Using Ultrasonic Mid-air Haptic Patterns in Multi-Modal User Experiences

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***Abstract*—Ultrasonic mid-air tactile displays offer a unique combination of high spatial and temporal resolution and can stimulate a wide range of tactile frequencies. Leveraging those features, a new modulation technique producing spatially distributed tactile sensations has recently been introduced. This new approach, referred to as Spatiotemporal Modulation (STM), draws lines, curves and shapes on users' palm by moving a mid-air tactile point rapidly and repeatedly along the path. STM parameters and their impact on tactile perception are yet to be studied systematically. In this work, we first study how varying the draw frequency and the size of a simple shape affects the participants perception of texture and their emotional responses. In the second part of our study, we used the most salient tactile patterns of the first study to extend the results within a multimodal context. We found that tactile patterns' perception was consistent within both studies. We also found instances when the tactile patterns could alter the perception of the audio and visual stimuli. Finally, we discuss the benefits of our findings and conclude with implications for future work.**

***Index Terms*—mid-air, haptics, tactile, multi-modal, user experience, multisensory**

I. Introduction

Mid-air haptics is a growing research field with the advantage that users do not need to hold or wear any attachments to feel tactile feedback while interacting with video games [1], movies [2], art pieces [3], and is therefore an emerging new Human Machine Interface (HMI) [4]. Moreover, mid-air haptics has the opportunity to compliment current media and create more compelling and realistic experiences. However, as with many new HMIs, how mid-air haptics stimulation impacts media perception is still not fully understood and merits further investigation.

In this paper, we focus on ultrasonic mid-air haptics to produce mid-air tactile stimuli. Following, a method introduced in 2008 [5], the mechanical properties of sound wave can be leveraged to create tactile feedback in mid-air. A set of ultrasonic transducers, if synchronised, can focus acoustic pressure at a desired location in space hence creating a pressure point in mid-air referred as a focal point. This focal point is able to indent the human skin, however the high frequency used by the ultrasonic transducers (in most cases around $40\,\text{kHz}$) is too high to be felt by human mechanoreceptors (the skin can feel vibrations up to $500\,\text{Hz}$ [6]). To alleviate this and cause a tactile sensation, the common approach is to modulate the amplitude of the signal at frequencies from $20\,\text{Hz}$ to $250\,\text{Hz}$. This approach, referred as Amplitude Modulation (AM), has been used in several work, to create emotional textures [7] or to augment short film content [2]. However, the AM patterns are localised and limited to just a few focal points, thus limiting the spatial information that can be conveyed.

With the aim to convey more complex patterns, a new approach has been produced referred to as Spatiotemporal Modulation (STM), where the focal point location is modulated instead of its amplitude [8]. With this technique, the amplitude of the point is maintained at a constant intensity, but its location is varying quickly alongside a desired curve (e.g. a circle). The focal point motion causes perceivable vibrations on the skin surface. The frequency of this vibration is mainly dominated by the number of times the point repeats the curve per second. In a first exploration, Frier et al. [8] showed that the perceived intensity of STM mid-air haptic feedback with a circle-shaped pattern was directly related to its speed (i.e. *frequency* $\times$ *perimeter of the circle*) and not its frequency as in AM. In a second study, Frier et al. [9] showed that the perceived intensity of the feedback was further dependent on the number of sample positions along the curve.

In this paper, we expand the previous works by the authors by exploring how STM parameters and patterns (i.e. frequency and size) impact people's tactile experience alone and within a multimodal context. Here, tactile experience refers to five variables used to assess how participants perceive the tactile patterns. These five variables are: a) intensity, b) roughness, c) regularity, d) roundness, and e) valence. To that end, we conducted and report on two perceptual studies. In the first study, we started by exploring a large set of mid-air haptic patterns to find any relationship between parameter space and the different perceptual dimensions assessed and construct associations – links between parameter space and perceptual space. Then, we ran a second and larger perceptual study using a subset of the first study with mid-air haptic stimuli in combination with audio and visual stimuli from a standardised database [10]. Our goal was twofold: (1) confirm that mid-air haptic parameters like frequency and pattern size can strongly affect tactile experience, and (2) assess how the perception of audio and visual stimuli is affected by mid-air haptic stimuli. Specifically, we choose to limit the investigations to mid-air haptic stimuli covering different perceptual spaces (e.g. soft and rough), while the combination of media and haptics was allowed to either be congruent or incongruent. The results of the first study showed that varying pattern size and frequency could indeed change the intensity, roughness, regularity, and roundness ratings. The results of the second study confirmed those results even in the presence of auditory and visual stimuli. Furthermore, the tactile patterns could successfully sway the perception of the auditory and visual content one way or another thus suggesting the possibility of haptic augmentation [11].

In summary, this paper presents a first exploration of STM ultrasonic mid-air haptics to create different tactile experiences in a multimodal setting. Namely, we applied those different patterns alongside standardised auditory and visual stimuli to understand how these other senses could be influenced. Our results present opportunities for new applications using mid-air haptic stimuli, especially in enriching and enhancing media content.

II. Apparatus and Setup

The ultrasonic tactile sensation was produced by an Ultrahaptics Evaluation Kit (UHEV1[1]) [12]. This device is composed of a 16×16 array of ultrasonic speakers controlled via a C# SDK (version 2.5). The device was updated at the highest rate possible with this SDK (i.e. $16\,\mathrm{kHz}$) using the time point streaming method, assuring the smoothest curve as possible for each pattern.

The ultrasonic board was embedded in an acrylic laser-cut black box to hide it from participants view. A hole of size $10 \times 10\,\mathrm{cm}$ was left open on the top of the box to allow the device to stimulate the participant's palm and feel the tactile sensations. This setup allowed a precise control of the distance from the board to the participant's hands ($16\,\mathrm{cm}$). Moreover, to avoid overheating, the bottom part of the box utilised a standard laptop cooler (see Figure 1).

The software and procedures used in this work was written in C# using Visual Studio 2017. The user study questionnaires were presented on-screen through a simple interface where only a mouse was required (only buttons and sliders). The auditory and visual stimuli were controlled by the same software, enabling smooth synchronisation and allowing a accurate control of the display time of each media.

In addition to the tactile feedback, participants used headphones with pink noise to cover the ambient noise and a 24 inches screen to display the questionnaires to the participants.

III. First Study: Haptic Perceptions

In this a first study, we sought to understand how different parameters of STM patterns affect the perceived experience. Since, there is no prior work studying the feelings and user experience resulting from STM mid-air haptics, this first exploratory study covers a wide range of stimuli to unveil any trends or differences. However, to keep the study scope focused, we limit the stimuli variability to two parameters: the pattern size (i.e. the length of the pattern's path), and the pattern frequency (i.e., how many times the pattern is drawn on the hand per second). In the section we report the design of the study, the procedure and the results.

[1]https://www.ultrahaptics.com/

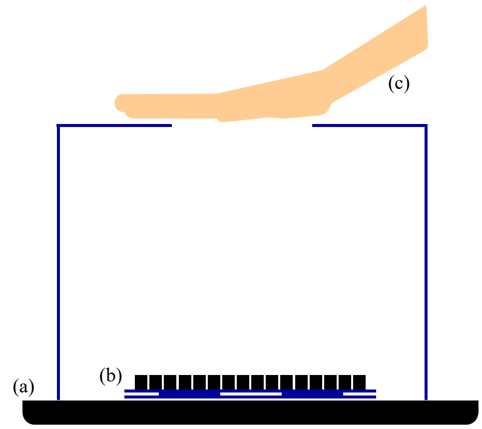

Fig. 1. The laser-cut acrylic box used for the study: (a) a laptop cooling pad placed below the ultrasonic mid-air board device to avoid overheating, (b) the ultrasonic mid-air board, and (c) the participant hand above the box, with their palm centred above the hole to which the ultrasonic waves are directed.

A. Study Design

To keep the design consistent with previous studies that use STM, all the tactile patterns used here where in the shape of a circle as it provides a perfectly regular shape (i.e. the geometric update to draw the circle is always the same). We also kept the same three sizes ($5\,\mathrm{cm}$, $10\,\mathrm{cm}$ and $20\,\mathrm{cm}$) [8] and 20 frequencies from $5\,\mathrm{Hz}$ to $100\,\mathrm{Hz}$ with a $5\,\mathrm{Hz}$ step, for a total of 60 tactile circles.

For each tactile pattern, five questions were asked to assess (1) the strength of the circle, (2) some tactile properties and (3) associated emotion (see Table I). To assess the strength of the tactile feedback, question one (Q1) used a ratio scaling method of magnitude estimation scale. To assess the tactile properties, three questions (Q2-Q4) were presented to the participants about the roughness (i.e., does the pattern feels soft or rough) and the regularity (i.e., does the stimulus feel constant over time or not), and the roundness (i.e., does the pattern feels like round) Finally, Q5 rated the induced emotion through a sad/happy scale using valence pictures of the self-assessment manikin [13].

TABLE I
The five questions asked in the first study and the scales used.

ID	Questions
Q1	Intensity rating on a magnitude estimation scale
Q2	Roughness rating on a Likert scale (1-9 from soft to rough)
Q3	Regularity rating on a Likert scale (1-9 from regular to irregular)
Q4	Shape recognition rating on a Likert scale (1-9 from not at all to very much)
Q5	Emotion rating on a Likert scale (1-9) with SAM Valence pictures

B. Procedure

After reading the information sheet and signing the consent form, participants were comfortably seated in front of a computer screen with a mouse. The ultrasonic haptic box was

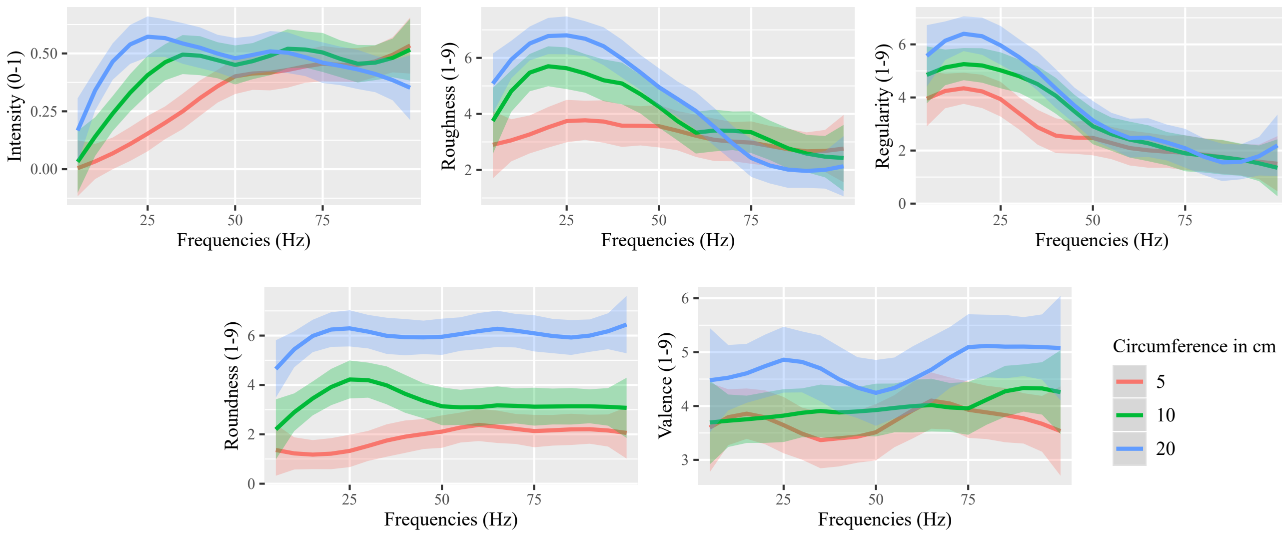

Fig. 2. Average ratings and standard error of the first study as function of pattern repetition frequency ranging between 5 Hz to 100 Hz, in increments of 5 Hz. Each panel corresponds to Q1-Q5, and plots the reported rating for a circle tactile pattern of perimeter 5 cm, 10 cm and 20 cm (red, green, blue curves), respectively.

placed under their left armrest with their palm adjusted and rested above the hole.

They were then introduced to the purpose of the study, including a description of the different scales used during the study. They were then invited to ask any questions related to safety of the collected data, the procedure of the experiment and the right to withdraw from the experiment at any time. After this, the users were presented with the different patterns, each for a duration of 5 s, and asked to rate them on the different scales.

C. Users

We recruited a total of 11 users (mean age 27.3 ± 4.2, 3 females). Users reported no impairments to their sense of touch. The experiment lasted on average 30 minutes and was rewarded with £5 (≈$6.5). This study has been approved by the ethics committee of the university.

D. Results

This first study was aimed at giving a first insight on how the different parameters of the STM might influence the perception and experience of different tactile patterns. In order to see any trends in the data, we plotted the mean data of questions Q1 to Q5 (see Figure 2). By analysing the Figure 2, we draw the following observations:

- Q1: the intensity follows and confirms the findings of [8], where the intensity rating is a result of the frequency by the size (i.e. the speed). For instance, the 5 cm circle reaches a plateau at 50 Hz (speed of $2.5\,\mathrm{m\,s^{-1}}$) and grows slowly to peak at 100 Hz (speed of $5\,\mathrm{m\,s^{-1}}$). Also, the 20 cm circle peaks at 25 Hz (speed of $5\,\mathrm{m\,s^{-1}}$) and decrease after 60 Hz (speed of $12\,\mathrm{m\,s^{-1}}$).
- Q2: for all the circle sizes, the roughness rating reached the highest value for a frequency value of around 25 Hz, with the 5 cm circle peaking at 3.75, 10 cm at 5.6 and the 20 cm at 6.8 on a 1 to 9 scale.
- Q3: the three circle patterns received are distinguishably different in terms of regularity for frequencies below 30 Hz, with the 5 cm circle peaking at 4.5, 10 cm at 5.2 and the 20 cm at 6.4 on a 1 to 9 scale, but then merge and are reported as being irregular.
- Q4: the roundness ratings seem to correlate positively with the size of the pattern. The 5 cm circle ratings are around 2, the 10 cm circle around 3 and the 20 cm circle around 6 on a scale from 1 to 9.
- Q5: the valence does not seem to follow any clear patterns, as standard error is wide and overlap each other, however the larger circle appears to be associated with higher valence for all frequencies tested.

E. Intermediary Discussion and Hypothesis

The results presented in this exploratory study give a first glimpse on how STM parameters could impact the tactile patterns experience.

The intensity's ratings are in line with previous studies, where the speed (*perimeter* × *frequency*) is the leading factor, with an optimal speed around $5\,\mathrm{m\,s^{-1}}$ to $10\,\mathrm{m\,s^{-1}}$. The roughness and the regularity present similar features with a maximal rating reached at frequencies around 25 Hz. Finally, both the roundness and valence ratings strongly depend on the pattern size while being impervious to pattern repetition frequency.

The above preliminary conclusions of the first study are now re-phrased as three hypothesis:

- Hypothesis 1: 25 Hz provides a significantly higher roughness than 75 Hz, especially when displaying a 20 cm circle.

- Hypothesis 2: 25 Hz provides a significantly higher regularity than 75 Hz, especially when displaying a 20 cm circle.
- Hypothesis 3: Larger circle size conveys a better sense of roundness irrespective of frequency.

IV. Second Study: Multimodal Perception

We used the results from the first user study to shape our second and larger study. Specifically, we are interested in the interplay of STM haptic patterns and audio-visual stimuli as used in recent works [2], [3], [7], [14]. For instance, can mid-air haptics have a significant effect on the 5 perceptual dimensions we tested (intensity, roughness, regularity, roundness, and valence) when displayed in conjunction with different audio and visual stimuli? To that end, we selected 4 tactile patterns from the previous study in combination with 4 audio stimuli and 4 visual stimuli from an emotional database [10]. The total number of selected stimuli is therefore 44; 12 individual stimuli (4 tactile, 4 visual and 4 audio stimuli), 16 pairs of tactile+audio, and 16 pairs of tactile+visual. Each pattern and each combination pair of tactile+audio and tactile+visual was rated on the same 5 perceptual dimensions as those used in the first user study.

A. Tactile Stimuli

To focus our results, we choose 4 tactile patterns from the first study of this paper. Namely, these 4 patterns where chosen such that we could test the hypothesis made in the previous section. The parameters chosen were:

- P1: 75 Hz & 20 cm
- P2: 75 Hz & 5 cm
- P3: 25 Hz & 20 cm
- P4: 25 Hz & 5 cm

B. Audio Visual stimuli

We selected the audio-visual stimuli from a standardised stimuli database [10] that is composed of:

- 10 pictures from the IAPS [15]
- 10 abstract art paintings
- 10 audio files for the IADS [16]
- 10 music extract from instrumental pieces

In order to reduce the number of audio-visual stimuli, we focused on getting 8 stimuli that fit the following four criteria: (1) four audio (2 music, 2 abstract sound) and four visual (2 pictures, 2 abstract) stimuli, (2) not distressful (e.g. avoiding dead bodies from IAPS), (3) cover different range of valence and roughness (with a low standard deviation), (4) no obvious link with scales used (removed round pictures). The chosen stimuli are presented in Table II.

C. Study Design

We selected 4 tactile patterns from the first study, 4 visual and 4 auditory stimuli from an emotional database and asked participants to rate them when presented alone (i.e. unimodal conditions) and alongside mid-air haptic stimuli (i.e. multimodal conditions: tactile+audio or tactile+visual).

TABLE II
List of audio and visual stimuli. The Media ID column refers to the ID from the original database. [10].

Media ID	Referred to as	Duration	Valence (0-100)	Arousal (0-100)
4	Music calm	45 s	69.17	58.32
6	Music fast	30 s	49.81	72.4
12	Sound bees	6 s	26.80	61.85
13	Sound waves	6 s	71.00	47.80
21	Abst. wave	5 s	56.66	31.78
25	Abst. art	5 s	60.96	47.35
32	Picture dog	5 s	24.91	62.75
37	Picture sunset	5 s	78.89	50.43

The five questions asked were the same as in the first study and it was explained to the users how to interpret the scales. Intensity and valence were mapped to the emotional response of users to the stimuli. The regularity corresponded to the changes over time (e.g. tempo, intensity, colours, style). The roughness was described as a scale going from smooth to rough. Finally, the roundness for the visual stimuli was interpreted as any association that could be made with a round shape. Similarly, for music it was left to users' preference to interpret and make an association between music and roundness.

D. Procedure

Users rated all stimuli alone (unimodal), as well as for each combination pair of tactile patterns and audio-visual stimuli (multimodal), giving a total of 44 unique stimuli. The unimodal conditions were used as based line for the multimodal conditions.

E. Users

We recruited a total of 20 users (mean age 28.25 ± 3.21, 7 females). Users reported no touch, vision, or auditory impairments. The experiment lasted on average 45 minutes and was rewarded with £5 ($\approx$\$6.5). This study has been approved by the ethics committee of the university.

F. Results

In this section, we report all the results of the analysis described in the previous section relating to the second study. Data were tested for violation of normality using a Shapiro-Wilk test. Result showed that the data were significant significantly different from a parametric distribution (p¡ 0.001). Therefore, we used only non-parametric tests in this section.

1) Unimodal Results: We first analysed the ratings of the different tactile patterns P1-P4, to see whether it was in line with the results from the first study. To do so, we stacked the data for each of the 4 tactile patterns used (i.e. consider both unimodal and multimodal conditions) and ran a Friedman's ANOVA test followed by a Kruskal-Wallis post-hoc test to see if there was any effect between each pair of patterns. The Friedman's ANOVA for the ratings for the tactile patterns were significantly different for the intensity $\chi^2(5) = 234.56$, the Valence $\chi^2(5) = 28.063$, the regularity $\chi^2(5) = 28.519$, the

TABLE III
LIST OF THE MEAN AND STANDARD DEVIATION FOR THE REPORTED TACTILE EXPERIENCES RESULTING FROM THE FOUR TACTILE PATTERNS P1-P4 IN THE SECOND STUDY.

Tactile Stimulus	Q1. Intensity		Q2. Roughness		Q3. Regularity		Q4. Roundness		Q5. Valence	
	mean	std.	mean	std.	mean	std.	mean	std.	mean	std.
75 Hz & 20 cm (P1)	0.441	0.233	3.444	1.874	3.311	1.862	4.400	2.248	4.233	1.547
75 Hz & 5 cm (P2)	0.413	0.235	3.263	1.880	3.022	1.760	3.153	2.033	4.200	1.372
25 Hz & 20 cm (P3)	0.536	0.273	5.333	1.820	5.025	1.864	4.061	2.273	3.830	1.684
25 Hz & 5 cm (P4)	0.296	0.221	3.370	1.925	3.450	1.842	3.083	2.074	4.181	1.489

roughness $\chi^2(5) = 21.077$ and the roundness $\chi^2(5) = 26.777$. In all cases the p-values were less than 0.001.

The post-hoc test comparison results are summarised in Table IV with the mean and standard deviation summarised in Table III.

TABLE IV
KRUSKAL-WALLIS POST-HOC TEST RESULTS FOR THE DIFFERENT HAPTIC PAIR PATTERNS. THE CRITICAL DIFFERENCE IS SET TO 64.62 AND SIGNIFICANT RESULTS ARE HIGHLIGHTED WITH AN *.

Comp.	Q1	Q2	Q3	Q4	Q5
P1 - P2	43.5	18.0	24.0	105.0*	4.5
P1 - P3	149.5*	253*	227.0*	45.5	105.0*
P1 - P4	214.0*	26.5	41.0	119.5*	3.5
P2 - P3	193.0*	235.5*	251.0*	59.5	109.5*
P2 - P4	170.5*	8.5	65.0*	14.5	8.0
P3 - P4	363.5*	227.0*	186.0*	74.0*	101.5*

2) Multimodal Results: We then explored how much the different patterns influenced the ratings when combined with the different media. To do so, we stacked the data for the 32 different multimodal combination pairs. For each of them, we plotted in Figure 3 the shifted normalised difference of each rating relative to the unimodal audio or visual baseline taken from [10]. Thus, this metric captures the mean influence of adding mid-air haptic patterns (P1-P4) to different types of non-haptic media.

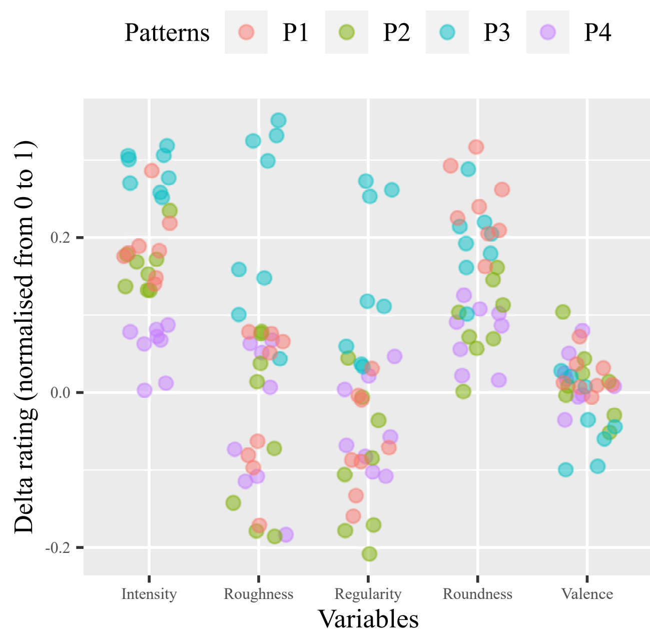

Fig. 3. Graphical representation of the effect of the tactile patterns on the media. The x axis shows the 5 perceptual dimensions asked to participants and the y axis represents the difference of the ratings of the media alone and the haptics+media conditions. For each perceptual dimension, 4x8 colourful points are plotted representing the 4 tactile patters (P1-P4) and their effect on the 8 chosen non-haptic media (4 audio and 4 visual).

V. SECOND STUDY: DISCUSSION OF RESULTS

In this section, we will first discuss the different patterns used in the second study and compare our results with the hypothesis made at the end of the first study (Section III-E). We then examine how the tactile patterns have impacted the multimodal stimuli ratings.

A. Mid-air Tactile Patterns

1) Intensity: The results shown in Table IV are in line with the previous study and previous work [8]. P3 is the strongest feedback with an optimal speed of $5\,\mathrm{m\,s^{-1}}$. P1 is above the optimal speed ($15\,\mathrm{m\,s^{-1}}$) where P2 and P4 are below ($3.25\,\mathrm{m\,s^{-1}}$ and $1.25\,\mathrm{m\,s^{-1}}$).

2) Roughness: Hypothesis 1: 25 Hz provides a significantly higher roughness than 75 Hz, especially when displaying a 20 cm circle. Table IV shows a significant difference in the post-hoc test for the pattern P3 compared to all other patterns. It seems that a perimeter of 20 cm and a frequency of 25 Hz is optimal for a high roughness feedback. This is in line with the first study, where the roughness ratings were peeking for those value and therefore com firm the first hypothesis.

3) Regularity: Hypothesis 2: 25 Hz provides a significantly higher regularity than 75 Hz, especially when displaying a 20 cm circle. Table IV has similar results for regularity than for roughness. Indeed, it seems that a perimeter of 20 cm and a frequency of 25 Hz is optimal for a low regularity feedback. This is also in line with the first study, where the regularity ratings was peeking for those value and therefore confirm the second hypothesis.

4) Roundness: Hypothesis 3: Larger circle size conveys a better sense of roundness irrespective of frequency. Table IV demonstrates that the post-hoc test gave a significant difference for each frequency (i.e. P1-P2 and P3-P4). For a frequency of 25 Hz, the roundness rating of the 20 cm circle is 0.98 points higher than the 5 cm circle. And for 75 Hz, the 20 cm circle is 1.25 points higher than the 5 cm circle.

5) Valence: The post-hoc test was significant for the pattern P3, which is the highest roughness and irregularity pattern. The mean score shows a slightly lower valence for this pattern (0.3 to 0.4 lower than other patterns), which might be indicating that roughness and irregular patterns can lead to a lower valence. But the mean difference seems too weak and further validation is required.

B. Multimodal Experiences

The Figure 3 shows how the different patterns influence the ratings of the audio and visual stimuli by comparing them with their baseline ratings.

The intensity rating showing that all four selected patterns P1-P4 have a positive impact on multimodal stimuli. Generally, P1 and P3 seem to have the strongest effect ranging from 15% to 25% increase.

The roughness and regularity ratings demonstrate both a positive and negative shift when mid-air haptics are applied to the benchmark media. Specifically, P3 resulted in higher rating of 10% to 30%, where the other patterns resulted in either no effect or lower ratings. This could signify that it is possible to change the texture perception of audio-visual-haptic content by selecting specific pairs of patterns.

The roundness rating presents similar features, showing an overall positive impact on the ratings. This was expected as we only used the circle STM pattern. Moreover, the patterns P1 and P3 seems to have overall higher ratings, which is likely to be linked to their bigger size.

Finally, the valence ratings did not show much of a change, as most ratings lie within a $\pm$ 10%. It is therefore unclear if haptic feedback can significantly influence the valence of audio-visual content. Further investigations are needed.

VI. Conclusion

Spatiotemporal modulation (STM) is a recent technique for producing mid-air ultrasonic tactile patterns. Previous work showed that speed and sampling rate can impact the perceived haptic feedback intensity [8], [9]. Building upon these works, we have conducted and reported on two user studies that showed that the pattern frequency and size can also affect the perceptual dimensions of roughness, regularity, and roundness. Moreover, we have showed that those tactile patterns could also influence the perception of auditory and visual media according to these same perceptual dimensions.

Our findings can help UX designers tailor STM parameters to deliver richer tactile and multimodal experiences that better reflect the desired effect. This would have direct applicability, as mid-air haptics could complement user experiences in gaming, movies, and interactive art installations.

The current work investigated the effect of two STM parameters on user experience, both in unimodal and multimodal scenarios. However, mid-air tactile patterns displayed using STM technique can be further tuned with additional parameters, as recent work [9] showed that device sampling rate, could change the perception of intensity for low frequency pattern. Future work could therefore investigate additional STM parameters and their impact on multisensory experiences and in particular their correlated effects and valence ratings.

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