine tactile path guidance [61]. On the other hand, continuous and intense tactile feedback helps guide our movements, particularly for tasks requiring precision.

As such, exploiting the uneven hand's sensitivity remains an underexplored factor which could influence perceived haptic shape intensity and continuity in UMH.

### 2.2 Sensitivity Regions on the Palm

Generally, two approaches have been adopted to investigate the sensitivity of the palm in the haptic domain. One is to explore it through the distribution of mechanoreceptors, and the other one is to empirically derive the sensitivity regions through experiments.

Four main types of mechanoreceptors provide information to the central nervous system regarding touch, pressure, and vibration. They can be classified as Slow Adapting I and II, and Rapid Adapting I (RAI) and II (i.e., Pacinian corpuscle) based on their sensitivity frequency and the receptive field characteristics [11].

The most discussed and studied receptor types in UMH are RAI and Pacinian corpuscle (PC). This is because both LM and STM create sensations by stimulating RAIs and PCs [16, 29, 46, 59] that are sensitive to motion. These two receptors, RAI and PC, however, react to different vibration frequencies. The RAI channel (Meissner's corpuscles) encodes vibrations from 5 to 50 Hz and is sensitive to

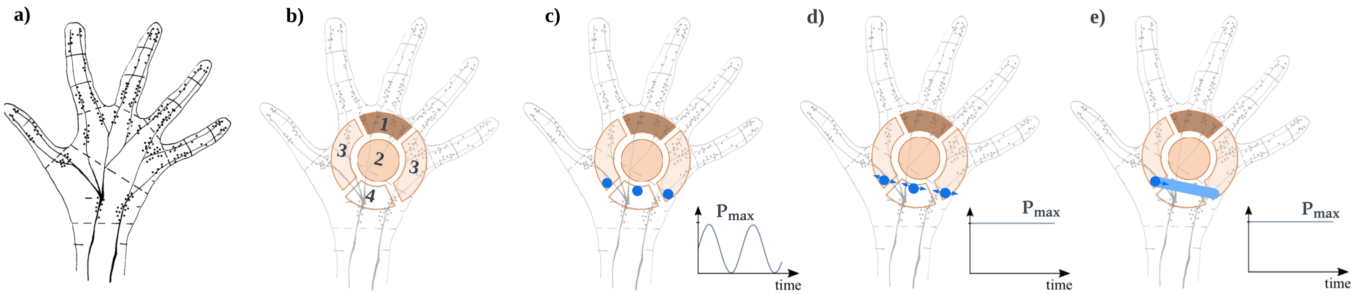


**Figure 2: UMH modulation techniques demonstrate the spatial arrangement of focal points and the pressure of points over time but overlooked the various sensitivity on the palm. a) A typical Pacinian receptor distribution is shown as dots on the hand [60]. b) Empirically derived sensitivity map of the palm in UMH literature based on Messiner's and Pacinian receptor frequency range [69] overlaid on Pacinian receptor distribution. Examples of how c) amplitude modulation, d) lateral modulation (LM), and e) spatiotemporal modulation (STM) work in rendering a line shape on the palm.**

the change rate in the spatial deformation [30]. The PC channel (Pacinian corpuscles) encodes vibrations from a wider frequency range (20 to 1000 Hz [52]). PCs sense vibrations and detect fine textures [30]. Figure 2a [60] shows the typical PC distribution on the human palm. While relevant, its nuance and complexity have made it hard to use such distribution to guide the delivery of UHM sensations.

HCI studies have explored sensitivity regions of the hand leading to simpler, but also more applicable models. For example, Chongyang et al. [9] tested the detection threshold of UMH stimuli based on different hand regions (i.e., palm, root, and the tip of middle finger). Their findings indicate that the perceptual threshold is lowest at the palm and highest at the tip of the finger and concluded that the palm is the most sensitive region to UMH stimuli.

Later research has further outlined the sensitivity regions of the hand [69]. In the study, the authors asked participants to report their perceptions across four palm regions. The results show that the most sensitive area was the top of the palm (above the distal palmar crease, see Figure 2b sector 1), followed by the middle of the palm (sector 2), the sides (sector 3), and the bottom parts (sector 4) of the palm being the least sensitive (see Figure 2b).

In this work, we reuse the palm sensitivity distribution suggested by [69]. As shown in Figure 2b, this mapping not only includes the distribution of Pacinian corpuscles (see Figure 2a, receptors from [60] marked as dots on the hand) but also incorporates the empirical findings from their UMH study (i.e., areas represented as circular sectors in Figure 2b).

## 2.3 The Potential of Tactile Illusions for Shape Perception

Tactile illusions create a sensation of continuity between discrete stimulation points. This could open the possibility of creating intense continuous sensations even if the shape spans across a low sensitivity area, provided that the discrete points used to create the illusion are placed on the sensitive areas. Funnelling (FE) and cutaneous rabbit effects (CRE) are two major tactile illusion techniques for vibration-based tactile feedback.

CRE stimulates the skin at two locations (P1 and P2) at specific time intervals (also known as inter-stimulus onset interval or ISOI), and the illusory sensation is felt in between the points [19]. Several parameters determine the illusion's strength and the sensation's continuity. This includes the burst time (BT, duration of stimulus exposure), inter-burst time (IBT, duration between the sequential two stimuli at P1), and ISOI [54] (see Figure 3b for more details).

FE typically works by simultaneously stimulating the skin at two different locations (see Figure 3b). Intensity transitions from one point to the other (i.e., although more than 2 points can be used), and the total duration (TD) of this transition can be tuned to trigger the illusion of a continuous tactile sensation moving between the points [42, 68].

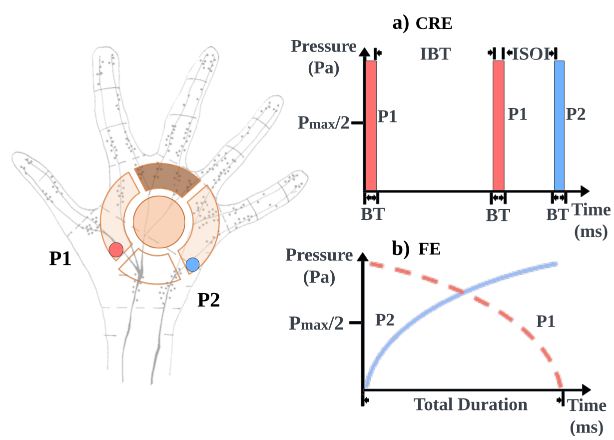


**Figure 3: The CRE and FE producing a horizontal line between points P1 and P2. a) CRE uses 3 taps (AM focal point bursts) over time, two at location P1 and one at P2. b) FE stimulates P1 and P2 simultaneously, modulating their pressure over time.**

Previous works in the general haptic domain (i.e., using vibrators, instead of UMH) attempted to improve haptic rendering using illusions. This includes the studies that facilitate continuous sensation rendering [2, 4, 48, 50, 72], enhance character or pattern recognition using both FE and CRE [2, 66], and assess how tactile illusion directions affect perceived shape continuity [53]. Further studies investigated how high-resolution haptic displays can be created using illusions [8, 65], reducing the number of actuators required [12]. All those studies suggested using tactile illusions to gain refined and high-resolution tactile shapes at low costs, but none has been applied to UMH.

Tactile illusions also work on non-continuous areas of the skin. Researchers have attempted to combine CRE with visual feedback [14, 33], and applied such saltation effect to non-continuous skin (e.g., across left and right arm) [13, 71]. Further research has also indicated that the saltation can be extended to body-worn objects and create an "out of the body" experience [40]. Similar results have been demonstrated using FE [35].

Recently, illusions have began to be explored in the UMH domain. These studies focus on recreating these continuous illusions as lines across the palm [72], or between hands [49], with point studies comparing lines rendered by FE and LM [42].

However, no systematic comparison between tactile illusions (i.e., CRE and FE) and conventional UMH techniques (e.g., STM) has been conducted, especially in terms of perceived intensity and continuity. As such, we still do not know how CRE and FE perform in terms of continuity and intensity, either compared to each other or to conventional UMH techniques (e.g., STM). We also do not know what timings and parameters (e.g., see Figure 3) are required to reproduce these illusions with UMH. It is unclear if the palm's sensitivity affects the effectiveness of these techniques (illusions or STM) and if in any scenarios using illusions could be better than standard modulation techniques or vice versa.

## 3 EXPERIMENT

This paper focuses on addressing four main questions.

- Do CRE and FE work in UMH, and what parameters should be used to trigger continuous and intense illusions?
- How do CRE and FE compare with each other, but also against STM, in terms of perceived continuity and intensity?
- How does the palm's sensitivity influence STM, CRE, and FE in terms of continuity and intensity, and which technique works better in which scenario?
- Does rendering direction across different sensitivity areas influence the perceived continuity and intensity of the CRE, FE and STM techniques?

We conducted an experiment to address these questions. We use the experimental approach in prior research [3, 20, 45], as to allow participants to explore and evaluate the optimal stimuli based on a given criteria (i.e., stimulus achieving highest continuity and intensity). The experiment has two parts. The first part allows participants to explore and select the *optimum* parameters (e.g., BT, IBT for CRE, see Figure 3) for each given stimulus (i.e. combination of a given tactile shape and technique).

In the second part, participants rate the perceived intensity and continuity of the optimal stimuli they designed during the first part. This allows us to compare stimuli across techniques/areas/directions on a best-case scenario (e.g., can CRE outperform STM in a low sensitivity area, even when the best parameters for that technique, area and participant are used?).

The subsections below detail our implementation of the techniques and choice of tactile shapes, and then describe our experiment design and procedures. Detailed analysis and results from the experiments can be found in section 4.

### 3.1 Choice of Haptic Shapes

Straight lines were selected as fundamental primitives to both preliminarily test our assumptions and establish a theoretical foundation for more complex shape construction (i.e., future studies could build other shapes by concatenating line segments). This choice minimized design complexity while preventing curvature or salient points from influencing intensity and continuity perception [37].

We used 4 straight lines as haptic shapes: two targeting areas of the hand with specific sensitivities (L and H, in Figure 4), and two spanning across areas of varying sensitivity and following different rendering directions (HL and LH, in Figure 4).

Our first *haptic shape* uses a horizontal line across the lower part (L) of the palm (see Figure 4b). This shape would theoretically benefit illusions (CRE and FE) over STM, as the start and end points (used by illusions) lay on higher-sensitivity areas, while most of the intermediate points in the STM stimuli would fall on low sensitivity areas.

In contrast, the second shape is a horizontal line higher up (H) on the palm (Figure 4a), predominantly spanning the high sensitivity region. This is the exact opposite case than before, potentially favoring STM over illusions.

Vertical lines were selected for the third and fourth haptic shapes (see Figure 4c-d), to understand how varying sensitivities affect each technique. STM would generate focal points across the palm (varying sensitivity), while illusions target one high-sensitivity area and one low-sensitivity area. The stimulus was applied in both directions, to understand if the order of the stimuli (e.g., first stimuli being stronger than last) affected overall perception. Finally, all line lengths were scaled according to each participant's palm size (physically measured during the experiment), so that the stimuli spanned across similar areas on their hands. Overall, H and L were used to test the effect of different techniques at different sensitivity regions, and HL, and LH were used to test techniques' effects across varying sensitivity regions.

### 3.2 Implementation of the Haptic Techniques

All three haptic techniques were implemented using ultrasonic mid-air haptics. For CRE, we selected the simple cutaneous rabbit [35, 40] line formation, where a total of 3 taps (i.e., focal points with amplitude modulation frequency of 200 Hz [22, 42, 69]) were generated at the two extremes of the line (positions P1 and P2 in Figure 3a). The first tap (focal point) is created at P1 for a duration BT. The second tap is again created at P1 after IBT. Finally, after ISOI, the last tap is created at P2 for a duration BT. In the experiment, participants were allowed to tune these 3 parameters, with BT ranging between 1 to 100 ms [54], IBT between 1 to 1000 ms, and ISOI between 1 to 100 ms [35, 40].

To render FE, we generated two simultaneous AM focal points, each placed at one extreme of the line (P1 and P2) and both with modulation frequencies of 200 Hz. Both tactile illusions employed

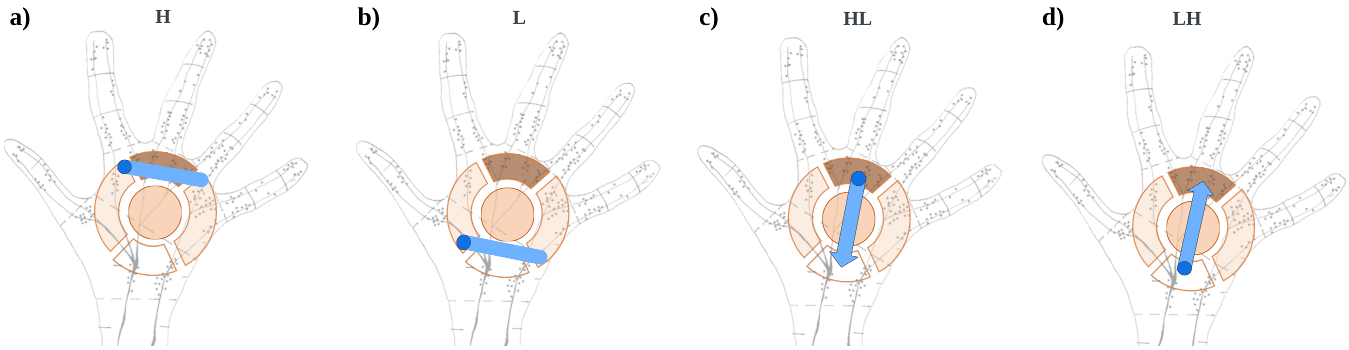


**Figure 4: Summary of *Haptic Shapes* used: a) A Horizontal line higher up (H) on the palm is rendered at the most sensitive region. b) A Horizontal line lower down (L) on the palm is rendered at the least sensitive region. c) A vertical line is rendered from high to low-sensitivity region (HL). d) A vertical line is rendered from low to high-sensitivity region (LH).**

200 Hz AM, identified as the "sweet-spot" frequency in this technique [22, 42, 69] to reduce complexity in parameter adjustments, study duration, and participant fatigue. This also aligns our method with previous 200 Hz AM-driven FE [42] that reliably produce a continuous sensation, facilitating direct comparison when introducing CRE. The amplitude change between the two points is based on the logarithmic function in [42] (see Figure 3b). In the experiment, participants were allowed to change the total duration (TD) of the amplitude change between 1-5000 ms [42].

Finally, STM stimuli used a single focal point, to ensure maximum perceived intensity [59]. The sampling rate was kept at 100 positions to avoid sampling effects [18]. During the experiment, participants were allowed to adjust $f_d$ between 1-20 Hz as to ensure maximum perceived intensity [1, 58], and effectively stimulate RAI and SAI receptors [42]. Moreover, previous research has shown that frequencies below 15 Hz with small sampling distances (<1 mm) reduce vibratory perception while producing a strong, continuous static sensation [43]. Staying within this range also mitigate the issue related to device heating and intensive phase changes at higher frequencies, preserving performance and ensuring consistent stimulus delivery throughout the experiment [58].

All stimuli were generated at 15 cm above the PAT, as to avoid discrepancies due to location [55] and all techniques were generated with the maximum pressure the device can offer [58].

Each technique's parameters (e.g., IBT, $f_d$) were adjustable using sliders presented in the GUI. One thing to notice is that CRE required three parameters (i.e., BT, IBT, ISOI), while FE and STM only required one (i.e., TD and $f_d$, respectively). To avoid inter-technique bias, all techniques were provided with three sliders to adjust in the UI, with the 2 additional sliders for FE and STM allowing different step sizes for the parameter adjustment. Correspondingly, the step sizes used for the sliders are: STM (1 Hz, 2 Hz, and 3 Hz); FE (100 ms, 300 ms, and 500 ms); and CRE (10 ms [BT], 100 ms [IBT], and 10 ms [ISOI]).

## 3.3 Experiment Design

When comparing perception of haptic shapes across techniques, the choice of the parameters used to render each shape has great effects on the perception of the UMH stimuli [1, 21]. Identifying *optimum* parameters has been subject to intense research for AM [55] and STM [58, 59], and remains unexplored to CRE or FE in UMH.

A systematic sweep across all parameters for each technique (e.g., testing any combination of BT, IBT and ISOI, for CRE) would have led to combinatorial explosion. This would not only be untreatable within the scope of this work, it would also be unnecessary until we first check whether CRE and FE can become a feasible alternative to render continuous UMH tactile shapes.

Thus, our experiment was designed to allow each participant to determine the *optimum* parameters for each shape and technique, that are the parameters resulting in the highest intensity and continuity, for that specific participant. As such, when comparing stimuli across users, techniques or sensitivity areas/haptic shapes, we can ensure that the stimuli compared are the best stimuli that could be found for that shape, technique and participant.

With that in mind, the experiment follows a within-subject design with two independent variables: the haptic *techniques* (CRE, FE, and STM), and our four *haptic shapes* (see Figure 4), leading to 12 combinations of technique and shape. The two dependent variables were the ratings of the intensity and continuity.

During the first part of the experiment, participants tuned the parameters for their 12 stimuli, structured as 3 blocks (one per technique). Within each block, participants were instructed to adjust the 3 sliders configuring the technique via a graphic user interface (GUI), until the stimulus generated felt most intense and continuous (i.e.,"continuous rather than a series of discrete points or intermittent stimulation"). Participants confirmed that they understood the criteria before starting the experiment.

A maximum of two-minutes were allowed for participants to adjust each shape in a block, with all participants indicating that such time was enough to find the *optimum* parameter settings. Upon changing a parameter, a 1-second gap was allowed (i.e., no stimulation) before presenting the next stimulus. This was done to minimize sensory bias [55] and prevent enhancement effects (i.e., a stimulus can enhance the perceived intensity of the next, for gaps of less than 500 ms [70]).

The block order is counterbalanced by a Latin square design for each participant. Participants were told that the adjustable parameters used in each block would be different and thus not applicable to other blocks. We did not disclose which technique was used in each block, the sensitivity regions, or the stimulus rendering directions to minimize experimental bias.

At the beginning of each block, an extra test was added for participants to familiarize themselves with the parameter settings in the new technique. The shape of the training sample is counterbalanced across participants using a Latin square design (i.e., 1st, 5th, 9th participants get the same shape at the beginning of each technique block), rendered using the corresponding technique for that block. The remaining four tests (shapes) were randomized. A one-minute rest was provided after each block. In total, there were 3 blocks * (4 shape tests + 1 extra training) = 15 tests for each participant.

In the second phase of our experiment, participants evaluated self-created stimuli for perceived continuity and intensity. Intensity ratings employed the absolute magnitude estimation method [25, 55], using a user-defined scale from 0 to infinity, and were later normalized between 0 and 1 aligning with established literature practices [17, 18, 58, 59]. We implemented an unbounded rating scale to enable participants to rate using their preferred numerical values, including fractions. This approach allows participants to rate based on their own scale and use numbers that make sense to them personally rather than fitting their perception into predefined categories. Moreover, the continuous nature of the data collected through an unbounded scale allows for more detailed analysis and interpretation. This means we can capture subtle differences in perceived intensity induced by the techniques we compared that bounded scales may miss.

Perceived continuity was evaluated using a 9-point Likert scale slider, again aligning with prior work [42]. Participants engaged with a fixed set of 3 training stimuli before actual ratings to facilitate familiarity with stimuli, testing procedures, and rating scales. We used 3 lines applied at H (1 per technique), with the following parameters: STM (20 Hz); CRE (100 ms BT, 1000 ms IBT, 100 ISOI); FE (5000ms TD). Please note that these training samples were not used in the analysis.

We repeated each stimulus presented in the second part of the experiment three times in randomized order for a total of 39 ratings (3 training + 4 shape tests * 3 techniques * 3 repetitions). Each stimulus was displayed for 5 seconds. Regular 1-minute breaks were provided every 10 tests to reduce fatigue [59].

## 3.4 Experiment Setup

In our experiment, we employed the OpenMPD platform [41], utilizing its software (GS-PAT algorithm at 10 KHz [51]) and hardware (UMH device equipped with 256 transducers, operating at 40 KHz and 18 V). The UMH device was placed within a sound-absorbing foam-covered black box, featuring a 12 cm by 12 cm aperture on top for delivering haptic stimuli to participants' hands. Participants were provided with adjustable seating and elbow support to ensure alignment and maintain a steady 15 cm distance, enhancing comfort, reducing fatigue, and promoting stable flat hand positioning throughout the experiment (i.e., ensuring effective focal point focus on the palm surface).

We utilized noise-canceling headphones playing pink noise to isolate participants from any ambient and device-generated noises.

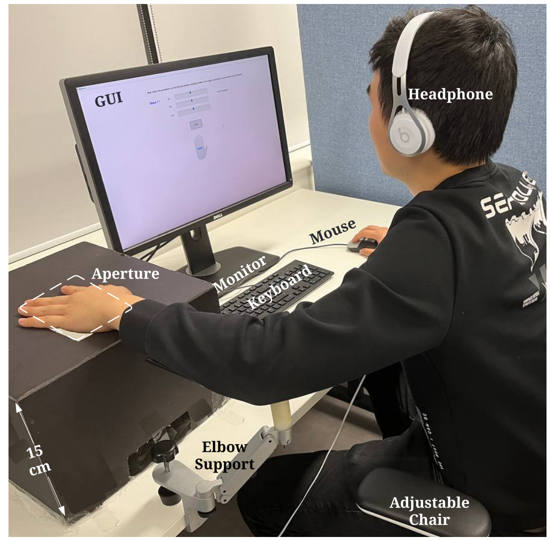


**Figure 5: The setup for the experiment. A Participant seated on an adjustable chair with noise-canceling headphones interacted with a GUI on a desk monitor. At the same time, the participant's hand engaged with an ultrasonic mid-air haptic device placed in a black foam box.**

Participants used their dominant hand to operate a mouse, facilitating parameter selection and response recording through a GUI displayed on a monitor positioned in front of them [58, 59, 71]. For a visual representation of the experiment setup, please refer to Figure 5.

## 3.5 Participants and Experimental Procedure

The experiment involved 21 participants (12 females, mean age $\pm SD$: 29.5 ± 9.4). Three participants had prior experience with UMH. Upon each participant's entry into the room, the setup was adjusted to their needs, including chair, box, and elbow support adjustments. An introductory video was presented to each participant to explain the experiment's procedure, GUI, tasks to be completed, and the rating scales.

Additionally, temperature measurements were conducted at the beginning of the experiment and during rest stages on the participant's palm to ensure a temperature above 35°C, to avoid loss of sensitivity due to cold [58].

Next, participants were asked to start the first part of the experiment and find the *optimum* parameter settings for each technique and haptic shape. After completion, participants were required to rest for 2 minutes before proceeding to the second part of the experiment. Finally, participants were asked to perceive each of the optimal stimulus they had created for 5 seconds and to rate its perceived intensity and continuity. The overall study duration was 45 minutes. At the end of the experiment, each participant received a £10 Amazon voucher for their participation. Ethical approval was obtained from our local ethics committee, and all participants gave informed consent.

**Table 1: Parameter ranges chosen by participants, clustered in 2 main categories per parameter (C1 and C2), together with their perceived intensity and continuity ratings (medians [lower confidence interval (CI), upper CI]) and percentage of participants selecting each cluster.**

| | Cluster 1 (C1) | | | Cluster 2 (C2) | | | |
|---|---|---|---|---|---|---|---|
| Parameter | Value (Mean ± STD) | Continuity (Median [95%, lower CI, upper CI]) | Intensity | Value | Continuity | Intensity | % C1 |
| CRE BT | 89.9 ± 12.0 | 0.54 [0.38, 0.70] | 0.57 [0.36, 0.71] | 25.4± 16.9 | 0.45 [0.37, 0.54] | 0.30 [0.21, 0.41] | 64% |
| CRE IBT | 37.3 ± 66 | 0.75 [0.64, 0.85] | 0.64 [0.45, 0.75] | 588.2 ± 259 | 0.23 [0.12, 0.38] | 0.23 [0.12, 0.38] | 85% |
| CRE ISOI | 8.38 ± 12.2 | 0.49 [0.46, 0.61] | 0.44 [0.31, 0.52] | 71.6 ± 20.63 | 0.46 [0.29, 0.62] | 0.42 [0.26, 0.61] | 67% |
| FE TD | 1493 ± 947 | 0.57 [0.55, 0.625] | 0.25 [0.222, 0.23] | 4146 ± 909 | 0.55 [0.52, 0.625] | 0.25 [0.22, 0.3] | 54.1% |
| STM $f_d$ | 19.0 ± 1.52 | 0.55 [0.5, 0.57] | 0.56 [0.5, 0.57] | 9.3 ± 4.6 | 0.53 [0.44, 0.57] | 0.56 [0.53, 0.59] | 82.1% |

# 4 RESULTS AND ANALYSIS

Our results are structured in two main sections. The first section analyzes the parameter values chosen by participants for each technique, when designing their *optimum* stimuli. This analysis is important given the relatively lack of research on the use of tactile illusions for UMH. This first subsection will allow us to confirm participants' ability to select reasonably optimized parameters, but also provides HCI practitioners with a preliminary exploration of parameter values to use when applying these techniques with UMH.

The second section then examines how our two key variables, namely *techniques* and *haptic shapes*, influence users' perception of intensity and continuity. By analyzing these factors, we can derive the best technique in general, and also understand how different sensitivity regions (L and H) and rendering directions (LH, and HL) impact the effectiveness of techniques on perceived intensity and continuity.

## 4.1 Analyzing Participants' Parameter Choices

We collected a total of 252 *optimum* parameter settings (21 participants x 3 techniques x 4 haptic shapes) from all participants during the initial phase of the experiment, and 756 normalized ratings of perceived continuity and intensity (21 x 3 x 4 x 3 repetitions), during the second phase.

We first analyzed the parameters chosen by participants across the complete sample dataset (252 stimuli). For CRE, parameter values were BT (mean±std: 66.7±33.9 ms), IBT (122.6 ms±231.8 ms), and ISOI (29.44±33.6 ms). It seems that participants always chose IBT values larger than ISOI (required for the technique to work [40]). For FE, participants chose a TD of 2724.7±1616.9 ms FE, close to the range suggested in [42]. Finally, participants chose a mean $f_d$ range for STM of 17.2±4.42 Hz, well within *optimum* parameters for this technique [58].

Even if within reasonable ranges, we wanted to further explore the spread of the parameter values chosen by participants, as to further refine the *optimum* value range for each parameter, as well as to assess participants' ability to choose good parameter values and the influence of each parameter on perceived intensity and continuity. To achieve this, we used the elbow method [62] and silhouette scores [27] to cluster our data according to each parameter, and report the 2 main clusters per parameter (C1 and C2, with C1 always being the *majoritarian* choice). Beyond parameter values used for each cluster (C1 and C2), we report the median intensity and continuity per cluster and the percentage of participants that chose C1.

These clustering results are summarized in Table 1. Parameters BT and IBT (from CRE), TD (FE) and $f_d$ (STM) all seem to have very strong influences on both continuity and intensity ratings, with C1 always having greater or comparable (intensity/continuity) scores than C2. Also, participants consistently chose parameter values from this better range (i.e., 54-85% chose C1), which both validates their ability to correctly refine the stimuli during the experiment and increases our confidence that the values in C1 are recommendable parameter ranges for these 5 parameters (and techniques) in terms of intensity and continuity. It worth noting that although the perceptual difference in two FE clusters is not obvious (54%), we identified the parameter ranges used in these clusters are close to two *optimum* parameter values (2.5 s and 4 s) tested in [42].

A further analysis was performed, clustering parameter choices for each haptic shape. This did not provide further significant insights, but is included in Tables 2-6 in supplementary material for completeness.

## 4.2 Data Processing Before Statistical Analysis

The resulting perceived intensity and continuity ratings seemed unlikely to follow a normal distribution across various factors, including techniques, tactile shape, and interaction effects (Shapiro-Wilk, $p < 0.05$). The sphericity assumption (Mauchly's test [39] with $p < .05$) was also violated when looking at the homogeneity of variances of the perceived intensity and continuity ratings across different techniques or tactile shapes. No outliers were found when investigating the effect of technique, sensitivity, direction, and their joint effects.

We used Friedman's tests, known for their robustness [6], and their freedom from normality and sphericity assumptions [7, 15]. These tests were utilized to evaluate the impact of techniques, tactile shape (skin sensitivity/ rendering direction), and their interaction effects on perceived intensity and continuity. Effect sizes were assessed using Kendall's $W$ Value [67]. Post-hoc analyses were conducted using Conover's tests [10]. Visual summaries and essential statistical parameters are presented in the remainder of this paper. Detailed statistical reports and post-hoc analyses are available in the supplementary material (Tables 7-19).

## 4.3 The General Effect of Rendering Techniques

Figures 6a&b summarize our participants' perceived continuity and intensity ratings per technique. Ratings for CRE and FE are greater than 0 and show small confidence intervals, confirming that both

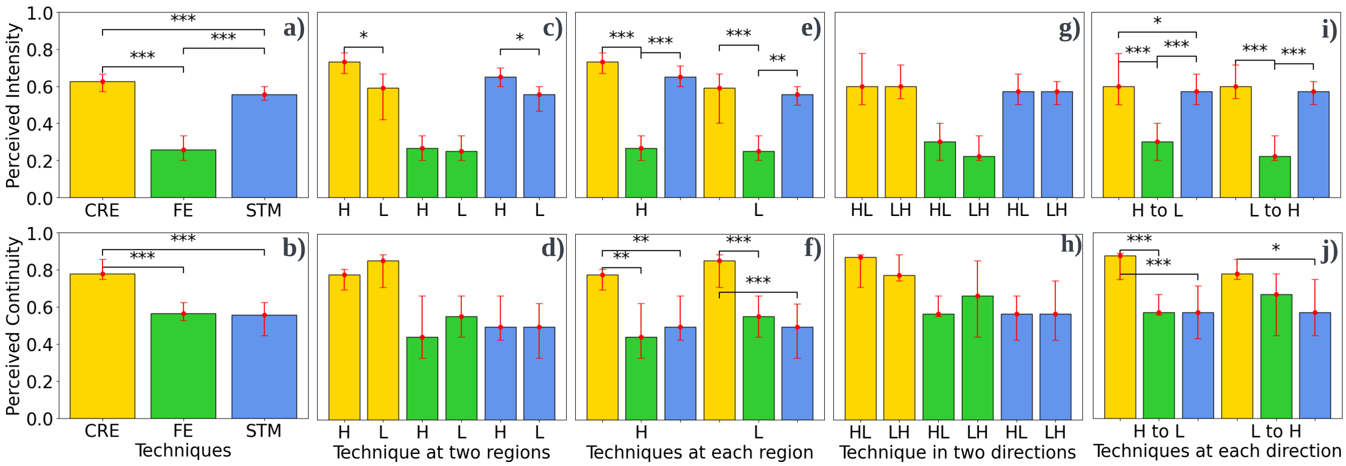


**Figure 6: Perceived intensity and continuity median and confidence interval compared at different conditions. a-b) Comparing three techniques (CRE, FE, and STM) in general. c-d) Comparing the same technique at two sensitivity regions (H and L). e-f) Comparing three techniques at the same sensitivity region (High and low). g-h) Comparing the same technique in two rendering directions (HL and LH). i-j) Comparing three techniques in the same rendering direction (HL and LH). * indicates *p*<=.05. ** indicates *p*< .01. *** indicates *p*< .001.**

illusions can be produced with UMH. Similarly, certain disparities can be found between intensity and continuity ratings, indicating that these two sensations are indeed different.

Our results also revealed significant effects of techniques on perceived intensity ($\chi^2(2)$=95.717, $p$ < .001, $W$=0.570), and continuity ($\chi^2(2)$=20.091, $p$ < .001, $W$=0.120). In general, CRE performed significantly better than other techniques in terms of continuity ratings, and offers significantly higher intensity ratings than STM.

FE while providing slightly higher perceived continuity, however, offers significantly lower perceived intensity, with significance marked as asterisks in Figure 6a&b. Thus, while the FE applies in UMH, this does not seem like a recommendable alternative to STM.

## 4.4 Techniques Performance per Sensitivity Region (L, H)

Shapes H and L (Figure 4a-b) target two different sensitivity regions (high and low, respectively), and we use them to understand if sensitivity affects the creation of intense and/or continuous sensations.

The ratings given for H (high-sensitivity area) showed significantly higher perceived intensity ($\chi^2(1)$=6.564, $p$=0.01, $W$=0.104) compared to L (the Low-sensitivity). This corresponds to the sensitivity distribution shown in Figure 4 and findings from previous work [69], and logically corresponded to the sensitivity map shown in Figure 2.

In terms of continuity, illusion techniques ratings offered higher perceived continuity in the low sensitivity region, suggesting the effectiveness of illusions in bridging tactile sensitivity. However, no significant effects of palm sensitivities were found ($\chi^2(1)$=0.643, $p$ = 0.423, $W$=0.010).

Next, we analyzed the interaction effect of palm sensitivity and techniques on the users' intensity ($\chi^2(5)$=54.207 $p$<.001, $W$=0.516) and continuity ($\chi^2(5)$=22.105, $p$<.001, $W$=0.210) perception. We do this from two perspectives, first by comparing L and H ratings within each technique (i.e., Figure 6c-d), and then by comparing performance across techniques for each sensitivity area (i.e., Figure 6e-f).

We first looked at the ratings of each sensitivity region (H or L) for each technique (Figure 6c-d). The intensity is significantly higher ($p$ <.05) for CRE, and STM when stimuli are applied in the high sensitivity region (H), which corresponded to previous assumptions. However, no significant differences could be found between H and L for FE. This could simply be due to the fact that FE is perceived as extremely weak. Nevertheless, slightly higher intensity can be observed for FE ratings when applied in the high-sensitivity region.

Tactile illusions appeared to enhance continuity in low-sensitivity regions (Figure 6d), supporting our assumption that they help bridge the sensitivity gap at L while providing comparable or even greater continuity perception than at H. In contrast, STM seemed to provide slightly higher continuity at high sensitivity region.

We then compared performance across techniques, in each sensitivity area (Figure 6e-f). Significant intensity rating differences were found between the FE and the other two techniques ($p$ < .001) at all sensitivity regions, indicating its poor performance at providing higher intensity. Significant differences were also found in continuity ratings between CRE and other two techniques, confirming its capability in offering comparable, more intense (Figure 6e), and significantly higher continuous sensation, irrespective of the applied sensitivity regions (Figure 6f).

As per FE and STM, this analysis seems to indicate that a trade-off between intensity and continuity exists for these two techniques (i.e., STM provides higher intensity, while FE provides slightly better continuity), especially at low-sensitivity region. This indicates that haptic designers should only be particularly concerned about this trade-off when stimulating areas of low sensitivity.

## 4.5 Rendering Direction Effects across Sensitivity Areas (LH, HL)

We analyzed the effects of rendering direction on intensity and continuity in general, for stimuli spanning across areas of varying sensitivity (LH, HL). The differences between LH and HL did not show statistical significance, neither in terms of intensity ($\chi^2(1)$=0.018, $p$=0.893, $W$=0.00028) or continuity ($\chi^2(1)$=0.153, $p$=0.696, $W$=0.0024).

We then analyzed the interactions between stimulus' direction and techniques on the users' intensity, and continuity perception. Significant interaction effects of stimulus rendering direction and techniques were found on perceived intensity ($\chi^2(5)$=50.070, $p$<.001, $W$=0.477) and continuity ($\chi^2(5)$=13.137, $p$=0.022, $W$=0.125). As in section 4.4, we explore this effect from 2 perspectives (i.e., across areas, and across techniques).

Post-hoc analysis for the same technique rendered at different directions (L first or H first) demonstrated no significant differences. Since rendering direction does not necessarily affect perception, this might reduce one confounding factor for practitioners designing stimuli using these techniques. Such results contradict prior findings on the effects of rendering direction on continuity [53], but this might be due to the use of different areas (i.e., elbow vs palm) or technologies (i.e., vibrators vs UMH).

Figure 6g-h explores these effects by looking at how the ratings of each independent technique were affected by direction (LH or HL). Generally, a higher perceived intensity was achieved when the stimulus was applied from a high to low sensitivity direction. This could be because participants pre-determined stimulus as stronger immediately after perceiving a relatively stronger stimulus at the high-sensitivity region. In any case, none of our paired comparisons showed any statistical significance, leading us to conclude that rendering directions are not crucial in terms of continuity or intensity, for the same stimuli we used across sensitivity areas.

Finally, Figure 6i-j compares ratings of all techniques at each rendering direction (HL and LH). Results for CRE in terms of perceived intensity ($p$<.001), and continuity ($p$<.001 for H to L and $p$=0.016 for L to H) were again better than STM, especially when stimuli were rendered from high to low sensitivity region. This again indicated that CRE can be a much better alternative to STM when the stimuli are rendered across sensitivity regions (i.e., especially for tactile shapes spanning across sensitivity regions).

Generally, FE demonstrated slightly higher continuity and STM provided higher intensity, while CRE provided much higher intensity and continuity.

# 5 DISCUSSION

In this section we summarize the findings derived from our exploration, using them to provide guidelines for practitioners interested in using CRE and/or FE with UMH, as well as identifying limitations and future opportunities for research, building on our results.

Our study systematically compared the effectiveness of tactile illusions, cutaneous rabbit effect (CRE) and funneling effect (FE), against spatiotemporal modulation (STM) in ultrasonic mid-air haptics (UMH).

We found that CRE generally outperformed both STM and FE in delivering comparable intensity or even significantly higher intensity and continuity in the tested parameter ranges, especially across sensitivity regions. This has made CRE a promising alternative for rendering continuous tactile shapes. FE, while offering slightly higher perceived continuity, lacked the intensity needed for robust shape perception, limiting its practical applicability. Additionally, our findings confirmed that palm sensitivity significantly affects perceived intensity, with higher sensitivity regions leading to stronger sensations, while rendering direction had negligible effects on perception.

## 5.1 Findings and Implications

### 5.1.1 *Effects of Tactile Illusions:*

First of all, our results confirm that both CRE and FE illusions work in UMH. Our analysis of participants' choices when designing their *optimum* haptic shapes has for the first time allowed us to identify parameter ranges that seem to lead to higher perceived intensity and continuity (i.e., IBT, ISOI and TD, see Section 4.1), which can facilitate future design and usage of these techniques. We also derived recommended parameter ranges (i.e., BT = 89.9±12.0 ms; IBT = 37.3±66; ISOI = 8.38±12.2; TD = 1493±947) to design such stimuli.

Secondly, we put the performance of these illusions in perspective against that of conventional UMH techniques (STM). This clearly shows that, CRE illusion worked at bridging sensitivity gaps, especially across sensitivity regions, and has led to comparable and significantly higher intensity and continuity ratings irrespective of the rendering directions, and applied sensitivity regions. While the FE illusions worked and provided higher perceived continuity, they also provided much lower intensity ratings, suggesting that FE might not be an *optimum* choice to generate continuous [42] and intense UMH shapes. The extremely weak FE stimuli may also be the reason why it, as a tactile illusion, did not provide comparable continuous feedback to CRE.

Our results consistently revealed a continuity/intensity trade-off exists between FE and STM (i.e., FE better continuity; STM higher intensity), when creating stimuli at low sensitivity area, or across sensitivity areas (LH). As such, practitioners should consider which parameter is more crucial for their application (i.e., continuity or intensity), before choosing one technique or the other.

Since CRE generally provided higher continuity and intensity ratings in all cases (rendering direction and sensitivity region), with much fewer sampling positions (STM: 20 Hz * 5 seconds * 100 sample positions = 10000 positions, CRE: 12 repetitions generally in 5 seconds, 12*3 taps = 36 positions), it stands as a potential replacer to STM. Such advantages open exciting opportunities when designing haptic shapes spanning across multiple sensitivity areas by deploying CRE or combining it with STM.

For instance, this technique can be used to achieve low-cost, fine tactile path guidance [61], promoting continuous line feedback, mitigating discontinuities or interruptions in instructions, thereby enhancing precision. Additionally, it helps reduce cognitive load, which can mitigate mental fatigue and confusion, especially in tasks requiring fine motor control.

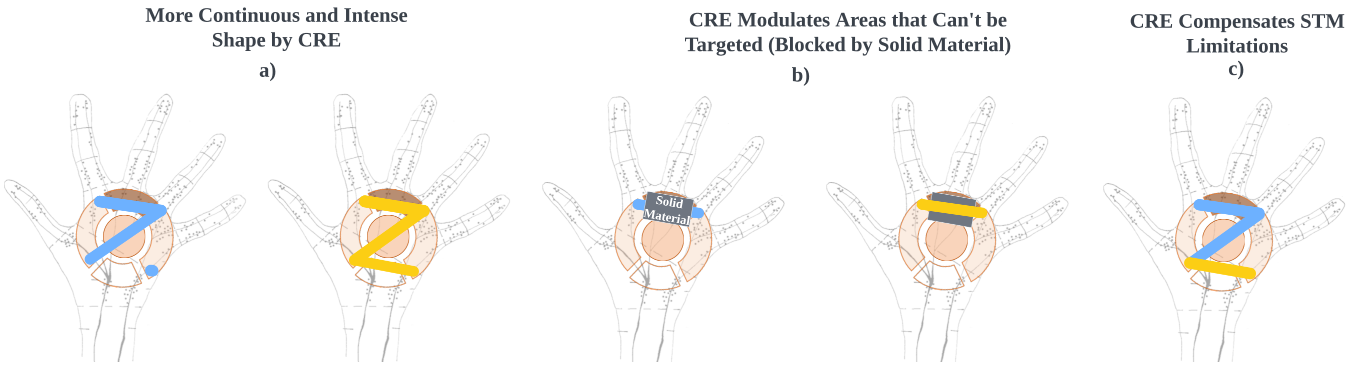


**Figure 7: Scenarios CRE, could enhance haptic perception. (a) Comparison of haptic patterns rendered by STM (blue) and CRE (yellow) in terms of shape continuity and intensity, demonstrating how CRE provides clearer shape perception in remote haptic communication. (b) CRE (yellow) enables continuous line sensations even when an object obstructs the area, whereas STM (blue) is interrupted by the obstacle. (c) CRE combined with STM to enhance stimuli present.**

Moreover, for the previously mentioned example in [69], since CRE provides significantly higher perceived intensity and continuity than STM within the tested STM range, whole parts or the lower horizontal line of the '2' could be rendered using CRE for improved intensity and continuity (see Figure 7a), which could improve line perception across this area, potentially improving shape recognition. This can also be applied to remote communication [47], where two users exchange haptic patterns. In this case, the integration of CRE with its *optimum* parameters enhances the perception of shapes transmitted from a loved one [47], making the experience more aroused [59], clear, and expressive.

Similarly, figure 7b illustrates a scenario in which users can perceive a designed stimulus on their palm even when a solid obstacle blocks the targeted area. This effect, achieved through illusory tactile bridging, is particularly useful in situations where users need to receive haptic information while an object is in the way. This technique also eliminates the need for complex algorithms, such as the boundary element method [38, 44], to enhance sensation by computing and directing wave scattering on the object mesh and to the hand. As a result, it enables the generation of intense and continuous sensations while significantly reducing computation load. Finally, Figure 7c depicts a scenario where our approach combines with traditional modulation techniques to avoid STM limitations (i.e., hard to target low or across sensitivity regions) for various pattern creation. Although these effects require further validation through extensive studies, they represent just a few of the many possibilities unlocked by our findings. This work paves the way for future applications that could redefine haptic interactions in both virtual and physical environments.

#### 5.1.2 *Effects of Skin Sensitivity and Rendering Direction:*

Our results also validated that the skin sensitivity region where the stimuli are applied is important. We revealed significantly higher perceived intensity when stimuli rendered by different techniques were applied at high sensitivity region, and further validated the previous sensitivity map derived [60, 69]. This finding helps future designers in optimizing balanced intensity stimuli, and informing, and reducing confounding factors when researchers design studies in UMH that are related to palm sensitivities (e.g., testing the designed stimuli intensities within the same sensitivity region for fair comparison). Our findings can also be potentially deployed to other haptic devices if they share similar vibrational properties to UMH stimuli.

Our findings also seem to challenge some of our own assumptions, which might also be informative to other practitioners. We did not find a significant effect of skin sensitivity regions on perceived continuity in the same technique. Two possible reasons exist. First, since tactile illusions such as CRE and FE bridged the sensitivity gap at L, it reduced differences in continuity ratings between H and L regions and even promoted continuity ratings. Second, while STM produced slightly higher continuity ratings at H, as expected, the difference between H and L was not statistically significant. This may be because perceived continuity was extremely low (i.e., felt as extremely discontinuous) in both regions (see Figure 6d), making differences difficult to detect. Notably, CRE effectively addressed this issue by significantly promoting perceived continuity across sensitivity regions, enabling more continuous and intense shape perceptions.

The effects of rendering directions were, in general, much smaller than expected, which can facilitate stimuli design by removing unnecessary confounding factors.

### 5.2 Limitations and Future Works

While our study confirms that CRE and FE illusions are effective, identifies CRE as a viable alternative to STM (i.e., CRE) for generating intense and continuous haptic shapes, and provides practical recommendations for their integration (e.g., combining them to enhance tactile shapes in areas where STM alone is insufficient), Our findings are still limited by their exploratory nature (i.e., the techniques, parameters, haptic shapes, and sensitivity regions used), all of which warrant further investigation. For example, further studies should investigate STM $f_d$ above 20 Hz and explore a wider range of AM frequencies. These parameters could not be tested in the present experiment due to the performance limitation, task complexity, extended testing durations, and the risk of participant fatigue. Thus, while the "*optimum*" parameters identified in our study represent the best-performing settings among those tested for each shape, technique, and participant, they should not be interpreted as "absolute" or "global" *optimum* across entire parameter space. Instead, they serve as a foundation for broader parameter exploration, an essential step toward identifying global *optimum* parameter ranges.

Also, the generalizability of the recommended parameters should be tested beyond the line segments, addressing other shapes such as circles, letters, or dynamic forms. Even then, our derived parameter setting can already offer potential for designing sparse feedback systems, such as tactile information delivery [47, 57], navigation [61] or menu selection [56] (e.g., up/down/left/right line feedback).

Additionally, the relationship between *optimum* parameter values and the distance between the extreme points of the illusion must be further investigated to ensure their effectiveness for general line segments (i.e., for a FE stimuli along a line segment of half the length, the value of TD might need to also be halved).

Our findings indicate that increasing perceived continuity and intensity in shape perception does not necessarily improve perceived intensity homogeneity in the shape. This suggests that intensity imbalance in global shape perception may persist. However, CRE could enhance intensity and continuity, making shapes more perceivable. It may also serve as an alternative solution by combining CRE with STM to minimize intensity differences across sensitivity regions (e.g., as shown in Figure 7c). However, future studies are required to further explore relevant parameter settings and reinforce these designs.

## 6 CONCLUSION

In this paper, we systematically compared the effectiveness of different haptic techniques (i.e., CRE, FE, STM) in achieving continuous and intense sensation at palms of non-uniformly distributed sensitivity. Additionally, we investigated the effectiveness of those techniques under different skin-sensitivity regions and stimulus-rendering directions. Our findings indicate that CRE can indeed be leveraged in ultrasonic mid-air haptics (UMH), and while skin sensitivity significantly affects the perceived intensity strength, the rendering direction of the stimulus does not seem to matter. Moreover, we found that CRE consistently provides comparable or higher perceived shape intensity and significantly greater continuity across different sensitive skin areas and rendering directions. In contrast, tactile illusions like FE are particularly effective at maintaining shape continuity across various skin regions. This indicated that tactile illusions could act as a potential replacement for STM to achieve better shape formation in UMH by filling the sensation gaps between the non-uniformly distributed sensitivities on the palm. Our research opens the opportunity for continuous and refined shape rendering in UMH, and encourages designers in the haptic domain to further explore and facilitate the use of tactile illusions.

## ACKNOWLEDGMENTS

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101017746, project Touchless. This project has also received funding from EPSRC funded Swarm Social Sound Modulators, project reference EP/V037846/1.

## REFERENCES

[1] Damien Ablart, William Frier, Hannah Limerick, Orestis Georgiou, and Marianna Obrist. 2019. Using Ultrasonic Mid-air Haptic Patterns in Multi-Modal User Experiences. In *2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)* (Subang Jaya, Malaysia). IEEE Press, 1–6. https://doi.org/10.1109/HAVE.2019.8920969

[2] David S Alles. 1970. Information transmission by phantom sensations. *IEEE transactions on man-machine systems* 11, 1 (1970), 85–91.

[3] Nika Balomenou and Brian Garrod. 2016. A review of participant-generated image methods in the social sciences. *Journal of Mixed Methods Research* 10, 4 (2016), 335–351.

[4] Ahmad Barghout, Jongeun Cha, Abdulmotaleb El Saddik, Julius Kammerl, and Eckehard Steinbach. 2009. Spatial resolution of vibrotactile perception on the human forearm when exploiting funneling illusion. In *2009 IEEE International Workshop on Haptic Audio visual Environments and Games.* IEEE, 19–23. https://doi.org/10.1109/HAVE.2009.5356122

[5] GV Bekesy. 1960. Experiments in Hearing. New York: McGrawHill Book Company.

[6] Alessio Benavoli, Giorgio Corani, and Francesca Mangili. 2016. Should we really use post-hoc tests based on mean-ranks? *The Journal of Machine Learning Research* 17, 1 (2016), 152–161.

[7] M José Blanca Mena, Rafael Alarcón Postigo, Jaume Arnau Gras, Javier García Castro, and Roser Bono Cabré. 2024. How to proceed when both normality and sphericity are violated in the repeated measures ANOVA. *Anales de Psicología, 2024, vol. 40, num. 3, p. 466-480* 40, 3 (2024), 466–480. https://hdl.handle.net/2445/218943

[8] Roger W Cholewiak and Amy A Collins. 2000. The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mode. *Perception & Psychophysics* 62 (2000), 1220–1235.

[9] SUN Chongyang, NAI Weizhi, and SUN Xiaoying. 2019. Tactile sensitivity in ultrasonic haptics: Do different parts of hand and different rendering methods have an impact on perceptual threshold? *Virtual Reality & Intelligent Hardware* 1, 3 (2019), 265–275.

[10] William Jay Conover. 1999. *Practical nonparametric statistics.* Vol. 350. john wiley & sons.

[11] Davide Deflorio, Massimiliano Di Luca, and Alan M Wing. 2022. Skin and mechanoreceptor contribution to tactile input for perception: a review of simulation models. *Frontiers in Human Neuroscience* 16 (2022), 862344.

[12] Mie Egeberg, Stine Lind, Niels C. Nilsson, and Stefania Serafin. 2021. Exploring the Effects of Actuator Configuration and Visual Stimuli on Cutaneous Rabbit Illusions in Virtual Reality *(SAP '21)*. Association for Computing Machinery, New York, NY, USA, Article 1, 9 pages. https://doi.org/10.1145/3474451.3476230

[13] Martin Eimer, Bettina Forster, and Jonas Vibell. 2005. Cutaneous saltation within and across arms: A new measure of the saltation illusion in somatosensation. *Perception & psychophysics* 67, 3 (2005), 458–468.

[14] Rüdiger Flach and Patrick Haggard. 2006. The cutaneous rabbit revisited. *Journal of Experimental Psychology: Human Perception and Performance* 32, 3 (2006), 717.

[15] Milton Friedman. 1937. The use of ranks to avoid the assumption of normality implicit in the analysis of variance. *Journal of the american statistical association* 32, 200 (1937), 675–701.

[16] William Frier. 2023. Rendering spatiotemporal mid-air tactile patterns. (6 2023), 115 pages. https://sussex.figshare.com/articles/thesis/Rendering_spatiotemporal_mid-air_tactile_patterns/23478383

[17] William Frier, Damien Ablart, Jamie Chilles, Benjamin Long, Marcello Giordano, Marianna Obrist, and Sriram Subramanian. 2018. Using spatiotemporal modulation to draw tactile patterns in mid-air. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications.* Springer, Springer International Publishing, Cham, 270–281.

[18] William Frier, Dario Pittera, Damien Ablart, Marianna Obrist, and Sriram Subramanian. 2019. Sampling Strategy for Ultrasonic Mid-Air Haptics *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300351

[19] Frank A Geldard and Carl E Sherrick. 1972. The cutaneous" rabbit": a perceptual illusion. *Science* 178, 4057 (1972), 178–179.

[20] Ricardo Gomez. 2020. Photostories: a participatory photo elicitation visual research method in information science. *Qualitative and Quantitative Methods in Libraries* 9, 1 (2020), 47–63.

[21] Daniel Hajas, Dario Pittera, Antony Nasce, Orestis Georgiou, and Marianna Obrist. 2020. Mid-air haptic rendering of 2D geometric shapes with a dynamic tactile pointer. *IEEE transactions on haptics* 13, 4 (2020), 806–817.

[22] Keisuke Hasegawa and Hiroyuki Shinoda. 2018. Aerial vibrotactile display based on multiunit ultrasound phased array. *IEEE transactions on haptics* 11, 3 (2018), 367–377.

[23] Takayuki Hoshi, Takayuki Iwamoto, and Hiroyuki Shinoda. 2009. Non-contact tactile sensation synthesized by ultrasound transducers. In *World Haptics 2009-Third Joint EuroHaptics conference and Symposium on Haptic Interfaces for Virtual*

*Environment and Teleoperator Systems*. IEEE, IEEE, 256–260. https://doi.org/10.1109/WHC.2009.4810900

[24] Thomas Howard, Karina Driller, William Frier, Claudio Pacchierotti, Maud Marchal, and Jessica Hartcher-O'Brien. 2023. Gap detection in pairs of ultrasound mid-air vibrotactile stimuli. *ACM Transactions on Applied Perceptions* 20, 1 (2023), 1–17.

[25] Yu Huang and Michael J Griffin. 2014. Comparison of absolute magnitude estimation and relative magnitude estimation for judging the subjective intensity of noise and vibration. *Applied Acoustics* 77 (2014), 82–88. https://doi.org/10.1016/j.apacoust.2013.10.003

[26] Takayuki Iwamoto, Mari Tatezono, and Hiroyuki Shinoda. 2008. Non-contact method for producing tactile sensation using airborne ultrasound. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, Springer Berlin Heidelberg, Berlin, Heidelberg, 504–513.

[27] Ylber Januzaj, Edmond Beqiri, and Artan Luma. 2023. Determining the Optimal Number of Clusters using Silhouette Score as a Data Mining Technique. *International Journal of Online & Biomedical Engineering* 19, 4 (2023), pp. 174–182.

[28] Roland S Johansson. 1978. Tactile sensibility in the human hand: receptive field characteristics of mechanoreceptive units in the glabrous skin area. *The Journal of physiology* 281, 1 (1978), 101–125.

[29] Roland S Johansson and J Randall Flanagan. 2009. Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience* 10, 5 (2009), 345–359.

[30] Roland S Johansson and Åke B Vallbo. 1983. Tactile sensory coding in the glabrous skin of the human hand. *Trends in neurosciences* 6 (1983), 27–32.

[31] Brian Kappus and Ben Long. 2018. Spatiotemporal modulation for mid-air haptic feedback from an ultrasonic phased array. *The Journal of the Acoustical Society of America* 143, 3 (2018), 1836–1836.

[32] Oliver Beren Kaul, Michael Rohs, Benjamin Simon, Kerem Can Demir, and Kamillo Ferry. 2020. Vibrotactile Funneling Illusion and Localization Performance on the Head. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (<conf-loc>, <city>Honolulu</city>, <state>HI</state>, <country>USA</country>, </conf-loc>) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–13. https://doi.org/10.1145/3313831.3376335

[33] Michael P Kilgard and Michael M Merzenich. 1995. Anticipated stimuli across skin. *Nature* 373 (1995), 663–663.

[34] Georgios Korres and Mohamad Eid. 2016. Haptogram: Ultrasonic point-cloud tactile stimulation. *IEEE Access* 4 (2016), 7758–7769.

[35] Jaedong Lee, Youngsun Kim, and Gerard Kim. 2012. Funneling and saltation effects for tactile interaction with virtual objects *(CHI '12)*. Association for Computing Machinery, New York, NY, USA, 3141–3148. https://doi.org/10.1145/2207676.2208729

[36] Benjamin Long, Sue Ann Seah, Tom Carter, and Sriram Subramanian. 2014. Rendering volumetric haptic shapes in mid-air using ultrasound. *ACM Transactions on Graphics (TOG)* 33, 6 (2014), 1–10.

[37] Jonatan Martinez, Adam Harwood, Hannah Limerick, Rory Clark, and Orestis Georgiou. 2019. Mid-air haptic algorithms for rendering 3D shapes. In *2019 IEEE International Symposium on Haptic, Audio and Visual Environments and Games (HAVE)* (Subang Jaya, Malaysia). IEEE, IEEE Press, 1–6. https://doi.org/10.1109/HAVE.2019.8921211

[38] Atsushi Matsubayashi, Kanta Shiku, Yasutoshi Makino, and Hiroyuki Shinoda. 2023. Focusing Reflected Ultrasound Using Boundary Element Model for Mid-Air Tactile Presentation. *IEEE Transactions on Haptics* 16, 4 (2023), 695–701.

[39] John W Mauchly. 1940. Significance test for sphericity of a normal n-variate distribution. *The Annals of Mathematical Statistics* 11, 2 (1940), 204–209.

[40] Makoto Miyazaki, Masaya Hirashima, and Daichi Nozaki. 2010. The "cutaneous rabbit" hopping out of the body. *Journal of Neuroscience* 30, 5 (2010), 1856–1860.

[41] Roberto Montano-Murillo, Ryuji Hirayama, and Diego Martinez Plasencia. 2023. OpenMPD: A Low-Level Presentation Engine for Multimodal Particle-Based Displays. *ACM Trans. Graph.* 42, 2, Article 24 (April 2023), 13 pages. https://doi.org/10.1145/3572896

[42] Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2020. Comparing lateral modulation and amplitude modulation in phantom sensation. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, Springer International Publishing, Cham, 122–130.

[43] Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2021. Non-vibratory pressure sensation produced by ultrasound focus moving laterally and repetitively with fine spatial step width. *IEEE Transactions on Haptics* 15, 2 (2021), 441–450.

[44] Joshua Mukherjee, Zhouyang Shen, Giorgos Christopoulos, Sriram Subramanian, and Ryuji Hirayama. 2025. "To BEM or not to BEM?": Does Modelling Sound Scattering Improve Ultrasonic Mid-Air Haptics?. In *Proceedings of the Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '25)*. Association for Computing Machinery, New York, NY, USA, Article 31, 7 pages. https://doi.org/10.1145/3706599.3720287

[45] Carey M Noland. 2006. Auto-photography as research practice: identity and self-esteem research. *Journal of research Practice* 2, 1 (2006), M1.

[46] Marianna Obrist, Sue Ann Seah, and Sriram Subramanian. 2013. Talking about Tactile Experiences *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1659–1668. https://doi.org/10.1145/2470654.2466220

[47] Marianna Obrist, Sriram Subramanian, Elia Gatti, Benjamin Long, and Thomas Carter. 2015. Emotions Mediated Through Mid-Air Haptics. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. Association for Computing Machinery, New York, NY, USA, 2053–2062. https://doi.org/10.1145/2702123.2702361

[48] Gunhyuk Park and Seungmoon Choi. 2018. Tactile Information Transmission by 2D Stationary Phantom Sensations. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173832

[49] Dario Pittera, Damien Ablart, and Marianna Obrist. 2019. Creating an illusion of movement between the hands using mid-air touch. *IEEE transactions on haptics* 12, 4 (2019), 615–623.

[50] Dario Pittera, Marianna Obrist, and Ali Israr. 2017. Hand-to-hand: an intermanual illusion of movement. In *Proceedings of the 19th ACM International Conference on Multimodal Interaction* (Glasgow, UK) *(ICMI '17)*. Association for Computing Machinery, New York, NY, USA, 73–81. https://doi.org/10.1145/3136755.3136777

[51] Diego Martinez Plasencia, Ryuji Hirayama, Roberto Montano-Murillo, and Sriram Subramanian. 2020. GS-PAT: high-speed multi-point sound-fields for phased arrays of transducers. *ACM Transactions on Graphics (TOG)* 39, 4 (2020), 138–1. https://doi.org/10.1145/3386569.3392492

[52] Julia C Quindlen, Henryk K Stolarski, Matthew D Johnson, and Victor H Barocas. 2016. A multiphysics model of the Pacinian corpuscle. *Integrative biology* 8, 11 (2016), 1111–1125.

[53] Lara Rahal, Jongeun Cha, and Abdulmotaleb El Saddik. 2009. Continuous tactile perception for vibrotactile displays. In *2009 IEEE International Workshop on Robotic and Sensors Environments*. 86–91. https://doi.org/10.1109/ROSE.2009.5355986

[54] Jukka Raisamo, Roope Raisamo, and Veikko Surakka. 2009. Evaluating the effect of temporal parameters for vibrotactile saltatory patterns. In *Proceedings of the 2009 International Conference on Multimodal Interfaces* (Cambridge, Massachusetts, USA) *(ICMI-MLMI '09)*. Association for Computing Machinery, New York, NY, USA, 319–326. https://doi.org/10.1145/1647314.1647381

[55] Ahsan Raza, Waseem Hassan, Tatyana Ogay, Inwook Hwang, and Seokhee Jeon. 2019. Perceptually correct haptic rendering in mid-air using ultrasound phased array. *IEEE Transactions on Industrial Electronics* 67, 1 (2019), 736–745.

[56] Davide Rocchesso, Francesco Saverio Cannizzaro, Giovanni Capizzi, and Francesco Landolina. 2019. Accessing and selecting menu items by in-air touch. In *Proceedings of the 13th Biannual Conference of the Italian SIGCHI Chapter: Designing the next interaction*. 1–9.

[57] Hasti Seifi, Sean Chew, Antony James Nascè, William Edward Lowther, William Frier, and Kasper Hornbæk. 2023. Feellustrator: A Design Tool for Ultrasound Mid-Air Haptics. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 266, 16 pages. https://doi.org/10.1145/3544548.3580728

[58] Zhouyang Shen, Zak Morgan, Madhan Kumar Vasudevan, Marianna Obrist, and Diego Martinez Plasencia. 2024. Controlled-STM: A Two-stage Model to Predict User's Perceived Intensity for Multi-point Spatiotemporal Modulation in Ultrasonic Mid-air Haptics. In *Proceedings of the 2024 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '24)*. Association for Computing Machinery, New York, NY, USA, Article 709, 12 pages. https://doi.org/10.1145/3613904.3642439

[59] Zhouyang Shen, Madhan Kumar Vasudevan, Jan Kučera, Marianna Obrist, and Diego Martinez Plasencia. 2023. Multi-point STM: Effects of Drawing Speed and Number of Focal Points on Users' Responses using Ultrasonic Mid-Air Haptics. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 83, 11 pages. https://doi.org/10.1145/3544548.3580641

[60] B Stark, T Carlstedt, RG Hallin, and M Risling. 1998. Distribution of human Pacinian corpuscles in the hand: a cadaver study. *The Journal of Hand Surgery: British & European Volume* 23, 3 (1998), 370–372.

[61] Shun Suzuki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2019. Midair Hand Guidance by an Ultrasound Virtual Handrail. In *2019 IEEE World Haptics Conference (WHC)*. 271–276. https://doi.org/10.1109/WHC.2019.8816123

[62] M A Syakur, B K Khotimah, E M S Rochman, and B D Satoto. 2018. Integration K-Means Clustering Method and Elbow Method For Identification of The Best Customer Profile Cluster. *IOP Conference Series: Materials Science and Engineering* 336, 1 (apr 2018), 012017. https://doi.org/10.1088/1757-899X/336/1/012017

[63] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. 2018. Lateral modulation of midair ultrasound focus for intensified vibrotactile stimuli. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*. Springer, Springer International Publishing, Cham, 276–288.

[64] Ryoko Takahashi, Keisuke Hasegawa, and Hiroyuki Shinoda. 2019. Tactile stimulation by repetitive lateral movement of midair ultrasound focus. *IEEE transactions on haptics* 13, 2 (2019), 334–342.

[65] Hong Tan, Robert Gray, J Jay Young, and Ryan Taylor. 2003. A haptic back display for attentional and directional cueing. 3, 1 (2003). http://hdl.handle.net/1773/34886

[66] Hong Z Tan and Alex Pentland. 1997. Tactual displays for wearable computing. *Personal Technologies* 1 (1997), 225–230.

[67] Maciej Tomczak and Ewa Tomczak. 2014. The need to report effect size estimates revisited. An overview of some recommended measures of effect size. online.

[68] G v. Békésy. 1958. Funneling in the nervous system and its role in loudness and sensation intensity on the skin. *The Journal of the Acoustical Society of America* 30, 5 (1958), 399–412.

[69] Madhan Kumar Vasudevan, Shu Zhong, Jan Kučera, Desiree Cho, and Marianna Obrist. 2023. MindTouch: Effect of Mindfulness Meditation on Mid-Air Tactile Perception. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 387, 12 pages. https://doi.org/10.1145/3544548.3581238

[70] Ronald T Verrillo and George A Gescheider. 1975. Enhancement and summation in the perception of two successive vibrotactile stimuli. *Perception & Psychophysics* 18, 2 (1975), 128–136.

[71] Jay P Warren, Marco Santello, and Stephen I Helms Tillery. 2010. Electrotactile stimuli delivered across fingertips inducing the Cutaneous Rabbit Effect. *Experimental brain research* 206 (2010), 419–426.

[72] Graham Wilson, Thomas Carter, Sriram Subramanian, and Stephen A. Brewster. 2014. Perception of ultrasonic haptic feedback on the hand: localisation and apparent motion. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Toronto, Ontario, Canada) *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 1133–1142. https://doi.org/10.1145/2556288.2557033