Multi-point STM: Effects of Drawing Speed and Number of Focal Points on Users' Responses using Ultrasonic Mid-Air Haptics

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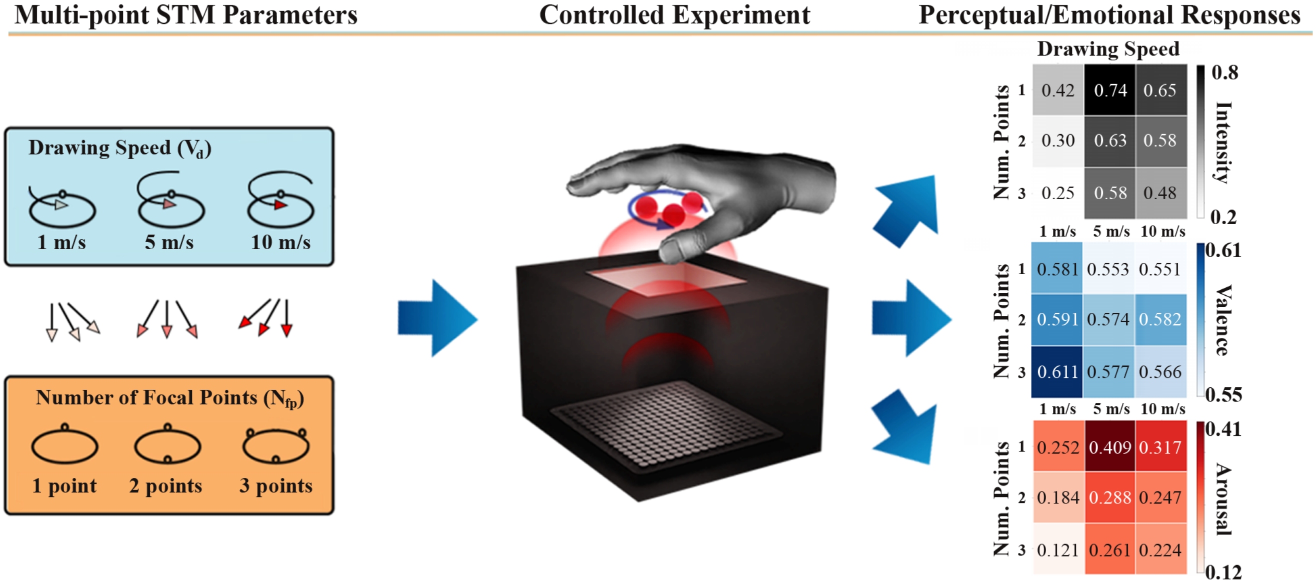

Num. Points (Intensity)	1 m/s	5 m/s	10 m/s
1	0.42	0.74	0.65
2	0.30	0.63	0.58
3	0.25	0.58	0.48

Num. Points (Valence)	1 m/s	5 m/s	10 m/s
1	0.581	0.553	0.551
2	0.591	0.574	0.582
3	0.611	0.577	0.566

Num. Points (Arousal)	1 m/s	5 m/s	10 m/s
1	0.252	0.409	0.317
2	0.184	0.288	0.247
3	0.121	0.261	0.224

Figure 1: We explored the effects of multi-point STM by testing different drawing speeds (1, 5, 10 m/s) and the number of focal points (1, 2, 3) in a controlled experiment, looking into users' perceptual and emotional responses (perceived intensity, valence and arousal). Different combinations of drawing speed and number of focal points formed 9 different conditions and can be seen on the left. An overview of the responses averaged across all participants for each condition, and measured response can be seen on the right.

ABSTRACT

Spatiotemporal modulation (STM) is used to render tactile patterns with ultrasound arrays. Previous research only explored the effects of single-point STM parameters, such as drawing speed (V_d). Here we explore the effects of multi-point STM on both perceptual (intensity) and emotional (valence/arousal) responses. This introduces a new control parameter for STM - the number of focal points (N_{fp}) – on top of conventional STM parameter (V_d). Our results from a study with 30 participants showed a negative effect of N_{fp} on perceived intensity and arousal, but no significant effects on valence. We also found the effects of V_d still aligned with prior results for single-point, even when different N_{fp} were used, suggesting that effects observed from single-point also apply to multi-point STM. We finally derive recommendations, such as using single-point STM to produce stimuli with higher intensity and/or arousal, or using multi-point STM for milder and more relaxing (less arousing) experiences.

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CCS CONCEPTS

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

KEYWORDS

mid-air haptics, perception, emotion

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1 INTRODUCTION

A range of haptic approaches have been proposed over the years, including haptic-gloves [25, 71], finger attachments [8, 16, 36, 49, 62, 69], electrical muscle stimulation [43–45], or even contactless approaches relying on air jets [22, 67], vortex rings [21], infrared [60], laser [39], electric arcs [65] or focused ultrasound waves [12]. Ultrasonic mid-air haptics (UMH) is gradually settling as one of the most feasible contactless approaches, enabling high quality feedback and relatively large working volumes.

Different approaches (i.e. modulation techniques) to deliver UMH lead to different user responses, and common approaches include Amplitude Modulation (AM) [26, 42], Lateral Modulation (LM) [51, 68], and Spatiotemporal Modulation (STM) [14]. Most relevant for this paper, STM uses a single high-pressure focus point, quickly moving on the users' skin to deliver the tactile stimuli. Several studies have tested the effects of STM, and various parameters have been shown to affect user responses (i.e., intensity, valence and arousal). These include the speed at which the focal point moves on the user's skin (drawing speed) [14, 55], the pattern size and number of discrete samples used to present the tactile pattern [15] or the number of times the point traverses the pattern per second (drawing frequency) [1].

For years, the popularity of the STM technique had been justified by its use of a single, fast-moving point. A single point allows maximum pressure output at all times, instead of dividing it across several points [68] or turning transducers on and off [26], while fast speeds allow the rendering of volumetric tactile shapes [47]. However, recent algorithms [56] proposed the use of STM using several points, demonstrating that similar overall pressure and pressure contrast can be delivered on the user's skin, and similar high speeds, even if several points are used. The effects of Multi-point STM and the validity of the modulation parameters inherited from traditional STM (e.g., drawing speed, size, number of samples), however, have never been tested.

This paper aims to fill this gap, using multi-point STM to study how STM parameters (i.e., drawing speed and the number of focal points) independently affect users' responses (perceived intensity, valence and arousal). More specifically, we tested different combinations of drawing speed and number of focal points (see Figure 1) on 30 participants (45 stimuli per participant). We used the absolute magnitude estimation method [28] to quantify their perceived intensity and Self-Assessment Manikin (SAM) [1, 4, 5, 17] to quantify valence and arousal.

Our results showed a negative effect of the number of focal points on perceived intensity, confirming advantages of single-point STM for maximum intensity. Emotional responses, however, showed an effect between the number of points and arousal, with more points leading to more calming responses. For each of the 3 measured responses (perceived intensity, valence and arousal), we found a unified relationship between drawing speed and the response, independent of the number of focal points used, suggesting that trends observed from single-point STM might also translate to multi-point STM stimulation.

Our results also suggest that single-point STM leads to stimuli with higher intensity and arousal. In contrast, multi-point STM is better equipped to produce stimuli with mild intensity and to help users relax. To the best of our knowledge, this is the first paper that studies the effect of the number of focal points on the human perceptual and emotional response to UMH stimuli, paving the way for additional tactile experiences and applications of this technology in terms of the perceptions and emotions it can produce.

2 RELATED WORK

Here, we review the key prior and related work concerning ultrasonic mid-air haptics (UMH) to demonstrate the gap and help understand the limits of previous research in the tactile experience design space.

2.1 Ultrasonic mid-air haptics (UMH) and modulation techniques

UMH applications are emerging in fields such as virtual reality [19, 30, 46, 61], digital advertising [40, 41] or automotive user interfaces [18, 24, 58, 63, 75]. UMH devices typically use arrays of ultrasound transducers, controlling their phases so that the sound waves from each transducer arrive at the same point at the same time, creating a point of high pressure (a focal point) [9, 32]. Later advances allowed focal points to be freely located in space [26, 27], simultaneous control of several points [7], as well as high-speed control of one [14] or many focal points [56].

However, humans cannot directly perceive the focal points created via UMH. These devices typically utilize 40 kHz soundwaves, i.e. vibration frequency that exceeds the human vibrotactile perception range (5-1000 Hz, 200 Hz as highest sensitivity [34]). Thus, focal points need to be modulated so that they can be detected by our mechanoreceptors.

There are three main UMH focal point modulation techniques to create tactile patterns perceivable by humans, which we summarize in Figure 2. The first one is amplitude modulation (AM) [26] shown in Figure 2a, which works by modulating the pressure of focal points within skin perceptible frequency (close to 500 Hz [33]). The second one is lateral modulation (LM) [51, 68] shown in Figure 2b. Instead of changing the pressure of focal points over time, LM retains the same pressure but continuously moves focal points back and forth in lateral paths. The third technique is spatiotemporal modulation (STM) [35], shown in Figure 2c.

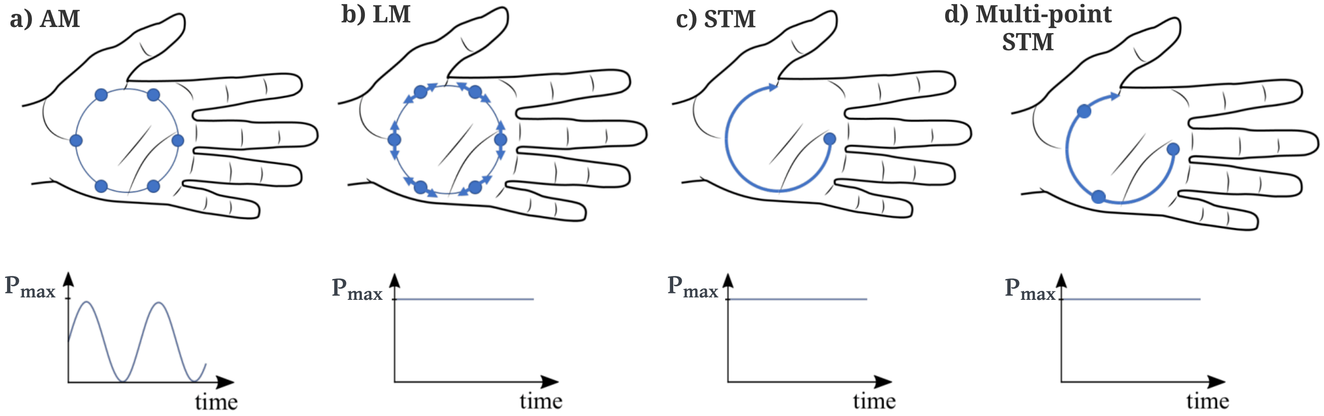


Figure 2: Existing UMH modulation techniques, showing their use of focal points (above) and evolution of the pressure of points over time (below): a) Amplitude modulation (AM); b) Lateral modulation (LM); c) Spatiotemporal modulation (STM); d) Multi-point STM (i.e., proposed by [56], but never explored).

STM works differently from the previous two modulation techniques by moving a single focal point with constant pressure along arbitrary pattern trajectories. This allows recreating complex tactile patterns and shapes while making optimum use of power (single point delivering maximum pressure all the time). This provides advantages over other techniques, which either make sub-optimum use of power (i.e., turning transducers on and off at the AM modulation frequency) or approximate shapes as a discretized set of points (AM/LM), with the intensity of each point decreasing as more points are used.

A multi-point STM alternative was proposed in [56]. Like the single-point STM method, the multi-point STM shown in Figure 2d can reveal arbitrary pattern trajectories using several points, while still providing similar overall pressure (Pa/s) as the single-point STM technique does. The technique also provides an additional degree of freedom (i.e., the number of points used) to control the delivery of the tactile feedback generated. While a technical characterization of the technique was provided, the effect of multi-point STM was never tested in real participants.

2.2 Effect of modulation parameters on users’ perception and emotions

For any given modulation technique, different modulation parameters also influence how humans perceive the UMH stimulus. Many studies have been conducted, but none of them tested the use of multi-point STM or the effect of its modulation parameters on perceptual responses.

The typical modulation parameters in AM are 1) stimuli intensity, the focal point pressure produced by the device in Pascals; and 2) modulation frequency, which is the period to turn the stimuli intensity on and off. Iwamoto et al. [32] first studied the relationship between the modulation frequency of a single focal point and its perceived intensity, finding stronger perception when the modulation frequency is around 20—250 Hz. Raza et al. [57] found that the detection threshold of haptic sensation changes, requiring different stimuli intensity as the modulation frequency changes, and derived a predictive model of the relationship between the modulation parameters and the perceived intensity.

In LM, the typical modulation parameters are 1) lateral path length and 2) drawing speed, defined by the speed at which points move along the lateral path. Takahashi et al. [68] found that LM could bring stronger perceived intensity than AM by changing the lateral path length and that speed also affected perceived intensity.

In STM, the common modulation parameters are 1) drawing speed, which describes how fast the focal point moves along the trajectory; 2) drawing frequency, which describes the number of times per second that the focal point traverses the trajectory; and 3) sampling rate, which describes the number of points used to discretize the trajectory. Frier et al. [14, 15] related drawing speed, pattern size and sampling rate with perceived intensity, but the way these parameters translate to multi-point STM is unknown.

Moreover, Frier et al. [14] argued that the use of more focal points in AM would reduce the pressure of each focal point, thus degrading the perceived intensity. In contrast, Plasencia et al. [56] showed that, if multi-point STM is used with a small number of points, the overall pressure delivered to the users’ skin (i.e., Pa/s delivered to each point along the trajectory) is very similar to single-point STM. However, it remains unclear if delivering the same overall pressure, but distributed across several points, still provides a similar perceived intensity.

Beyond perceived intensity, modulation parameters have also been found to influence emotional responses. Obrist et al. [53] investigated the possibility of using modulation frequencies to vary the users’ valence and arousal levels.

Tsumoto et al. [70] found that inconsistently moving the focal point modulated by AM with a speed of 0.3 m/s without lateral frictions yields an increase in reported pleasantness. Ablart et al. [1] found that by changing drawing frequency and pattern size used in single-point STM, users can perceive different levels of intensity, roughness, regularity, roundness and valence. Pittera et al. [55] used single-point STM and studied how the distance between a linearly moving focal point and both dorsal and volar parts of the forearm affects perceived intensity, temperature and spatial definition. They also reported how drawing speed affects users' perceived temperature and valence level on the dorsal part of the hand as well as the volar part of the forearm. Still, no study has explored multi-point STM and revealed the effects of its modulation parameters on users' emotional responses.

In summary, many studies have been conducted to independently understand how each modulation parameter affects users' perceptual or emotional responses. However, none attempted multi-point STM, and none looked at both perceptual (intensity) and emotional responses (valence and arousal). Even if conceptually similar, the way single-point STM parameters (e.g., drawing speed) translate to multi-point STM remains unknown, as well as the effects on users' tactile experiences of the additional degree of freedom allowed by multi-point STM (i.e., number of points used).

3 CONTROLLED EXPERIMENT

Our goal is to understand the effects of multi-point STM parameters on user responses and compare them with that of single-point STM parameters. To do this, we conducted a controlled experiment varying drawing speed (V_d) and number of focal points (N_{fp}) (i.e., our *independent variables*), and measuring their effects on perceived intensity, valence and arousal (i.e., our *dependent variables*). The aims of our exploratory study are:

1) to investigate if the effect on user's response of V_d (i.e., a modulation parameter of single-point STM) also applies to multi-point STM, indicating that lessons may be transferable across both techniques.

2) to study how N_{fp} (i.e., the new degree of freedom introduced by multi-point STM) influences users' perceptual and emotional responses.

3.1 Experiment Design

To test the effects of drawing speed (V_d) and number of points (N_{fp}), we created 9 multi-point STM stimuli, using 3 different levels of V_d and N_{fp}, as detailed next.

The 3 chosen values of V_d were 1, 5 and 10 m/s (see in Figure 3a), as these speeds correspond to the lower bound (1 m/s), peak (5 m/s) and higher bound (10 m/s) of perceived intensity (i.e., increases from 1 m/s, peaks at 5 m/s and decreases at 10 m/s, see [14]). This allowed us to reduce the number of conditions tested, which was crucial to keep the experiment short and avoid user fatigue. Also, it allowed us to observe whether the trends applying to single-point STM were still valid for multi-point STM, a key contribution to transferring lessons learnt from one type of stimulation to the other.

We also chose stimuli with 1, 2 or 3 focal points (N_{fp}), created with GS-PAT [56]. This ensures very similar levels of overall pressure to be delivered on users' skin (i.e., Pa/s) by all stimuli, but also that the intensity of each focal point remains similar (Pa/point) [56].

We fixed the remaining STM modulation parameters to avoid confounding factors. For pattern shape, we used a circle (to avoid salient points/corners' influence [47]), with a diameter of 6.5 cm (within the typical size of an adult's palm of 7.5—9.5 cm [37]) and an overall length of $\approx$ 20 cm. We also fixed our sampling to 100 points along the shape [15], yielding a separation between samples of 0.2 cm (i.e., 20 cm / 100 samples). Given that the diameter of a focal point is nearly 1 cm [7], adjacent samples 0.2 cm apart overlap significantly, and the discretization of the shape still results in a continuous sensation. We also fixed the position of the stimuli and the users' hands, placing them 15 cm above the array to avoid effects due to stimuli location [57].

We used a within-subjects experimental design, with each participant being exposed to each of our stimuli five times (i.e. 9 stimuli x 5 repetitions = 45 stimuli in total), as summarized in Figure 3. Stimuli were pseudo-randomized for each participant to reduce learning effects. Ethical approval was obtained from University College London's internal ethics committee and all participants gave informed consent (approval number: UCLIC_2021_014_ObristPE). .

3.2 Experiment Setup and Procedure

Our experimental setup made use of the open software and hardware provided by the OpenMPD platform [50], configured to use the GS-PAT solver at 10 kHz. The device was enclosed inside a black acrylic box, with a 9.5 cm by 11 cm aperture on the top so that the haptic stimuli could reach the participants' hands. The box also helped participants to align their hands above the device, keeping it at the right distance of 15 cm. An adjustable chair and elbow support were provided, adjusting them for participant's comfort, to avoid fatigue and to ensure they kept their hand still for the stimulation period. Noise-cancelling headphones playing pink noise were used to prevent participants from being affected by ambient noises and noise from the ultrasonic mid-air haptic device. Participants were required to use their dominant hand to interact with the keyboard and mouse to record their responses through a GUI displayed on a 22" monitor in front of them. The overall experiment setup can be seen in Figure 4a.

A total of 30 participants were recruited (20 females, mean age $\pm SD$: 29±9.12, 2 of them with prior experience with UMH). After welcoming each participant into the room, the setup (i.e., box, elbow support and chair) was adjusted to the participant's needs. Each participant was asked to watch a video explaining the experiment procedure, tasks to complete, and instructions on how to use the GUI and rate perceived intensity, valence and arousal. Moreover, participant responses and instructions were provided via the GUI. This ensured all participants received the same information, minimizing potential biases introduced by the researcher's instructions.

After being instructed, a fixed set of 18 training stimuli was used to help participants familiarize themselves with the testing and rating procedure and the stimuli and to consolidate their rating scale (particularly relevant given the unbounded scale used for intensity, which we explain below).

After training, each participant was presented with each of the 45 test stimuli. After perceiving one stimulus for 5 seconds (i.e., a given combination of V_d and N_{fp} in Figure 3a), the GUI instructed the participant to enter their estimated value for perceived intensity, valence and arousal.

Perceived intensity was rated using the absolute magnitude estimation method [28, 57], following a user-defined scale from 0 to infinity, which was then normalized as per related (single-point) STM studies [15]. Self-Assessment Manikin (SAM) sliders, from extremely unpleasant/calming to extremely pleasant/activating, were

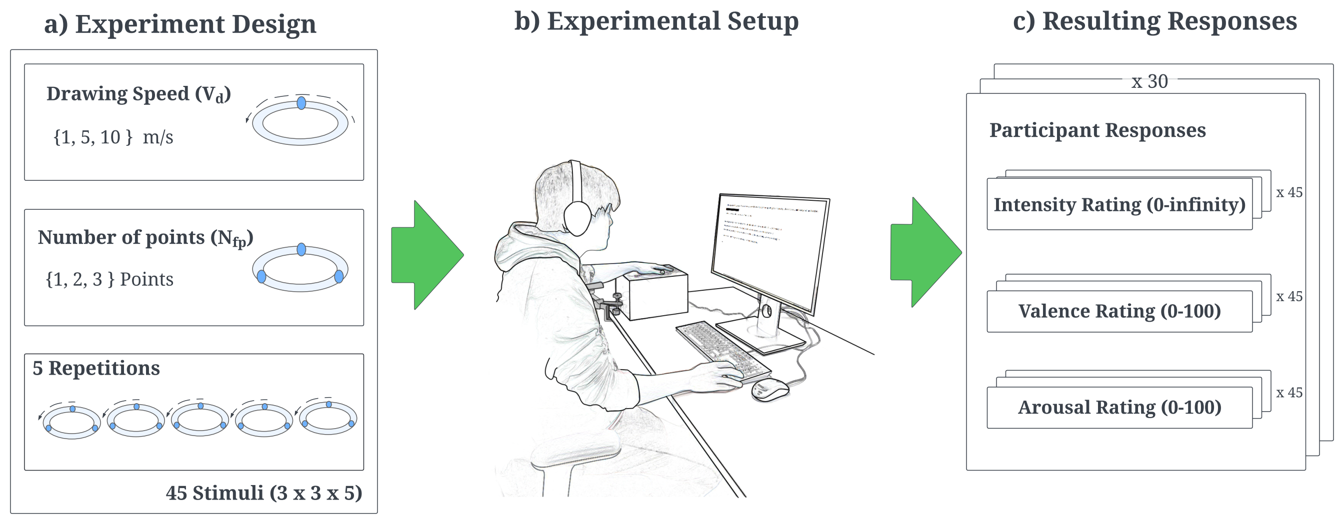
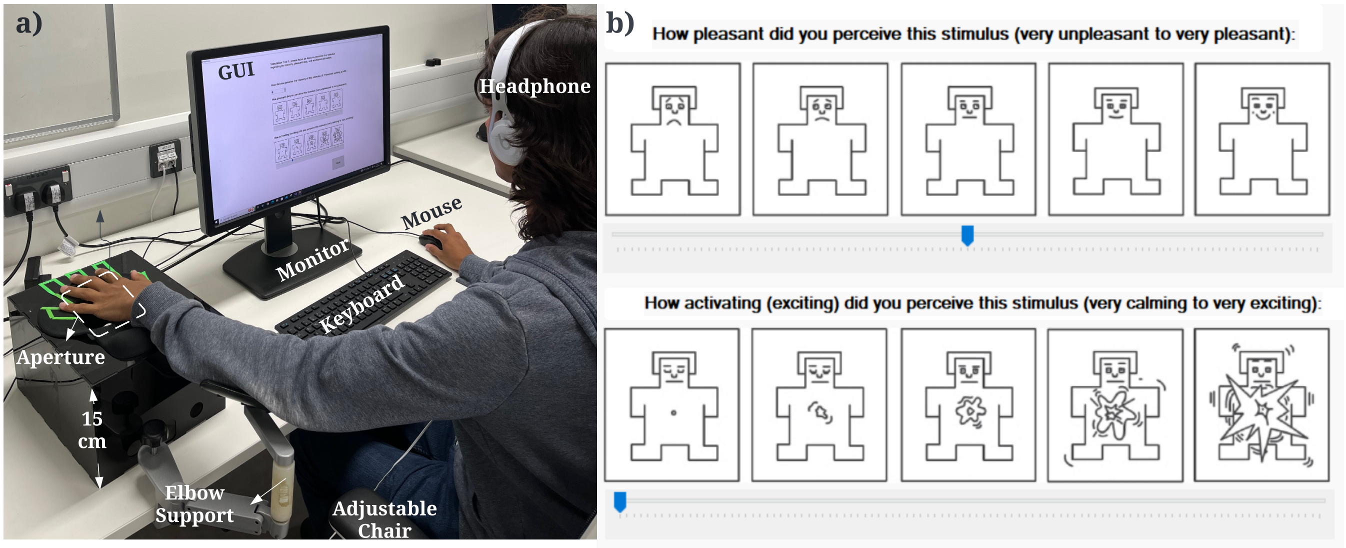


Figure 3: Summary of our experiment design. a) Each participant was presented with 45 multi-point STM stimuli, as a combination of different drawing speeds (V_d = 1, 5, 10 m/s) and number of points (N_{fp} = 1, 2, 3), each of them repeated 5 times. b) Overview of the experimental setup, with participants using their non-dominant hand to feel the patterns and dominant hand to interact with a GUI to provide perceived intensity, valence and arousal ratings. c) Results obtained from 30 participants, each providing 45 ratings for perceived intensity (using a scale from 0 to infinity), valence and arousal (using a 0-100 slider).



How pleasant did you perceive this stimulus (very unpleasant to very pleasant):

How activating (exciting) did you perceive this stimulus (very calming to very exciting):

Figure 4: a) Overview of the experimental setup used. b) Self-Assessment Manikins as shown by our GUI to aid users' rating of valence and arousal.

used to rate valence and arousal (see Figure 4b), using icons to facilitate participant's rating [1, 4, 5, 17].

After participants provided their responses for a stimulus, they proceeded to the next stimulus, repeating the same procedure until all 45 stimuli were completed. A 2 minute break was provided every 20 trials, and the overall duration of the experiment was about 30 minutes. At the end of the experiment, each participant received a 5 pounds amazon gift card for the duration they participated.

4 ANALYSIS AND RESULTS

We here report and analyze the effects of the two STM parameters explored (N_{fp} and V_d) on our dependent variables (perceived intensity, valence and arousal). We explore each parameter independently first (i.e., N_{fp} and V_d) and then consider them jointly, and we also look at valence and arousal using the circumplex model. Each subsection will summarize specific results but also highlight immediate implications and observations that can be derived from those results. A broader discussion, looking at all of these as a whole is provided in Section 5.

We collected responses from 30 participants, obtaining a total of 30 x 45 = 1350 ratings of perceived intensity, valence and arousal. For each of the 45 ratings provided by each participant, we averaged the responses for each stimulus (i.e., a specific combination of N_{fp} and V_d). We then normalized all reported intensity ratings to 0 to 1 by dividing each participant's ratings by their highest response [15, 66]. Emotional ratings were also normalized to 0 to 1, by dividing each participant's ratings by the highest value allowed by the slider (set to 100 and hidden from participants).

The resulting perceptual and emotional ratings seemed unlikely to follow a normal distribution (Shapiro-Wilk, $p = 0.02839$ for intensity, $p = 0.01271$ for valence and $p = 0.0001389$ for arousal), and also violated sphericity assumptions (Mauchly's test [48] with $p < .05$). We found 5, 4 and 1 outliers (i.e., below or above the 1.5∗interquartile range) in intensity, valence and arousal ratings, respectively. Removing them, however, did not affect the results obtained. Thus, we considered the outliers as subjectivity involved in the experiment (rating emotional dimensions in ultrasonic mid-air haptics is known to be hard [53]) and continued our data analysis with the complete sample of 30 participants.

Our analysis used Friedman's tests (not requiring the prior assumptions [13] and robust to outliers [3]) to assess the significant effect of V_d and N_{fp} on intensity, valence and arousal and interpreted effect sizes using η^2 proposed by Cohen [10]. Conover's post-hoc tests [11] with Bonferroni correction were used to reduce the chance of obtaining type I errors while analysing rating differences between pairs of each independent variable. The rest of the paper provides visual summaries and key statistical parameters from our results. Full results in tabular form can be found in Table 1 and 2 in the supplementary material (as well as equivalent results with outliers removed, in Tables 3 and 4). Mean and standard deviation values for the plots in Figure 5 can be found in Table 5.

4.1 Effect of drawing speed on users' responses

Our results on the effects of V_d were summarized in Figure 5a. We found a significant effect of V_d with large effect sizes on perceived intensity ($\chi^2(2) = 95.638$, $p < 0.001$; partial $\eta^2 = 0.786$) and arousal ratings ($\chi^2(2) = 44.145$, $p < 0.001$; partial $\eta^2 = 0.512$). However, no significant effect of V_d on valence ratings was found ($\chi^2(2) = 3.119$, $p = 0.210$).

We then investigated pair-wise effects of V_d on intensity and arousal ratings. For intensity ratings, significant differences were found between speeds 1 m/s and 5 m/s ($p < 0.001$), and between 1 m/s and 10 m/s ($p = 0.006$). As per arousal ratings, significant differences were only found between speeds of 1 m/s and 5 m/s ($p = 0.007$).

Our results showed that perceived intensity reached its peak value when the V_d was at 5 m/s, decreasing for other values (particularly for 1 m/s) , which aligned with previous observations from Frier et al. [15]. This seemed to indicate that the effects of V_d observed on single-point STM also translated to multi-point STM, when a reduced number of points was used. The results also showed that V_d can influence arousal (most calming at 1 m/s, more exciting at higher speeds), a result that had not been reported before.

The lack of observable effects on valence could simply reflect the difficulty of participants to rate such feeling [53] and also aligned with the results from Pittera et al. [55] on the volar part of the forearm. However, this result is surprising when considered together with the results from Ablart et al. [1] - which showed that drawing frequency (f) and pattern size (L) influenced participants' valence. In contrast, our results showed that V_d did not seem to induce strong effects, even if it is implicitly related to frequency and size (V_d= L∗f/N_{fp} as explained in [56]). Finally, our results from valence should consider the results from [70], which reported that speeds of 0.3 m/s maximized users' pleasantness. Thus, it is possible that the peak value for users' pleasantness actually occurs at speeds below 1 m/s.

4.2 Effect of number of focal points on users' responses

The results of N_{fp} were summarized in Figure 5b. We found significant effect of N_{fp} with large effect sizes on perceived intensity ($\chi^2(2) = 28.091$, $p < 0.001$; partial $\eta^2 = 0.651$) and arousal ($\chi^2(2) = 40.675$, $p < 0.001$; partial $\eta^2 = 0.543$). Again, no significant effect was found on valence ($\chi^2(2) = 1.227$, $p = 0.542$). Pair-wise comparisons for different N_{fp} showed significant differences between 1 and 3 points on perceived intensity ($p = 0.047$), and also on arousal ratings ($p = 0.016$).

Perceived intensity reached its peak value when 1 point was used, decreasing gradually with the increase in N_{fp} and with significantly weaker intensity for $N_{fp} = 3$. This illustrates the difference between multi-STM and more conventional vibrator-based haptics. Using several vibrators, each of them would be able to deliver their full stimulation independently, leading to stronger sensations. In the case of multi-STM, the UMH device's power is limited, and its acoustic power needs to be divided among several focal points (i.e., decreasing their individual intensity).

This result also provides evidence to settle the debate between [14] and [56], supporting the suggestion from Frier et al. [14] that the use of a single point maximizes perceived intensity. Given that the physical stimuli actually deliver a very similar overall pressure (i.e., total Pa delivered on the skin by the points) for N_{fp} = 1, 2, 3 [56], this also indicates that perceived intensity is more related to the pressure of each point, rather than to the summation of their pressures. This could be the result of usual psycho-physical responses, where only the part of a stimulus exceeding a minimum threshold (i.e., Pa level) triggers a logarithmic response to intensity increases. As such, absolute summation of pressure by all points should not be compared (as implied by [56]), but rather, the overall summation of pressure from the points that actually exceed such minimum perceivable threshold.

The increase in N_{fp} also decreased arousal, particularly between 1 and 3 points. This suggests that using more points could be an effective way to produce more calming user responses. The lack of effects of N_{fp} on valence aligned again with prior results from V_d, reinforcing the difficulty to measure such response and also that, while frequency and pattern length affected valence (as reported by [1]), neither V_d nor N_{fp} did.

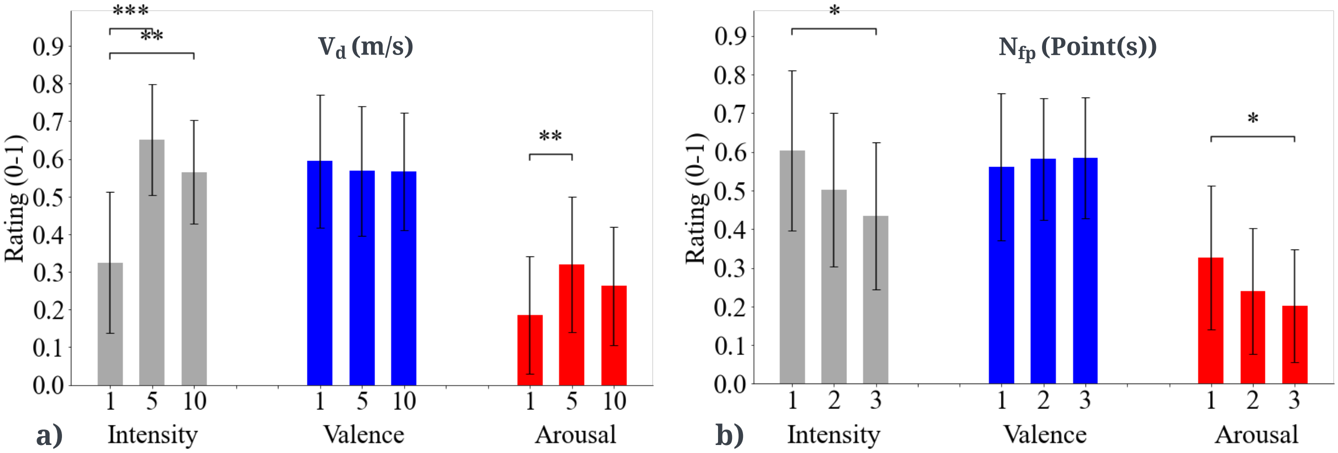


Figure 5: Summary of results on perceived intensity, valence, and arousal according to: a) Drawing speed (V_d); and b) number of points (N_{fp}). Bars represent the mean, error bars represent the standard deviation and statistical differences between pairs are shown as asterisks (* represents p≤0.05, ** represents p≤0.01, *** represents p≤0.001).

4.3 Joint effects of drawing speed and number of focal points on perceptual and emotional responses

The above analysis considered the effects of each modulation parameter (V_d and N_{fp}) independently. We also considered whether some trends could be observed when considering them jointly.

The variation of intensity, valence, and arousal with respect to the V_d for each N_{fp} is shown in Figure 6.

We can observe that the average trend of the effect of V_d on intensity, for each different N_{fp} was similar even with changes in N_{fp}, and they were visually similar to the average trends shown in Figure 5a. The same principle also applied to valence and arousal ratings. Moreover, when the stimulus V_d increased from 5 to 10 m/s, participants tended to rate the stimulus more neutral (not very pleasant or unpleasant). However, a large variance in ratings can also be spotted in Figure 6. We presume that the amount of deviation from the averaged plots of Figure 6 showed the effects of subjectivity involved in this experiment, but these were also in line with those observed in single-point STM [15]. It is interesting that the effect of V_d on perceived arousal across different N_{fp} was similar to that of V_d on perceived intensity across different N_{fp}.

We visualized the effect of N_{fp} and V_d on participants' valence and arousal using the circumplex model [59]. Figure 7 shows such distribution, according to the speed used (sub-plots a), b) and c)), with the number of points identified by the marker colour (i.e., red = 1, blue = 2, black =3 points). We normalized valence and arousal ratings between -1 and 1, and also used PCA to determine the ellipse fitting participants' responses for each category (i.e., same V_d and N_{fp}).

Most of the responses were concentrated towards the positive valence, low arousal quadrant (bottom-right), representing calm and pleasant/positive emotions. When V_d was slow (1 m/s, see Figure 7a), participants perceived stimuli as more pleasant and calming (closer to the sleepiness category [59]) and thus more relaxing). When the V_d was higher (V_d = 5 or 10 m/s, in Figures 7b) and c), respectively), participants perceived stimuli as more neutral in valence but more arousing (stimulating).

Looking at results according to the number of points, we found that the more N_{fp} we used (blue and black markers), the more calming participants felt. On the other hand, using a single point (red markers) led to higher arousal.

Both results provide further insight into the relationships between perceived intensity and arousal/valence. Highest intensity ratings were obtained for V_d = 5 m/s and N_{fp} = 1, which in turn led to more arousing and relatively unpleasant stimuli (red ellipse in Figure 7b). For medium intensity ratings (V_d = 10 m/s and N_{fp} of 2 or 3 points), participants reported lower valence and arousal (blue and black ellipses closer to origin, in Figure 7c). Lowest intensities (V_d = 1 m/s and the N_{fp} of 2 or 3 points) resulted in more pleasant, calming and thus relaxing or comforting responses (blue and black ellipses closer to bottom-right corner, in Figure 7a). These results further supported the existence of a potential relationship between perceived intensity and arousal. Such a result would align with observations from Obrist et al. [53], who studied the effects of intensity on valence and arousal, even if they did so for a different technique (AM). They indeed found that lower intensity could introduce positive valence and low arousal, which held in our case where the intensity level was the lowest (blue and black ellipses in Figure 7a). They also found that medium intensity could introduce negative or neutral valence with low arousal, which was not obvious from our results (no clear effects on valence). However, this also indicated that results observed from other techniques (i.e., AM) can also be partially reusable for multi-point STM.

5 DISCUSSION AND DESIGN IMPLICATIONS

In this paper, we investigated the effect of two multi-point STM parameters (V_d and N_{fp}) on perceived intensity, valence and arousal.

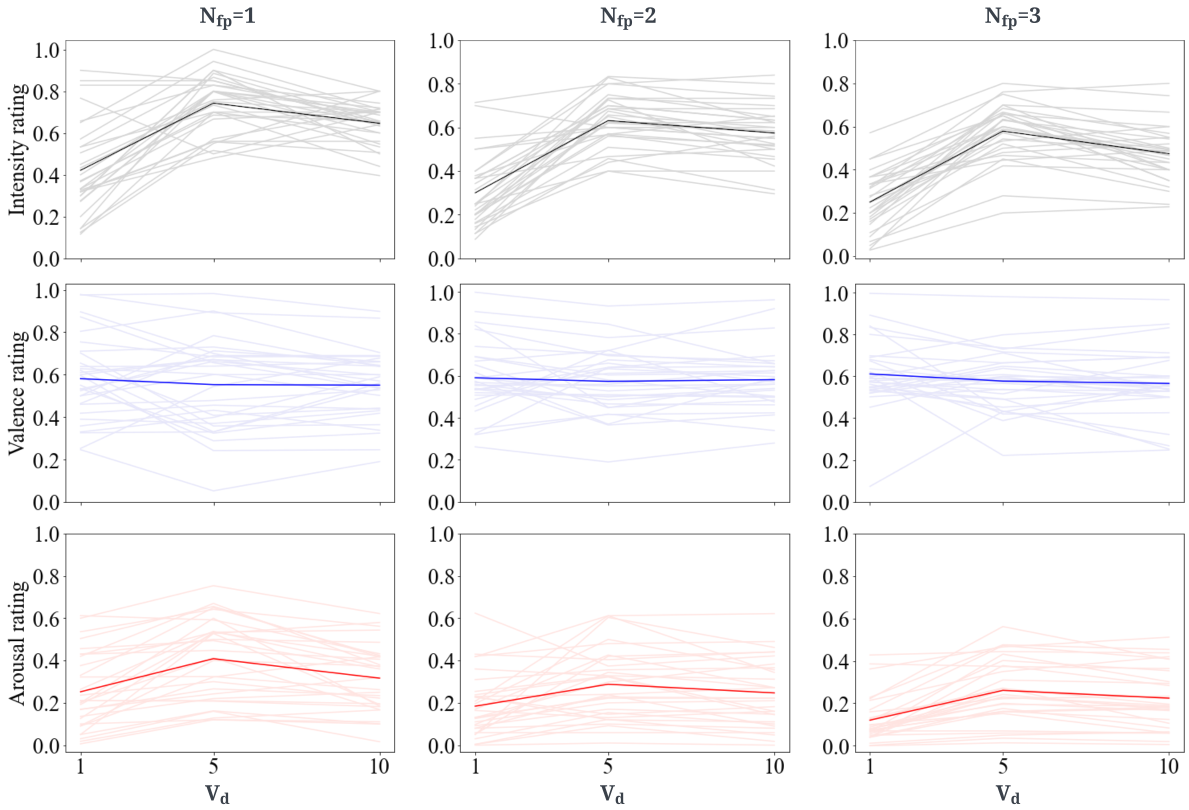


Figure 6: Overview of all participants' responses per V_d and N_{fp}. Darker lines represent average ratings across all participants.

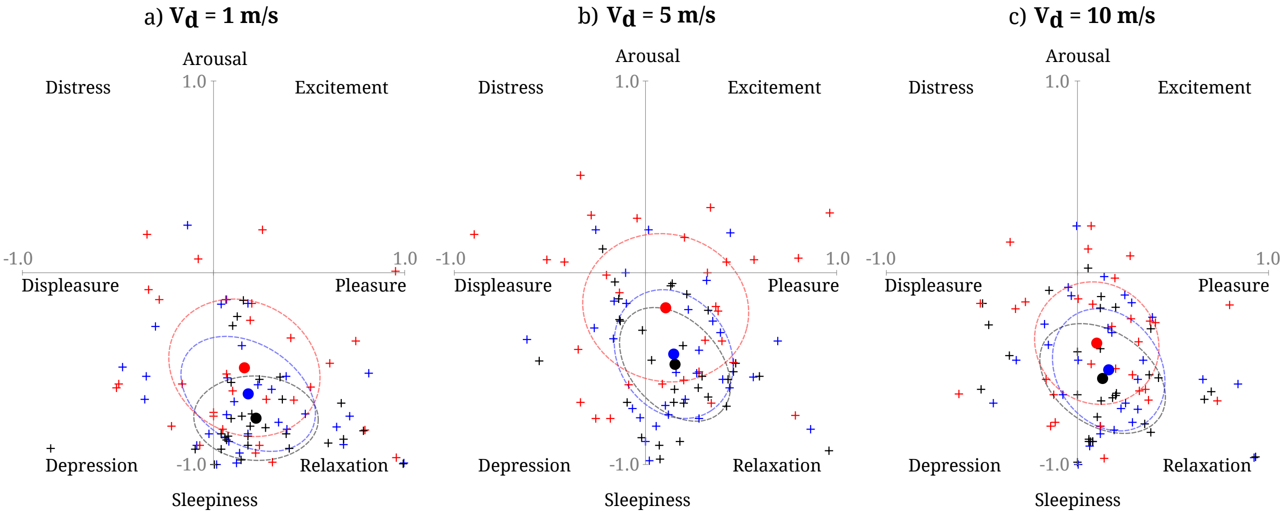

a) V_d = 1 m/s
b) V_d = 5 m/s
c) V_d = 10 m/s

Figure 7: Valence and Arousal responses of participants presented on the circumplex valence-arousal model. Each plot presents a different Drawing Speed (i.e., a) V_d= 1 m/s; b) V_d= 5 m/s; c) V_d= 10 m/s), with The colour of each sample indicating the number of points used (red = 1 point; blue = 2 points; black = 3 points). Centroid and fitting ellipse for each category (combination of V_d and N_{fp}), are presented by larger symbols and dashed lines. (See Figure 1 in supplementary material for clear colour contrast version)

Our results could be further extended by testing further modulation parameters (e.g., different shapes, sizes or drawing frequencies). Objective measurements such as skin conductance responses (SCR) [17, 20, 74], electroencephalography signals [72] and heart rate responses [2] could also be included to reinforce our understanding. Further exploration of the apparent correlation between users' perception of stimuli intensity and their emotions would certainly be required. However, even within its limited scope, our study provides useful insight into how to use multi-point STM parameters to provide different perceptual and emotional responses.

For designers and makers within the UMH domain, our findings suggest that the way V_d affects users' perceptual and emotional response in STM also applies to multi-point STM.. This result should be confirmed for other parameters and conditions (e.g., shapes), but it would facilitate reusing knowledge, lessons learned, or even tools in this new domain. For instance, this would allow using more focal points in STM, but using optimum speeds and frequencies selected/tested from single-point STM.

Our findings also provide insights on how to use V_d to affect perceived intensity and arousal (for either STM or multi-point STM), showing that:1) lower V_d provides low intensity, arousing and high valence stimuli; 2) higher V_d provides high intensity, neutral valence and more arousing stimuli; and 3) we can use V_d to alter users' perceived intensity and arousal without interfering with their valence due to the non-significant effect of V_d on valence responses. For instance, we can use UMH in VR games or phone conversations [54] to uniquely express user's feelings of excitation to others or even to people with visual or auditory impairment [64]. We can also combine UMH with digital advertising applications [40, 41] to provide more emotionally activating trailers for gaining potential customers.

Our results enable N_{fp} as an additional degree of freedom to play with, illustrating a trade-off in which more points reduce the perceived intensity and arousal but also lead to more pleasant stimuli. These observations could inspire designers to use UMH with applications requiring emotional (i.e., rather than functional) haptic feedback. For instance, we can merge UMH with VR music rhythm games [19], leveraging arousal to enhance the musical interaction experience, or aim for more exciting (arousing) stimuli for more lively storytelling experiences [31]. From an educational perspective, we can introduce UMH to educational or therapeutic applications to help understand the emotional state of juveniles [38, 52]. Also, our results show that overall perceived intensity and arousal do not degrade significantly when extended to 2 focal points. This opens opportunities to explore more complicated shapes [23], or some of the additional techniques suggested by [56], such as each point using a different drawing speed for multi-frequency feedback, which could in turn open new possibilities for UMH.

Our results also confirmed a correlation between perceived intensity and arousal, observed for AM by [53] and which could be exploited for multi-point STM. For example, our experiment results could benefit other applications that use stimulus intensity to drive user emotional activation.

To summarize, we found that lower perceived intensity, arousal, and higher valence could be achieved using a higher number of points and slower drawing speed. Medium perceived intensity, relatively higher arousal and neutral valence can be achieved using a lower number of points and higher drawing speed. Finally, higher perceived intensity, arousal and lower valence can be achieved using a single point and higher drawing speed. Therefore, our results indicated that single-point STM should be used when we want to introduce stimuli with higher intensity and emotionally activate users. Multi-point STM should be used when we want to introduce stimuli with mild intensity or help users relax. For designers and makers, these factors can be reused in multi-point STM for various applications. We can affect users' perceived pleasantness and significantly affect arousal with multi-point STM, and our findings can be applied to the technologies that provide relaxation [73] or help with meditation [6, 29, 72]. We can add a new dimension (arousal) to existing applications that currently provide varying intensity feedback only.

6 CONCLUSION

In this paper, we investigated the independent effect of drawing speed (V_d) and the number of points (N_{fp}) on user perceptual and emotional responses using multi-point STM rendered by ultrasonic mid-air haptics. Generally, we found that parameter from single-point STM also apply to multi-point STM. This provided opportunities for reusing knowledge, lessons learned, or even tools in this new domain. We also could confirm that the selected parameters affect almost all measures we considered (prior studies did not look at all of them together). The trend of how drawing speed affects responses was very similar between single-point STM and multi-point STM. Our results indicated that single-point STM should be used when we want to introduce stimuli with higher intensity and emotionally activate users. Multi-point STM should be used when we want to introduce stimuli with mild intensity or help users relax. Our findings help to understand how humans perceive mid-air haptic stimuli, specifically with STM, and advance the design of mid-air haptic systems that elicit emotional responses and its related applications by introducing a new degree of freedom - the number of focal points (N_{fp}) in terms of user tactile experience.

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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] Russell M Bauer and W Edward Craighead. 1979. Psychophysiological responses to the imagination of fearful and neutral situations: The effects of imagery instructions. *Behavior Therapy* 10, 3 (1979), 389–403. https://doi.org/10.1016/S0005-7894(79)80027-1

[3] Alessio Benavoli, Giorgio Corani, and Francesca Mangili. 2016. Should We Really Use Post-Hoc Tests Based on Mean-Ranks? *J. Mach. Learn. Res.* 17, 1 (jan 2016), 152–161. https://doi.org/10.5555/2946645.2946650

[4] Hayfa Blaiech, Mohamed Neji, Ali Wali, and Adel M Alimi. 2013. Emotion recognition by analysis of EEG signals. In *13th International Conference on Hybrid*

Intelligent Systems (HIS 2013) (Gammarth, Tunisia). IEEE, IEEE, 312–318. https://doi.org/10.1109/HIS.2013.6920451

[5] Margaret M Bradley and Peter J Lang. 1994. Measuring emotion: the self-assessment manikin and the semantic differential. *Journal of behavior therapy and experimental psychiatry* 25, 1 (1994), 49–59. https://doi.org/10.1016/0005-7916(94)90063-9

[6] Antoinette Leanna Bumatay and Jinsil Hwaryoung Seo. 2015. Investigating the role of haptic stimulation in mobile meditation tools. In *International Conference on Human-Computer Interaction*. Springer, Springer International Publishing, Cham, 451–456. https://doi.org/10.1007/978-3-319-21383-5_75

[7] Tom Carter, Sue Ann Seah, Benjamin Long, Bruce Drinkwater, and Sriram Subramanian. 2013. UltraHaptics: multi-point mid-air haptic feedback for touch surfaces. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (St. Andrews, Scotland, United Kingdom) *(UIST '13)*. Association for Computing Machinery, New York, NY, USA, 505–514. https://doi.org/10.1145/2501988.2502018

[8] Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. 2017. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology* (Québec City, QC, Canada) *(UIST '17)*. Association for Computing Machinery, New York, NY, USA, 119–130. https://doi.org/10.1145/3126594.3126599

[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. https://doi.org/10.3724/SP.J.2096-5796.2019.0009

[10] J Cohen. 1988. edition 2. Statistical power analysis for the behavioral sciences. , 567 pages. https://doi.org/10.4324/9780203771587

[11] William Jay Conover. 1999. *Practical nonparametric statistics*. Vol. 350. john wiley & sons. https://books.google.co.uk/books?hl=zh-TW&lr=&id=n_39DwAAQBAJ&oi=fnd&pg=PA1&ots=L9gvYHrpI5&sig=RnN6Wox0vW1NYjs362h8YDav9MI&redir_esc=y#v=onepage&q&f=false

[12] Diane Dalecki, Sally Z Child, Carol H Raeman, and Edwin L Carstensen. 1995. Tactile perception of ultrasound. *The Journal of the Acoustical Society of America* 97, 5 (1995), 3165–3170. https://doi.org/10.1121/1.411877

[13] 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. https://doi.org/10.1080/01621459.1937.10503522

[14] 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. https://doi.org/10.1007/978-3-319-93445-7_24

[15] William Frier, Dario Pittera, Damien Ablart, Marianna Obrist, and Sriram Subramanian. 2019. Sampling strategy for ultrasonic mid-air haptics. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems* (Glasgow, Scotland Uk) *(CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–11. https://doi.org/10.1145/3290605.3300351

[16] Antonio Frisoli, Massimiliano Solazzi, Fabio Salsedo, and Massimo Bergamasco. 2008. A fingertip haptic display for improving curvature discrimination. *Presence: Teleoperators and Virtual Environments* 17, 6 (12 2008), 550–561. https://doi.org/10.1162/pres.17.6.550

[17] Elia Gatti, Elena Calzolari, Emanuela Maggioni, and Marianna Obrist. 2018. Emotional ratings and skin conductance response to visual, auditory and haptic stimuli. *Scientific data* 5, 1 (2018), 1–12. https://doi.org/10.1038/sdata.2018.120

[18] Orestis Georgiou, Valerio Biscione, Adam Harwood, Daniel Griffiths, Marcello Giordano, Ben Long, and Tom Carter. 2017. Haptic in-vehicle gesture controls. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications Adjunct* (Oldenburg, Germany) *(AutomotiveUI '17)*. Association for Computing Machinery, New York, NY, USA, 233–238. https://doi.org/10.1145/3131726.3132045

[19] Orestis Georgiou, Craig Jeffrey, Ziyuan Chen, Bao Xiao Tong, Shing Hei Chan, Boyin Yang, Adam Harwood, and Tom Carter. 2018. Touchless haptic feedback for VR rhythm games. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEE Computer Society, Los Alamitos, CA, USA, 553–554. https://doi.org/10.1109/VR.2018.8446619

[20] Mark K Greenwald, Edwin W Cook, and Peter J Lang. 1989. Affective judgment and psychophysiological response: dimensional covariation in the evaluation of pictorial stimuli. *Journal of psychophysiology* 3 (1989), 14 pages. https://psycnet.apa.org/record/1990-03841-001

[21] Sidhant Gupta, Dan Morris, Shwetak N Patel, and Desney Tan. 2013. Airwave: Non-contact haptic feedback using air vortex rings. In *Proceedings of the 2013 ACM international joint conference on Pervasive and ubiquitous computing* (Zurich, Switzerland) *(UbiComp '13)*. Association for Computing Machinery, New York, NY, USA, 419–428. https://doi.org/10.1145/2493432.2493463

[22] Hakan Gurocak, Sankar Jayaram, Benjamin Parrish, and Uma Jayaram. 2003. Weight Sensation in Virtual Environments Using a Haptic Device With Air Jets. *J. Comput. Inf. Sci. Eng.* 3 (2003), 130–135. https://doi.org/10.1115/1.1576808

[23] 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. https://doi.org/10.1109/TOH.2020.2966445

[24] Kyle Harrington, David R Large, Gary Burnett, and Orestis Georgiou. 2018. Exploring the use of mid-air ultrasonic feedback to enhance automotive user interfaces. In *Proceedings of the 10th international conference on automotive user interfaces and interactive vehicular applications* (Toronto, ON, Canada) *(AutomotiveUI '18)*. Association for Computing Machinery, New York, NY, USA, 11–20. https://doi.org/10.1145/3239060.3239089

[25] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. 2018. Dextres: Wearable haptic feedback for grasping in vr via a thin form-factor electrostatic brake. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology* (Berlin, Germany) *(UIST '18)*. Association for Computing Machinery, New York, NY, USA, 901–912. https://doi.org/10.1145/3242587.3242657

[26] 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 (WHC '09)*. IEEE, IEEE Computer Society, USA, 256–260. https://doi.org/10.1109/WHC.2009.4810900

[27] Takayuki Hoshi, Masafumi Takahashi, Takayuki Iwamoto, and Hiroyuki Shinoda. 2010. Noncontact tactile display based on radiation pressure of airborne ultrasound. *IEEE Transactions on Haptics* 3, 3 (2010), 155–165. https://doi.org/10.1109/toh.2010.4

[28] 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

[29] Mahmoud Mohamed Hussien Ahmed, Chaklam Silpasuwanchai, Kavous Salehzadeh Niksirat, and Xiangshi Ren. 2017. Understanding the role of human senses in interactive meditation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4960–4965. https://doi.org/10.1145/3025453.3026000

[30] Inwook Hwang, Hyungki Son, and Jin Ryong Kim. 2017. AirPiano: Enhancing music playing experience in virtual reality with mid-air haptic feedback. In *2017 IEEE world haptics conference (WHC)* (Munich, Germany). IEEE, IEEE, 213–218. https://doi.org/10.1109/WHC.2017.7989903

[31] Ali Israr, Siyan Zhao, Kaitlyn Schwalje, Roberta Klatzky, and Jill Lehman. 2014. Feel effects: enriching storytelling with haptic feedback. *ACM Transactions on Applied Perception (TAP)* 11, 3, Article 11 (sep 2014), 17 pages. https://doi.org/10.1145/2641570

[32] 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* (Madrid, Spain) *(EuroHaptics '08)*. Springer, Springer Berlin Heidelberg, Berlin, Heidelberg, 504–513. https://doi.org/10.1007/978-3-540-69057-3_64

[33] 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. https://doi.org/10.1038/nrn2621

[34] ER Kandel, JH Schwartz, TM Jessell, SA Siegelbaum, AJ Hudspeth, and S Mack. 2012. Principles of Neural Science, 5th Edn, eds A. Sydor and H. Lebowitz.

[35] 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. https://doi.org/10.1121/1.5036027

[36] Hwan Kim, HyeonBeom Yi, Hyein Lee, and Woohun Lee. 2018. Hapcube: A wearable tactile device to provide tangential and normal pseudo-force feedback on a fingertip. 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, 1–13. https://doi.org/10.1145/3173574.3174075

[37] Sashidharan Komandur, Peter W Johnson, Richard L Storch, and Michael G Yost. 2009. Relation between index finger width and hand width anthropometric measures. In *2009 Annual International Conference of the IEEE Engineering in Medicine and Biology Society* (Minneapolis, MN, USA). IEEE, IEEE, 823–826. https://doi.org/10.1109/iembs.2009.5333195

[38] GE Lancioni, AJ Cuvo, and MF O'reilly. 2002. Snoezelen: an overview of research with people with developmental disabilities and dementia. *Disability and rehabilitation* 24, 4 (2002), 175–184. https://doi.org/10.1080/09638280110074911

[39] Hojin Lee, Ji-Sun Kim, Seungmoon Choi, Jae-Hoon Jun, Jong-Rak Park, A-Hee Kim, Han-Byeol Oh, Hyung-Sik Kim, and Soon-Cheol Chung. 2015. Mid-air tactile stimulation using laser-induced thermoelastic effects: The first study for indirect radiation. In *2015 IEEE World Haptics Conference (WHC)* (Evanston, IL, USA). IEEE, IEEE, 374–380. https://doi.org/10.1109/WHC.2015.7177741

[40] Hannah Limerick. 2020. Call to interact: Communicating interactivity and affordances for contactless gesture controlled public displays. In *Proceedings of the 9TH ACM International Symposium on Pervasive Displays* (Manchester, United Kingdom) *(PerDis '20)*. Association for Computing Machinery, New York, NY, USA, 63–70. https://doi.org/10.1145/3393712.3395338

[41] Hannah Limerick, Richard Hayden, David Beattie, Orestis Georgiou, and Jörg Müller. 2019. User engagement for mid-air haptic interactions with digital signage. In *Proceedings of the 8th ACM international symposium on pervasive displays* (Palermo, Italy) *(PerDis '19)*. Association for Computing Machinery, New York, NY, USA, Article 15, 7 pages. https://doi.org/10.1145/3321335.3324944

[42] 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, Article 181 (nov 2014), 10 pages. https://doi.org/10.1145/2661229.2661257

[43] Pedro Lopes and Patrick Baudisch. 2013. Muscle-propelled force feedback: bringing force feedback to mobile devices. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 2577–2580. https://doi.org/10.1145/2470654.2481355

[44] Pedro Lopes, Sijing You, Lung-Pan Cheng, Sebastian Marwecki, and Patrick Baudisch. 2017. Providing haptics to walls & heavy objects in virtual reality by means of electrical muscle stimulation. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 1471–1482. https://doi.org/10.1145/3025453.3025600

[45] Pedro Lopes, Sijing You, Alexandra Ion, and Patrick Baudisch. 2018. Adding force feedback to mixed reality experiences and games using electrical muscle stimulation. 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, 1–13. https://doi.org/10.1145/3173574.3174020

[46] Jonatan Martinez, Daniel Griffiths, Valerio Biscione, Orestis Georgiou, and Tom Carter. 2018. Touchless haptic feedback for supernatural VR experiences. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*. IEEE, IEEE Computer Society, Los Alamitos, CA, USA, 629–630. https://doi.org/10.1109/VR.2018.8446522

[47] 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

[48] John W Mauchly. 1940. Significance test for sphericity of a normal n-variate distribution. *The Annals of Mathematical Statistics* 11, 2 (1940), 204–209. http://www.jstor.org/stable/2235878

[49] Kouta Minamizawa, Domenico Prattichizzo, and Susumu Tachi. 2010. Simplified design of haptic display by extending one-point kinesthetic feedback to multipoint tactile feedback. In *2010 IEEE Haptics Symposium (HAPTIC '10)*. IEEE, IEEE Computer Society, Los Alamitos, CA, USA, 257–260. https://doi.org/10.1109/HAPTIC.2010.5444646

[50] Roberto Montano-Murillo, Ryuji Hirayama, and Diego Martinez Plasencia. 2023. OpenMPD: A Low-Level Presentation Engine for Multimodal Particle-Based Displays. *ACM Trans. Graph.* (feb 2023), 22 pages. https://doi.org/10.1145/3572896 Just Accepted.

[51] 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. https://doi.org/10.1109/toh.2021.3125843

[52] Neda Novakovic, Milica Pejovic Milovancevic, Slavica Djukic Dejanovic, and Branko Aleksic. 2019. Effects of Snoezelen—Multisensory environment on CARS scale in adolescents and adults with autism spectrum disorder. *Research in developmental disabilities* 89 (2019), 51–58. https://doi.org/10.1016/j.ridd.2019.03.007

[53] 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

[54] Young-Woo Park, Kyoung-Min Baek, and Tek-Jin Nam. 2013. The roles of touch during phone conversations: long-distance couples' use of POKE in their homes. In *Proceedings of the SIGCHI conference on human factors in computing systems* (Paris, France) *(CHI '13)*. Association for Computing Machinery, New York, NY, USA, 1679–1688. https://doi.org/10.1145/2470654.2466222

[55] Dario Pittera, Orestis Georgiou, Abdenaceur Abdouni, and William Frier. 2021. " I can feel it coming in the hairs tonight": Characterising Mid-Air Haptics on the Hairy Parts of the Skin. *IEEE Transactions on Haptics* 15, 1 (2021), 188—199. https://doi.org/10.1109/toh.2021.3110722

[56] 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

[57] 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 (jan 2019), 736–745. https://doi.org/10.1109/TIE.2019.2910036

[58] Sonja Rümelin, Thomas Gabler, and Jesper Bellenbaum. 2017. Clicks are in the air: how to support the interaction with floating objects through ultrasonic feedback. In *Proceedings of the 9th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Oldenburg, Germany) *(AutomotiveUI '17)*. Association for Computing Machinery, New York, NY, USA, 103–108. https://doi.org/10.1145/3122986.3123010

[59] James A Russell. 1980. A circumplex model of affect. *Journal of personality and social psychology* 39, 6 (1980), 1161. https://doi.org/10.1037/h0077714

[60] Satoshi Saga. 2015. HeatHapt thermal radiation-based haptic display. In *Haptic Interaction*, Hiroyuki Kajimoto, Hideyuki Ando, and Ki-Uk Kyung (Eds.). Springer Japan, Tokyo, 105–107. https://doi.org/10.1007/978-4-431-55690-9_19

[61] Antti Sand, Ismo Rakkolainen, Poika Isokoski, Jari Kangas, Roope Raisamo, and Karri Palovuori. 2015. Head-mounted display with mid-air tactile feedback. In *Proceedings of the 21st ACM symposium on virtual reality software and technology* (Beijing, China) *(VRST '15)*. Association for Computing Machinery, New York, NY, USA, 51–58. https://doi.org/10.1145/2821592.2821593

[62] Samuel B Schorr and Allison M Okamura. 2017. Fingertip tactile devices for virtual object manipulation and exploration. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3115–3119. https://doi.org/10.1145/3025453.3025744

[63] Gözel Shakeri, John H Williamson, and Stephen Brewster. 2018. May the force be with you: Ultrasound haptic feedback for mid-air gesture interaction in cars. In *Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications* (Toronto, ON, Canada) *(AutomotiveUI '18)*. Association for Computing Machinery, New York, NY, USA, 1–10. https://doi.org/10.1145/3239060.3239081

[64] Calle Sjostrom. 2001. Designing haptic computer interfaces for blind people. In *Proceedings of the Sixth International Symposium on Signal Processing and its Applications (Cat. No. 01EX467)* (Kuala Lumpur, Malaysia), Vol. 1. IEEE, IEEE, 68–71. https://doi.org/10.1109/ISSPA.2001.949777

[65] Daniel Spelmezan, Deepak Ranjan Sahoo, and Sriram Subramanian. 2017. Sparkle: Hover feedback with touchable electric arcs. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 3705–3717. https://doi.org/10.1145/3025453.3025782

[66] Paul Strohmeier and Kasper Hornbæk. 2017. Generating haptic textures with a vibrotactile actuator. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (Denver, Colorado, USA) *(CHI '17)*. Association for Computing Machinery, New York, NY, USA, 4994–5005. https://doi.org/10.1145/3025453.3025812

[67] Yuriko Suzuki and Minoru Kobayashi. 2005. Air jet driven force feedback in virtual reality. *IEEE computer graphics and applications* 25, 1 (jan 2005), 44–47. https://doi.org/10.1109/MCG.2005.1

[68] 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. https://doi.org/10.1007/978-3-319-93399-3_25

[69] Shan-Yuan Teng, Pengyu Li, Romain Nith, Joshua Fonseca, and Pedro Lopes. 2021. Touch&Fold: a foldable haptic actuator for rendering touch in mixed reality. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 736, 14 pages. https://doi.org/10.1145/3411764.3445099

[70] Kai Tsumoto, Tao Morisaki, Masahiro Fujiwara, Yasutoshi Makino, and Hiroyuki Shinoda. 2021. Presentation of Tactile Pleasantness Using Airborne Ultrasound. In *2021 IEEE World Haptics Conference (WHC)* (Montreal, QC, Canada). IEEE, IEEE, 602–606. https://doi.org/10.1109/WHC49131.2021.9517249

[71] Hajime Uchiyama, Michael A Covington, and Walter D Potter. 2008. Vibrotactile glove guidance for semi-autonomous wheelchair operations. In *Proceedings of the 46th Annual Southeast Regional Conference on XX* (Auburn, Alabama) *(ACM-SE 46)*. Association for Computing Machinery, New York, NY, USA, 336–339. https://doi.org/10.1145/1593105.1593195

[72] Dangxiao Wang, Mu Xu, Yuru Zhanq, and Jing Xiao. 2013. Preliminary study on haptic-stimulation based brainwave entrainment. In *2013 World Haptics Conference (WHC)* (Daejeon, Korea (South)). IEEE, IEEE, 565–570. https://doi.org/10.1109/WHC.2013.6548470

[73] Esko O Dijk Alina Weffers. 2010. Breathe with the ocean: a system for relaxation using audio, haptic and visual stimuli. *EuroHaptics 2010* 47 (2010), 14 pages. https://core.ac.uk/download/pdf/11475618.pdf#page=57

[74] Ward M Winton, Lois E Putnam, and Robert M Krauss. 1984. Facial and autonomic manifestations of the dimensional structure of emotion. *Journal of Experimental Social Psychology* 20, 3 (1984), 195–216. https://doi.org/10.1016/0022-1031(84)90047-7

[75] Gareth Young, Hamish Milne, Daniel Griffiths, Elliot Padfield, Robert Blenkinsopp, and Orestis Georgiou. 2020. Designing mid-air haptic gesture controlled user interfaces for cars. *Proceedings of the ACM on Human-Computer Interaction* 4, EICS, Article 81 (jun 2020), 23 pages. https://doi.org/10.1145/3397869