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Using Spatiotemporal Modulation to Draw Tactile Patterns in Mid-air

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Abstract. One way to create mid-air haptics is to use an ultrasonic phased-array, whose elements may be controlled to focus acoustic pressure to points in space (referred to as focal points). At these focal points the pressure can then deflect one's skin and induce tactile sensation. Furthermore, by rapidly and repeatedly updating the position of a focal point over a given trajectory, ultrasound phased-array can draw two dimensional curves (refereed to patterns) on users' hands. While producing these patterns, there are three major parameters at play: the rate at which the pattern is repeated, the pattern length, and the focal point speed. Due to the interdependence between these parameters, only the repetition rate (frequency) or the speed can be set for a tactile pattern of a given length. In the current study, we investigate which approach between optimising for frequency or for speed is most effective at maximising tactile patterns sensation. We first carried out a vibrometry study to show that optimising the speed can maximise the deflection caused by a focal point following circular patterns. A further user study was undertaken to show that optimising the speed consequently maximises the perceived intensity of the tactile pattern. In both studies, the optimal speed result is shown to be equivalent to the speed at which surface waves propagates from the skin deflection effected by the focal point. Overall, our investigations highlight the importance of the speed of stimulation movement in the design of tactile patterns.

1 Introduction

With the arrival of gesture tracking technologies (Kinect, Leap Motion), the interaction space is no longer constrained to tangible surfaces and can now move to mid-air. Yet, the lack of tangibility in these mid-air interactions pushed researchers to develop solutions to convey feedback in the form of haptics in mid-air. Some solutions make use of air vortices [19] and air-jets [20]. But the leading technology in such applications currently uses ultrasonic-phased arrays [1, 5, 6].

Ultrasonic phased-arrays focus acoustic pressure to points in space (referred to as focal points). At these focal points, the pressure can slightly deflect human skin and induce tactile sensation. Yet, in such systems, the ultrasonic transducers are driven at high-frequencies (e.g. 40 kHz [6] or 70 kHz [5]), while mechanoreceptors within the skin are sensitive to frequencies ranging from 0.4 Hz to 500 Hz

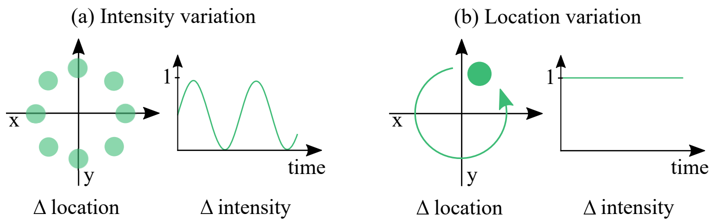

Fig. 1. A comparison between intensity modulation and location modulation when displaying a circle: (a) is displaying 8 fixed points with a change of intensity over time where (b) has a constant intensity over time but a changing location. The points in (a) are dimmer to represent the weaker acoustic power.

[4]. Therefore, the common approach, referred to as amplitude modulation, is to modulate the focal point to a lower frequency (referring to amplitude modulation frequency or F_{AM} for short). The perception of the focal point varies with the value of F_{AM} [16] and therefore F_{AM} is often fixed to 200 Hz which induces the strongest haptic response. Amplitude modulation can therefore be considered to be similar to and applied as one would use a mechanical vibrator for vibrotactile stimulation. Alternatively, one can create a cluster of focal points and apply amplitude modulation to each point, in order to render patterns or volumetric shapes [13] (see Figure 1.a). Yet as the number of simultaneous focal points increases, the acoustic power produced by the device is divided between the points, making each individually weaker. When the number of simultaneous focal points becomes too large (e.g. in large patterns), the focal points are no longer perceived.

To get around this issue, an alternative approach exists that we refer to as spatiotemporal modulation. In spatiotemporal modulation the position of a single focal point is rapidly and repeatedly updated so as to describe a pattern by moving along a continuous trajectory, while the intensity remains at its maximum. Spatiotemporal modulation can still induce tactile sensation as mechanoreceptors are sensitive to motion [7]. Additionally, the temporal resolution of touch perception is only of few milliseconds (the exact value may range from 2 ms to 40 ms according to Loomis [14]). Therefore, if the focal point can complete the trajectory faster than the temporal resolution, the users will perceive the resulting stimulation as a single tactile pattern rather than a succession of tactile points or a moving sensation (see Figure 1.b). The effect is similar to the persistence of vision, where a source of light can be seen as shape and not distinct points, when moved fast enough.

As far as we know, spatiotemporal modulation has never been studied, and so it is unclear as how its parameters should be chosen to maximise the created sensation. One naïve approach would be to consider the rate at which patterns are drawn (we defined this rate as the spatial modulation frequency -F_{STM} for short-) and assign that rate to be the same as the amplitude modulation frequency (i.e. having $F_{\text{STM}} = F_{\text{AM}}$). The argument behind that approach is that if the pattern is periodic, each point forming the pattern will be repeated at a given frequency as in the case of amplitude modulation. For instance, if one observes the acoustic field in one position of the pattern, one will note an alternation of high and low acoustic power, which correspond to the focal point coming and going from this position, with a rate equal to F_{STM}. The observation that the displacement at a stationary point in the pattern looks a lot like amplitude modulation, and therefore one could optimise F_{STM} the same way one optimises F_{AM}, leads to fixing F_{STM} to 200 Hz or thereabouts. However, the average acoustic power present at that position will be far weaker than having an amplitude modulated focal point at this position, especially for large patterns.

Another approach is to consider the speed of the focal point during the stimulation (referred to as FP_{speed}). If L is the length of a given spatiotemporally modulated pattern, then we can define $FP_{\text{speed}} = F_{\text{STM}} \times L$. A useful analogy to spatiotemporal modulation can be made involving trains, where the carriages (analogously to focal points) move along the rails (here the pattern) and produce vibrations on the soil (similarly to the skin). To further continue the analogy, it has been both numerically predicted and experimentally demonstrated that in high speed rail networks, ground vibrations can be amplified when the speed of the travelling trains approaches or exceeds the speed at which the surface waves propagate in the ground [12, 11]. In the light of recent studies, which show that tactile stimuli produce surface waves that propagate on the skin and affect our perception [2, 15, 18], the above train analogy becomes even more likely for the case of spatiotemporal modulation when surface waves are considered. Therefore, we hypothesise that if the focal point moves at a correct speed, constructive interference will result and the deformation it induces could amplify the propagating surface wave it produces and *vice versa*. We then predict that there is an optimal speed for which the deformation induced with a focal point is amplified to a maximum, and moreover the required speed is equal to the propagation speed of surface wave across the skin. We further hypothesise that the speed of the focal point will have more impact on the resulting perception than F_{STM}, due to the predicted surface wave effect.

To test our hypotheses and investigate whether the surface wave phenomenon in our analogy also holds true for spatiotemporally modulated patterns, we ran a series of vibrometry measurements where we recorded spatiotemporally modulated circles of different radii that were drawn at different speeds. A complementary user study was also performed to assess whether there was any effect of the spatiotemporal modulation speed of circular patterns on the perceived intensity of tactile sensations.

2 Vibrometry

In this study, we wanted to test for the existence of an optimal speed to drive spatiotemporally modulated patterns, which would ideally induce maximal displacement on a surface. We believe that the optimal focal point speed should be equal to the surface wave propagation speed. Additionally, we hypothesise that speed related effects on displacement are greater than frequency related effects. To measure the displacement induced with spatiotemporally modulated patterns, as well as their interference with resulting surface waves, we ran a series of vibrometry measurements.

2.1 Measurement Set-Up

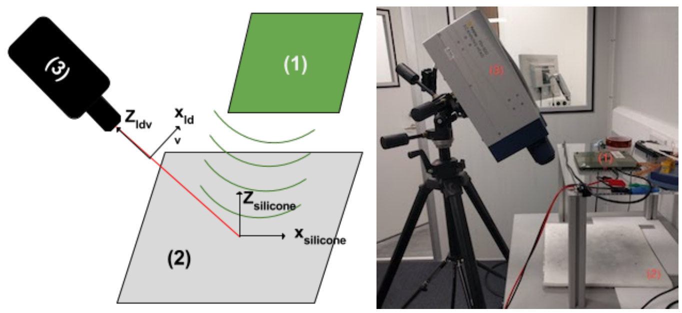

Fig. 2. Experimental Set-up: 1) The ultrasound phased array, 2) the silicone slab and 3) the Laser Doppler Vibrometer

Our measurement set-up was composed of three main elements: An ultrasound-phased-array to produce spatiotemporally modulated patterns, a silicone slab on which the patterns were projected and a Laser Doppler Vibrometer to measure the displacement induced by the spatiotemporally modulated patterns (as shown on Figure 2).

The ultrasound phased-array we used was a Ultrahaptics Evaluation Kit from Ultrahaptics Ltd.[3] and was composed of 16×16 (i.e 256) ultrasound transducers. The ultrasound phased-array is producing focal points 8.6 mm in diameters at a given position and with a given acoustic power. The produced output can be updated with a 16 kHz sampling rate.

The spatiotemporally modulated patterns were projected on a $35\,\mathrm{cm} \times 35\,\mathrm{cm}$ wide and 1 cm thick slab, cured with commercially available silicone, Ecoflex 0010[4], which was used as a mechanical analogue for human skin. The use of silicone rather than human subjects, provided control over the measurement condition. Ecoflex 0010, was selected as an analogue for human skin due to it having a similar density ($1100\,\mathrm{kg\,m^{-3}}$ for human skin, where the silicone is $1030\,\mathrm{kg\,m^{-3}}$) and similar viscoelastic material properties in both surface effects and in bulk [9, 17]. We acknowledge that the mechanical behaviour of Ecoflex will not be the identical to real skin, due to human skin being a much more complex structure (e.g., multiple layers and anisotropy) [3], however, it is thought that the vibrometry of silicone will provide insight into the general behaviour of viscoelastic materials when excited by focused ultrasound.

Due to the small amplitude of the vibrations, we used a laser Doppler vibrometer (abbreviated to LDV) to measure them. The LDV is a common tool

[3] https://www.ultrahaptics.com/products/evaluation-kit/
[4] Ecoflex 0010: https://www.smooth-on.com/products/ecoflex-00-10/

to carry out non-contact vibration measurement. Vibrometry data is obtained by firing a laser beam from the LDV towards the surface to be measured and capturing reflected incident photons using a photodetector diode also inside the LDV head. Differences between the original and reflected laser signal are analysed to find the vibration modes of the reflecting surface based on the Doppler effect. For this study, we used a PSV-500-Scanning-Vibrometer from Polytec[5].

The silicone was placed on an experimental bench, on top of which, the ultrasonic phased-array was maintained up-side down with a stand, parallel to the silicone and at a distance of 28.5 cm. The LDV was placed at a 60° angle and pointed towards the silicone, which was 36.4 cm away from the LDV head. For each measurement scan, the LDV was measuring surfaces with a resolution of 1 mm. Each measurement point lasted 256 ms, was recorded with a sampling rate of 128 kHz and was repeated 6 times before being averaged. Each measurement was synchronised between the LDV and the Ultrasound phased-array using a trigger signal. Furthermore, a 50 ms null output was preceding and following each measurement. Two types of measurement were conducted: line measurements (see Section 2.2) and square measurements (see Section 2.3). The line measurements involved a 17.5 cm long section of the silicone and lasted 30 minutes, while the area measurements covered an area of 10 cm×10 cm and lasted 105 minutes. Micro-reflective beads were spread on the surface of the silicone to improve laser reflection and hence measurement quality.

The raw data obtained from the LDV is composed of the velocity over time for each coordinate position on the measured surface. Firstly, due to the 60° between the LDV and the silicone, the measurements from the LDV were in a different coordinate space relative to the silicone (see Figure 2). Using a Python script with the `scipy` package, we pre-processed the data, transforming each point into the correct basis using projective geometry. Further, measurements were carried in an anechoic room and band-pass filtered to remove the ultrasonic 40 kHz carrier frequency and remaining noise, where the low cut-off was at 50 Hz and the high cut-off frequency at 1 kHz. Finally, to be able to work with displacement data, we applied a time integral on the velocity data, hence obtaining the variation of displacement over time rather than the variation of velocity over time. We describe how we used the displacement data, according to the information we wanted to extract, in sections 2.2 and 2.3.

2.2 Preliminary Measurement

Our study focuses on the displacement induced by the spatiotemporally modulated patterns and their associated surface waves. However surface waves propagate differently on different media, hence our first step was to characterise the surface wave propagation on the silicone we were using. To that end, we generated a focal point at the centre of the silicone slab and measured how induced surface waves propagated away from the position stimulated. As the silicone is

[5] https://www.polytec.com/uk/vibrometry/products/full-field-vibrometers/psv-500-scanning-vibrometer/

a dispersive medium, surface waves with different frequencies travel at different speeds. To measure this we modulated the focal point at known frequencies ranging from 200 Hz to 1 kHz with 100 Hz steps. We assumed the silicone to be an homogeneous and isotropic medium, and therefore focus our measurements on a single line going from the silicone slab centre towards the edge (17.5 cm long in total). From the measurements data, we extracted the surface wave propagation speed and the frequency response of the silicone.

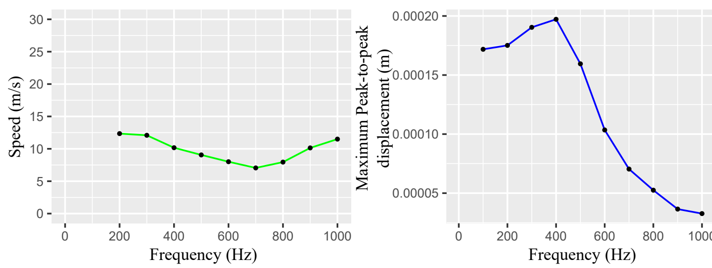

Fig. 3. Surface wave propagation speed and resonant frequency: Left-Measured propagation speed. Right-Measured frequency response, one can see the 400Hz resonant frequency.

Surface wave propagation speed To extract the surface wave propagation speed across the silicone, we calculated the speed at which wavefronts of surface waves propagated along the measured direction and took the average of repeated measurements of the speed. As predicted, the surface wave propagation speed varied with the frequency (see Figure 3) but remains in the interval of $7\,\mathrm{m\,s^{-1}}$ to $13\,\mathrm{m\,s^{-1}}$, and has for average $10\,\mathrm{m\,s^{-1}}$. The average propagation speed is slightly greater than the one measured by Manfredi et al. [15] on the fingertip, but the general trend is similar. Therefore, we assume the difference in mechanical behaviour between the two media to be responsible for the differences observed.

Frequency response To extract the frequency response of the silicone, we analysed the maximum peak-to-peak displacement at the focal point position and repeated over the frequency range. We found that the peak-to-peak displacement was also varying with frequency (see Figure 3) and was maximum at 400 Hz. This result suggests that the silicone slab has a resonant frequency at 400 Hz. It is sometimes suggested that human skin also possess a resonant frequency around 200 Hz [15]. Once again, we assume the differences in material properties to be responsible for the difference in the measured resonant frequency.

Overall, we can see that the silicone measurement shows similar behaviour to the skin even though the exact values differ.

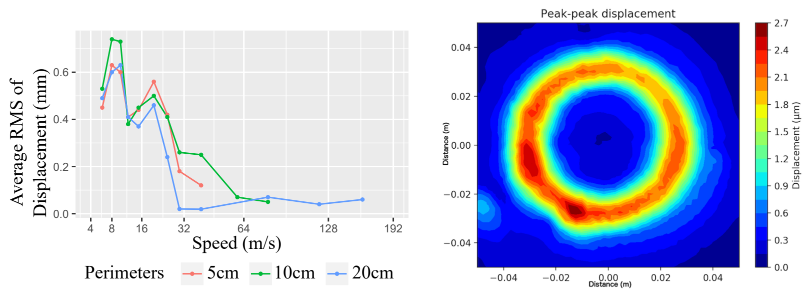

Fig. 4. Left: Average root-mean-square of displacement as function of speed for circular patterns with different perimeters. Right: Example of the measurement obtained for the root-mean-squared displacement of a circular pattern.

2.3 Spatiotemporally Modulated Patterns

After characterising the surface wave propagation speed on the silicone and the silicone frequency response, we undertook to investigate the effect of surface waves on the displacement that spatiotemporal patterns induced. To that end, we generated a spatiotemporally modulated circular pattern, with its centre matching the silicone centre (equivalent to Figure 1). We chose a circular pattern for its numerous properties (continuous, periodic, without self-crossing points), which limits possible pattern-specific artefacts. We then used the LDV to measure a square area of the surface encompassing the pattern (see Figure 4). As defined in the introduction, knowing the pattern length (here the circle perimeters), one can go from the focal point speed to the spatiotemporal modulation frequency as follow: $FP_{\text{speed}} = F_{\text{STM}} \times$ perimeter. To compare the different effects of FP_{speed} and F_{STM} individually, we repeated the measurement while varying the perimeter and FP_{speed} each in turn. In our data set, we had 3 different circle perimeters of 5 cm, 10 cm, and 20 cm of perimeter. We chose these circle sizes as they could fit the user's palm that is 7.5 cm-9.5 cm wide on average [10]. We picked 8 speeds around the measured average surface wave propagation speed and 4 additional speeds that match to 4 frequencies around the measured resonant frequency. Yet, for certain perimeter lengths, some speed values overlapped, making for somewhere between 9 and 12 distinct speeds measured per perimeter. In total 32 area measurements were taken. For each measurement, we computed the root-mean-square value for peak-to-peak displacement and extracted the average value along the measured circular path (see Figure 4).

2.4 Results

In Figure 4, we plotted the measured average root-mean-square values of peak-to-peak displacement induced by focused ultrasound on circular patterns with different perimeters, for which spatiotemporal modulation is run at different speeds. These results show that the quantity of displacement varies with the focal point speed but remains similar across circle perimeters. Moreover, the displacement is maximum for speed between 8 and 10 $\mathrm{m\,s^{-1}}$, which corresponds to the average of the surface wave propagation speed measured previously. Therefore, the results seem to support our hypothesis about a constructive interference between spatiotemporally modulated patterns and the wave surfaces they produced, when the focal point speed matches the speed of the surface waves propagation. Additionally, the results show a second maximum appearing at a focal point speed of $20\,\mathrm{m\,s^{-1}}$, which corresponds to twice the propagation speed of the surface waves. This behaviour that could be anticipated from the periodic property of the studied pattern is reminiscent of the kind of behaviour governed by "harmonics" often found in acoustics. Finally, the data does not show any evidence of a resonating mode, which should appear at 20, 40 and 80 $\mathrm{m\,s^{-1}}$ for the perimeters 5, 10 and 20 cm, respectively.

The conclusion of the current vibrometry study was finally that varying the spatiotemporal modulation speed has a large effect on the indentation of the silicone along circular patterns. Because silicone Ecoflex-0010 possesses numerous similarities with human skin, it is likely that equivalent amplification phenomenon could be observed on human skin, but it is difficult to predict to what extent. However, repeating the above measurement on human skin will not inform us about the consequences on the haptics of such spatiotemporally modulated patterns as they will be influenced by perceptual effects beyond simple displacement. To investigate the perceptual implications and especially the patterns perceived strength, we decided to run a user study with similar spatiotemporally modulated patterns. We hypothesise that there will be an effect of speed on the haptic stimulus perceived strength, although the nature of the interaction with haptics and whether it is detectable is not immediately clear.

3 User Study

In this user study, we assessed the perceived intensity of haptic circles of different sizes and speeds. To this end, users rated the intensity of 39 different circles: 3 sizes (i.e. perimeter of 5 cm, 10 cm, and 15 cm) and 13 speeds (i.e. from $2\,\mathrm{m\,s^{-1}}$ to $20\,\mathrm{m\,s^{-1}}$ with gaps of $1.5\,\mathrm{m\,s^{-1}}$). The different conditions (i.e. sizes and velocities) were fixed after pilot testing involving 15 people. Users rated each condition 3 times, giving a total of 117 trials (i.e. 39×3).

First, users were given an oral introduction to the study and the software used, before signing a consent form. They were invited to sit comfortably on a chair in front of a computer screen and asked to place their left-hand on a custom-made armrest that was built as a box integrating the mid-air haptic device. Users would then put their left palm above an opening, so that they can perceive the haptic stimulus from below. They were then invited to wear headphones playing white-noise to remove auditory cues and were given two trials to familiarize themselves with the haptic set-up and the software. Users were asked not to move the left hand during the experiment and used the mouse with their right hand to answer the questions displayed on the screen between stimuli.

The study itself involved a succession of 117 trials. In order to avoid any order effects, trials were pseudo-randomized. To move to the next trial, users were instructed to click on a next button on the screen in front of them. Then, a four-second countdown was displayed and the haptic stimulus was then played for five seconds. After each stimulus, the users were asked on screen if they perceived it. If so, they were invited to rate the intensity of the haptic pattern using a ratio scaling method of magnitude estimation, which can be used to find the optimal parameters of a device [8]. This approach is composed of 2 steps: (1) ask participants to rate the intensity of the stimulus on an arbitrary scale chosen by the participant and (2) normalize the values of each participant. No discrimination nor other qualitative information were asked during the experiment.

Software used A combination of two software parts was used in the study: `c++` for programming the mid-air haptic device, and `c#` for presenting questions.

Participants We recruited 16 users (mean age 30.0 ±4.5, 3 female). Users had no touch, or auditory impairments. The experiment lasted on average 35 minutes. An ethics approval was obtained in advance.

		Perimeter			
		5		10	
		p	cor	p	cor
Perim.	10	**<0.001**	0.901	∅	∅
	15	**<0.001**	0.856	**<0.001**	0.960

Table 1. *Summary of correlation matrix of the intensities ratings for the 5,10 and 15cm perimeter.*

Results The data collected was normalized between 0 and 1 for each participant. Non-felt stimuli were set at 0. In order to assess if the speed of the point was driving the intensity felt by participants, we separated the data into 3 groups, depending on the perimeter of the circle used for the feedback (see Figure 5). We then averaged the data for each speed and computed the Pearson correlation coefficients between the different pairs of perimeter sizes. The results are summarized in Table 1. The very high coefficient of correlation of intensity between the three perimeters shows that the haptic feedback strength is independent from the perimeter and dependant of the speed.

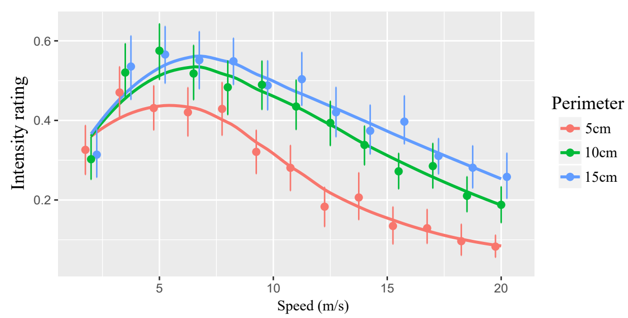

Fig. 5. A plot of the intensity ratings of the haptic feedback by perimeter size.

4 Discussion

The vibrometry study showed that the variation in silicone displacement, caused by spatiotemporally modulated patterns, is function of the spatiotemporal modulation speed. Moreover, the displacement seems independent of the circle perimeter and is maximised when the focal point speed equals the surface wave propagation speed. These results suggest that there is constructive interference occurring between spatiotemporal modulated patterns and the surface waves they induce, which leads to an amplification of the silicone displacement. However the results show no relation between silicone resonant frequency and displacement, even though the patterns studied were periodic. One could argue that variations in medium mechanical properties will lead to different results. Therefore, future work will investigate the effect of spatiotemporal modulation on silicone slabs of different mechanical properties. Ultimately, measurement on human skin would more conclusively prove the amplification phenomenon existence we describe. Yet, such measurements on human skin could be proved challenging.

The user study showed that the tactile pattern perceived strength is also function of the spatiotemporal modulation speed. Moreover, the results showed that user perceived stronger the circles that are drawn around 5 and $8\,\mathrm{m\,s^{-1}}$, which is close to the surface wave propagation speed measured by Manfredi et al. on human fingertips [15]. The similarities between the vibrometry results and the user study results suggest that the increase in displacement measured in the vibrometry study is responsible for the increase in perceived strength in the user study. Therefore one could conclude that matching spatiotemporal modulation speed with surface waves propagation speed ensures the maximum perceived strength for human participants experiencing the tactile patterns. One could argue that an individual mechanoreceptor, along the stimulation path, perceives a periodic signal with a given frequency. Therefore, to optimise the perceived strength, the stimulation frequency should match the mechanoreceptor frequency response. Yet, if figure 5 was expressed using frequency as abscissa, the similarities between the different pattern sizes would disappear. (each curve would be stretched along the abscissa-axis proportionally to their perimeters). Therefore, in the current study, the effect related to spatiotemporal modulation speed prevail over any effect related to the mechanoreceptors' frequency response. Additionally, the user study shows, in a lesser extent, that perceived strength is function of circles perimeters. The 5 cm perimeters are perceived weaker than those with 10 and 15 cm perimeters. We believe this effect might be resulting from the fact that the 5 cm circle covers less surface than the other two circles sizes, and therefore involve spatial summation [4]. However, additional investigations would be required to confirm the supposition, as well as finding a relation linking surface of stimulation, focal point speed and perceived intensity.

Our results have implications for the design of mid-air tactile stimuli, highlighting the focal point speed importance as a parameter in the tactile patterns perception. To scale up or down a given tactile pattern, the spatiotemporal modulation frequency must be scaled accordingly, to maintain the spatiotemporal modulation speed constant, and hence insuring a similar perceived strength of the tactile pattern. For instance, let's consider a circular pattern of perimeter P_1, our study show that the pattern should be driven at a rate $F_{\mathrm{STM}_1} = FP_{\mathrm{speed}} \div P_1$, where FP_{speed} produces the desired perceived strength. To scale that circle such as $P_2 = 2 \times P_1$ then, the spatiotemporal modulation frequency will need to be updated such as $F_{\mathrm{STM}_2} = 2 * F_{\mathrm{STM}_1}$. Being able to scale up and down a given pattern is particularly useful when rendering 3D-volumetric shapes [13]. Adapting our results to more complex and abstract patterns could prove challenging and would certainly require further investigations.

5 Conclusion

The current study showed that the vibrations generated in silicone with mid-air tactile patterns can be increased when selecting an appropriate speed for spatiotemporal modulation. The outcome of the user study compliment this result, and show a clear peak in the perceived intensity which occurs around $5 - 8\,\mathrm{m\,s^{-1}}$ across three different circle sizes. However, before it can be concluded that the skin displacement generated on the users' hand, and thus increases in the perceived strength of sensation are caused by the appropriate selection of speed, further vibrometry measurements of real human hands should be made to ascertain what the actual displacement across the hand is for a range of tactile patterns at different speeds. Yet, the current results are promising and already providing interesting guidelines for future mid-air tactile patterns' design.

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