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Howard, Thomas; Driller, Karina; Frier, William; Pacchierotti, Claudio; Marchal, Maud; Hartcher-O'brien, Jessica

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Gap Detection in Pairs of Ultrasound Mid-air Vibrotactile Stimuli

THOMAS HOWARD, Univ Rennes, INSA, IRISA, Inria, CNRS, France
KARINA DRILLER, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, The Netherlands & ISIR, Sorbonne Université, Paris, France
WILLIAM FRIER, Ultraleap, United Kingdom
CLAUDIO PACCHIEROTTI, CNRS, Univ Rennes, Inria, IRISA, France
MAUD MARCHAL, Univ Rennes, INSA, IRISA, Inria, CNRS and IUF, France
JESSICA HARTCHER-O'BRIEN, Faculty of Industrial Design Engineering, Delft University of Technology, The Netherlands

Ultrasound mid-air haptic (UMH) devices are a novel tool for haptic feedback, capable of providing localized vibrotactile stimuli to users at a distance. UMH applications largely rely on generating tactile shape outlines on the users' skin. Here we investigate how to achieve sensations of continuity or gaps within such two-dimensional curves by studying the perception of pairs of amplitude-modulated focused ultrasound stimuli. On the one hand, we aim to investigate perceptual effects that may arise from providing simultaneous UMH stimuli. On the other hand, we wish to provide perception-based rendering guidelines for generating continuous or discontinuous sensations of tactile shapes. Finally, we hope to contribute toward a measure of the perceptually achievable resolution of UMH interfaces. We performed a user study to identify how far apart two focal points need to be to elicit a perceptual experience of two distinct stimuli separated by a gap. Mean gap detection thresholds were found at 32.3-mm spacing between focal points, but a high within- and between-subject variability was observed. Pairs spaced below 15 mm were consistently (>95%) perceived as a single stimulus, while pairs spaced 45 mm apart were consistently (84%) perceived as two separate stimuli. To investigate the observed variability, we resort to acoustic simulations of the resulting pressure fields. These show a non-linear evolution of actual peak pressure spacing as a function of nominal focal point spacing. Beyond an initial threshold in spacing (between 15 and 18 mm), which we believe to be related to the perceived size of a focal point, the probability of detecting a gap between focal points appears to linearly increase with spacing. Our work highlights physical interactions and perceptual effects to consider when designing or investigating the perception of UMH shapes.

CCS Concepts: • **Human-centered computing → Haptic devices**; **User studies;**

Additional Key Words and Phrases: Ultrasound haptics, mid-air haptics, haptic perception

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T. Howard and K. Driller contributed equally to this research.

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Authors' addresses: T. Howard, IRISA, 263 Av. Général Leclerc, 35000 Rennes, France; email: thomas.howard@irisa.fr; K. Driller, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, Landbergstraat 15, 2628 CE Delft, The Netherlands & ISIR, Sorbonne Université, 4 Pl. Jussieu 65, 75005 Paris, France; email: K.K.Driller@tudelft.nl; W. Frier, Ultraleap, The West Wing, Glass Wharf, Bristol BS2 0EL, United Kingdom; email: william.frier@ultraleap.com; C. Pacchierotti, IRISA, 263 Av. Général Leclerc, 35000 Rennes, France; email: claudio.pacchierotti@irisa.fr; M. Marchal, IRISA, 263 Av. Général Leclerc, 35000 Rennes, France; email: maud.marchal@irisa.fr; J. Hartcher-O'Brien, Faculty of Industrial Design Engineering, Delft University of Technology, Delft, Landbergstraat 15, 2628 CE Delft, The Netherlands; email: J.Hartcher-OBrien@tudelft.nl.

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1 INTRODUCTION

Ultrasound mid-air haptic (UMH) devices are a novel technology for tactile feedback requiring no direct physical contact between the device and user. Several detailed surveys of the technology, its functioning principle, and its applications have been published [9, 31].

These devices use an array of ultrasonic transducers to emit acoustic waves timed in such a way as to coincide at fixed positions in their workspace, called focal points. This generates a localized region where the air pressure oscillates, with pressure maxima high enough to indent the skin in an oscillatory motion. However, this motion occurs at a rate equal to the ultrasound transducers' operating frequency, usually between 40 [4] and 70 kHz [17], well outside the range of human tactile perception capabilities [3]. It is therefore necessary to apply some form of lower frequency amplitude modulation to the pressure generated at individual points on the user's skin to obtain a perceivable stimulus. There are several methods for achieving this required amplitude modulation. The most straightforward method is to attenuate the output of the transducers cyclically over time, i.e., amplitude-modulating the transducers' outputs [4, 18]. This method is commonly referred to as **amplitude modulation (AM)** (see Figure 1(a)). A more versatile approach consists of rapidly moving an unmodulated focal point between neighboring positions, while controlling the frequency at which the focal point passes any given position, through techniques called lateral modulation [35] or spatio-temporal modulation [20] (see Figure 1(a)). Effectively, these techniques also lead to an amplitude modulation of the pressure signal at any fixed position along the focal point's path (see, e.g., pressure curves for positions 1 through 4 in Figure 1(a)).

UMH interfaces are capable of simultaneously generating multiple focal points [4] whose positions can be updated at rates up to the array's transducers' operating frequency and that can be either in or out of phase with one another. By moving focal points along a path, through sequential AM or **spatio-temporal modulation (STM)** (see Figure 1), it is possible to generate the perception of continuous vibrotactile shapes [4, 7, 11], surfaces, or textures [1]. UMH interfaces are increasingly finding applications in human–computer interaction [16, 34] and mid-air gesture interfaces [23], yet there are still only relatively few studies on the perception of focused ultrasound haptic stimuli despite such information being crucial in informing stimulus design for haptic rendering with these interfaces (see Rakkolainen et al.'s review [31] and the related work section from Mulot et al.'s recent work [25] for an overview of existing work on ultrasound haptic stimulus perception).

We discuss related work relevant to this article in more detail in Section 2. We then present a human participant experiment and simulation study investigating the perception of neighboring simultaneous focal points (Section 3). In this experiment, we record gap detection probabilities as a function of spacing between pairs of focal points (defined as per Figure 1(c)), which can be explained both through perceptual phenomena as well as physical interactions between neighboring focal points. To help interpret the human participant experiment results, we run acoustic simulations of the pressure fields generated in the experiment, which we describe in Section 4. Finally, we discuss limitations of our work, draw conclusions regarding the perception of UMH stimuli, and provide avenues for future work in Sections 5 and 6.

Our contributions are as follows:

- A replication and extension of the preliminary human subject experiment presented by Carter et al. [4], aimed at understanding perceptual aspects of rendering continuous and discontinuous shapes with UMH.
- A detailed simulation study investigating the possible physical interactions between focal points that could explain the observed gap detection behavior.

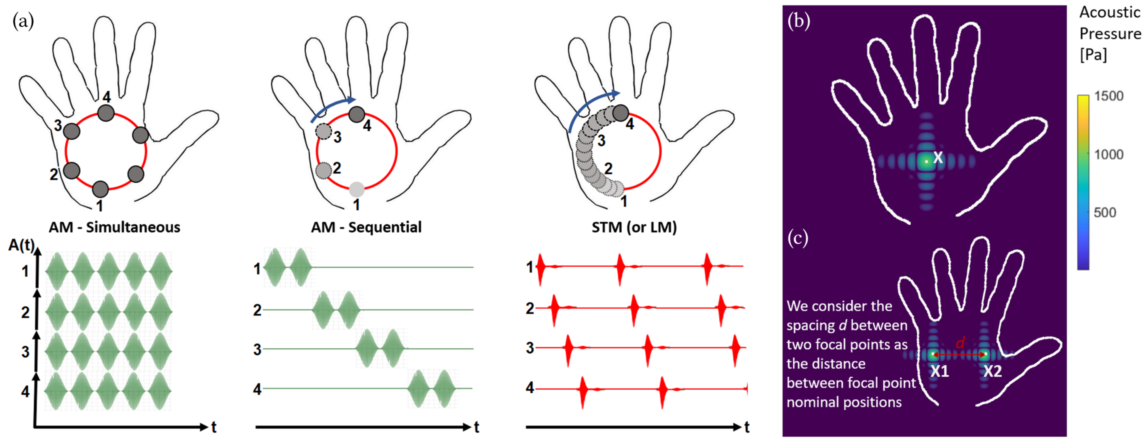

Fig. 1. (a) Tactile shapes with ultrasound mid-air haptics can be achieved through amplitude modulation of distinct points along the shape, either presented simultaneously [32] or sequentially [11, 14, 21]. Alternatively, a much finer step size can be used to sweep an unmodulated focal point across the shape in so-called spatio-temporal [7] or lateral modulation [35]. The plots schematically show the temporal evolution of acoustic pressure $A(t)$ at four arbitrary points for each of the methods (time axes t are not at scale). (b) While ultrasound arrays usually enable users to command specific nominal coordinates for the focal point, the resulting pressure distribution affects a relatively large area of the skin. The acoustic pressure distribution in the plane for a single focal point at nominal position X is shown roughly at scale with the outline of a hand. (c) Here we define the spacing within pairs of focal points as the distance between both focal points' nominal positions.

With this work, we intend to provide guidelines for rendering continuous or discontinuous tactile shapes by determining how close two simultaneous focal points need to be to produce a continuous sensation or, conversely, how far apart they need to be to produce the sensation of a gap between them. For rendering purposes, this can then serve as a basic building block for more complex continuous or discontinuous mid-air tactile geometries. Ultimately, our results may also contribute toward understanding the perceived size of focal points.

2 RELATED WORK

UMH stimuli are built around focal points. Despite their name and the fact that these are defined through nominal focal point coordinates, the generated vibrotactile stimulus is far from feeling like a point. When rendering a focal point at a nominal position X, UMH devices will generate a continuous pressure distribution in three-dimensional (3D) space with a maximum at X and a gradual decrease from this maximum as one moves away from X (see Figure 1(b)). The shape of this pressure function is usually symmetrical around X but differs according to the direction considered [14, 18]. This pressure distribution gives rise to tactile stimuli that are described as localized areas of vibration on the skin [14] with fuzzy boundaries [26], which we refer to as the *perceived focal point*. The exact relationship between focal point pressure distribution and dimensions of the perceived focal point are not clearly understood. Early work on the topic often assumed this perceived focal point to have a diameter of roughly 8 mm based on the wavelength of the ultrasound in air for arrays operating at 40 kHz [4, 18]. To date, only one preliminary study has attempted to estimate the perceived diameter of a focal point, finding a mean value of 13.1 mm for a 70-kHz array [17]. However, these data are far from sufficient to understand the relationship between pressure and the perceived focal point size. Furthermore, knowing the perceived focal point's size by itself is still not sufficient to inform all aspects of rendering, as focal points are rarely used alone nor at static positions.

The ability for UMH devices to display multiple focal points at once [4] has been proposed as a means of displaying multiple tactile elements (e.g., in mid-air tactile user interfaces [12]). In this scenario, it is imperative to understand how close such tactile elements can be in different conditions while still allowing a user to easily discriminate between elements. A study by Carter et al. [4] investigated the ability of UMH devices to indicate different spatial regions or elements within a set. The authors performed a small-scale study on the discrimination of neighboring focal points at identical or different modulation frequencies. They found that participants were rarely capable of accurately distinguishing two focal points of same frequency below 50 mm apart, a performance that improved down to 20 mm apart for focal points of different modulation frequencies. Since the authors were not explicitly concerned with UMH shape rendering, they did not address the question of perceived continuity or gaps in shapes as a function of focal point spacing as we do here. Also because of its preliminary nature, their work did not provide a precise two-point threshold measure.

Multiple simultaneous focal points can also be used to draw shapes that either feel continuous or have holes or gaps within them (see "Simultaneous AM" in Figure 1(a)). For example, Rutten et al. used a certain number of static sensations made from four simultaneous AM focal points in a study on shape identification [32]. In this case, the approach remains limited to sensations using few distinct focal points, since the energy output of the device must be split between multiple focal points [4].

In addition, the ability to rapidly move the focal point in space makes UMH interfaces uniquely suited to drawing tactile geometric shapes (see "Sequential AM" and "STM" in Figure 1(a)). Depending on the chosen method and focal point motion parameters, the resulting sensations are either static shapes [7] or the sensation of a stimulus moving along a shape [11]. Freeman et al. detail some of the relationships between these parameters in their work on focal point motion [5].

In early work on UMH, Hoshi et al. used sequential AM focal points to draw mid-air tactile shapes [14], a method that was later successfully applied to rendering the outline of larger shapes [21, 25]. Although no longer limited by achievable focal point intensity, this method requires a minimum amount of time to be spent at each spatial sampling position along the shape and can thus run into limitations for rendering shapes that must appear static. The most effective method in terms of achievable intensity and freedom in the design of shapes is STM [5, 7, 8, 15], which usually uses a very large number of closely spaced focal point positions which are rapidly scanned with an unmodulated focal point. While it affords great freedom in designing UMH shapes, STM is not as suitable as AM for displaying sets of static focal points, which may be detrimental to some applications. Sand et al. compared the effects of focal point motion speed, shape, and pattern repetitions on mid-air haptic shape identification for shapes drawn with sequential AM and STM [33].

The process of transforming an abstract geometric shape into a concrete geometric mid-air tactile pattern can be summed up under the notion of *sampling strategy*, introduced for STM by Frier et al. [8] and later formalized and extended to all modulation approaches by Mulot et al. [25]. Depending on the application, it may be desirable to adjust the sampling strategy to produce shapes that either feel continuous (i.e., that have no gaps in their contour) or discontinuous (i.e., that have perceivable gaps in their contour). This in turn requires understanding of the spacing limits beyond which focal points are perceived as distinct stimuli rather than merging into a single continuous shape sensation. Howard et al. [15] proposed an approach to simulate holes in an STM contour by overlaying a position-dependent intensity modulation onto a standard STM sampling strategy. The stimuli tested used 50-mm "holes" in 150-mm STM lines and yielded mixed results in terms of perceptual accuracy. Since the number of spatial sampling points that can be used is limited, in particular for simultaneous and sequential AM shape rendering, this information is even more critical for optimizing rendering. The present work aims to shed light on the basic building block of continuous or discontinuous UMH shapes, i.e., pairs of focal points at varying distances from one another.

3 GAP DETECTION EXPERIMENT

We conducted a user study to identify how far apart two focal points need to be to elicit a perceptual experience of two distinct stimuli separated by a gap. The experimental design is inspired by investigations into tactile

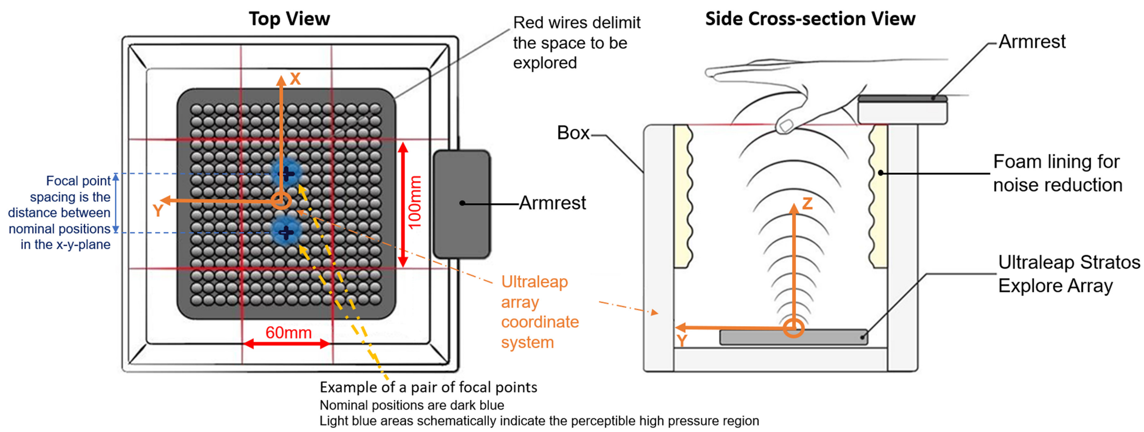

Fig. 2. Experimental setup. The exploration space (central rectangle, dimensions: 10x6 cm) is indicated to the participant using red wires. Focal point pairs are centered within this exploration space.

two-point discrimination thresholds, a well established procedure for measuring tactile acuity [19]. Our study, however, is notably different from conventional two-point discrimination threshold studies, first because it deals with vibrotactile stimuli rather than static skin indentation. Second, and more importantly, our study does not aim to provide any threshold measures relating to human physiology (contrary to studies on vibrotactile acuity, e.g., References [22, 28, 29]), since the stimulus used is not suitable for this. Vibrotactile stimuli generated by focal points are not localized enough for such a task, with skin indentation for a single focal point occurring over diameters that are of the same order of magnitude as vibrotactile two-point thresholds reported in the literature (see Figure 1(b)).

3.1 Materials and Methods

3.1.1 Apparatus and Setup. The setup comprised a desktop computer that drove the Ultraleap Stratos Explore focused ultrasound array [37]. The device was placed in front of the dominant hand of the participant, inside an open wooden box resting on a tabletop. The box was equipped with an arm rest that positioned the participant's arm 20 cm above the transducer array while the hand could still be moved freely. Furthermore, four red wires were spun 18 cm above the device surface to act as a visual indication of the space in which stimuli could be expected (see Figure 2 (left)). A keyboard was placed in front of the participant's non-dominant hand. Participants wore noise canceling headphones playing pink noise throughout the experiment to ensure that the feedback received was purely haptic in nature. No blindfolding was required given the invisibility of the stimuli to the user and absence of visual cues indicating device operation. The participants' hand was visible to them at all times.

3.1.2 Procedure. Focal point spacing was defined as per Figure 1(c), as the distance between the nominal positions of both focal points in the emitted pair (see also Figure 2). We used an interleaved staircase procedure varying the spacing between focal points following a two-down–one-up algorithm [24]. Bounds were set at 5 and 50 mm as starting values. Staircases were terminated after eight reversals or when boundaries were reached 5 times in a row. The average of the last six reversals was taken as an estimate of the gap detection threshold for a given condition. This gap detection threshold indicates the mean distance below which two simultaneous focal points are perceived as one single stimulus versus two separate stimuli at least 50% of the time.

We evaluated the threshold for three different focal point amplitude modulation frequencies (50, 125, and 200 Hz) to assess possible effects of frequency on gap detection. We chose the 200-Hz AM frequency, since this value is largely regarded as being optimal (e.g., Reference [13]) because of its proximity to peak Pacinian

Table 1. Overview of the Experimental Design

SUBJECT ID	FREQUENCY CONDITION ORDER	REPETITIONS	RESPONSE KEY ARRANGEMENT
1			Y – N
7	50 Hz - 125 Hz - 200 Hz		N – Y
13			Y – N
2			N – Y
8	125 Hz - 50 Hz - 200 Hz	x3	Y – N
14			N – Y
3			Y – N
9	200 Hz - 50 Hz - 125 Hz		N – Y
15			Y – N

SUBJECT ID	FREQUENCY CONDITION ORDER	REPETITIONS	RESPONSE KEY ARRANGEMENT
4			N – Y
10	50 Hz - 200 Hz - 125 Hz		Y – N
16			N – Y
5			Y – N
11	125 Hz - 200 Hz - 50 Hz	x3	N – Y
17			Y – N
6			N – Y
12	200 Hz - 125 Hz - 50 Hz		Y – N
18			N – Y

sensitivity in humans [3]. The 50-Hz AM frequency was chosen because it lies on the lower end of the Pacinian's response range [3]. Finally, 125 Hz was chosen as an intermediary value between both other frequencies. These modulation frequency choices are in line with other literature studies (e.g., References [35, 36]). A larger range of frequencies was not considered due to time constraints.

The experiment was split into nine blocks (three for each frequency condition). The order of blocks (i.e., frequencies) was balanced between participants as shown in Table 1. The duration of each block was approximately 5 minutes. During the experiment, participants were instructed to keep their posture still but encouraged to explore the whole stimulus space with their palm (but not their fingers) while the stimulus was displayed. A pilot study on four participants had shown no difference in threshold values, measured via a two-down–one-up staircase procedure, for active versus passive exploration. In each trial, the stimulus was presented for 2 seconds, after which the question "Did you feel two points of stimulation?" appeared on the screen. Following a 2-alternative forced choice paradigm, a "Yes" or "No" response had to be given by pressing the corresponding key (left or right arrow, balanced across participants; see Table 1). The next stimulus was then displayed with a response-stimulus interval of 300 ms.

Participants were not explicitly trained on what constituted a focal point or a gap between focal points. However, since participants were mostly unfamiliar with UMH devices, they performed a minimum of five test trials with stimuli in the modulation frequency of the first block before the experiment proper. Participants were not provided feedback on their performance during these test trials to avoid altering their experience of the stimulus. They were told that there was no right or wrong answer but that it was their perception that mattered. The test trials were halted when the participants indicated that they understood the task and could relate it to the novel sensation. Participants were carefully informed that they would be experiencing either one or two stimulation areas on their palm. If they experienced one area, then it could possibly vary in size, and if they experienced two areas, then these could vary in size and in spacing along the horizontal axis. Participants were told that focal points might partly overlap or touch each other but that a significant decrease in stimulus intensity had to be perceived in between two more intense points of stimulation to qualify as a gap.

3.2 Participants

Fifteen students (7 male, 8 female, ages 19 to 33 (mean 24.07, SD = 4.25)) with no reported neurological disorders or issues with somatosensory function took part in the study. All but three participants were right handed (M = 0.8, SD = 0.41) as assessed by the Edinburgh Handedness Inventory [27]). All participants gave written informed consent to participate in line with the Human Ethics Committee of Delft University of Technology and the Helsinki Declaration.

3.3 Results

We recorded responses for all focal point pair spacing values at three amplitude modulation frequencies. We observed a strong within- and between-subject variability, possibly indicating a high task difficulty (see Figure 3).

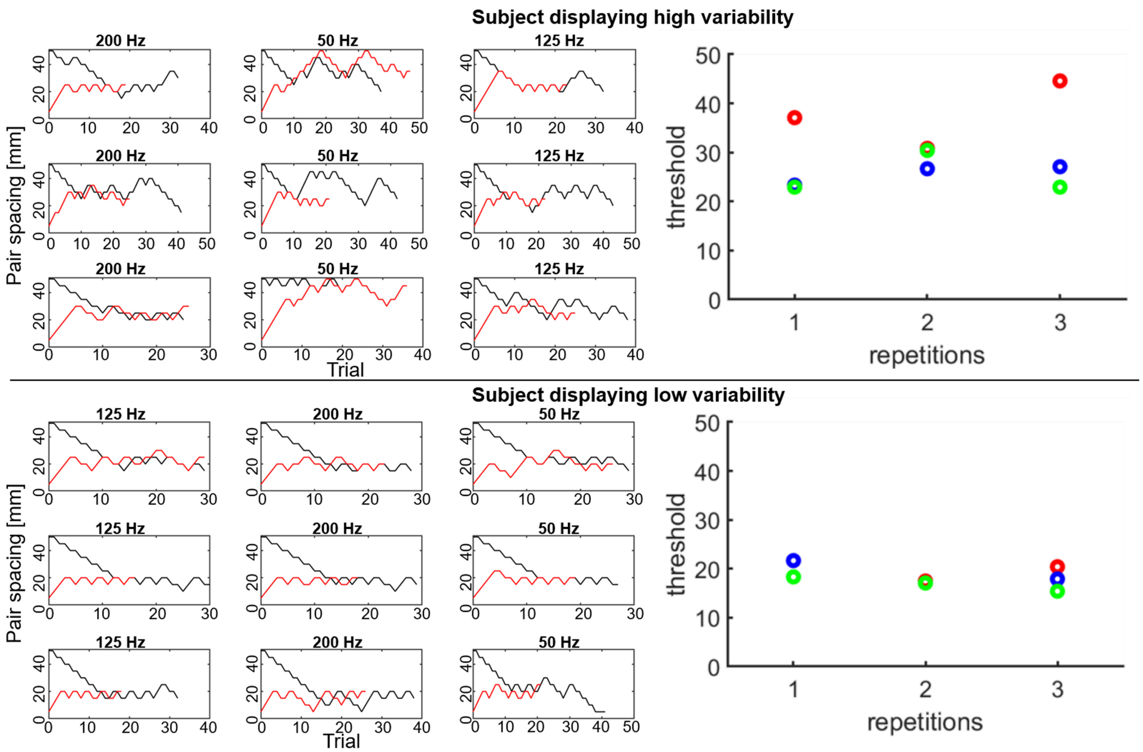

Fig. 3. Recorded responses for a participant exhibiting high variability between repetitions (top) and one exhibiting low variability between repetitions (bottom). The black lines show the progression of pair spacing for the descending staircase trials, the red lines show the progression of spacing for the ascending staircase trials. The plots on the right show the corresponding thresholds for the 50 Hz (red), 125 Hz (green), and 200 Hz (blue) trials across all repetitions. Similar plots were processed for each of the participants.

For each participant, we calculated the mean threshold for each of the repetitions and for each modulation frequency according to the procedure outlined in Section 3.1.2 (see Figure 4). Shapiro–Wilk tests on data grouped by modulation frequencies failed to reject the null hypothesis according to which data were normally distributed ($W(50\text{ Hz}) = 0.92$, $p(50\text{ Hz}) = 0.17$; $W(125\text{ Hz}) = 0.95$, $p(125\text{ Hz}) = 0.48$; $W(200\text{ Hz}) = 0.97$, $p(200\text{ Hz}) = 0.83$). Bartlett's test failed to reject the hypothesis according to which samples had unequal variances ($B = 0.14$, $p = 0.93$). We thus performed repeated-measures ANOVAs and found a significant difference between modulation frequencies ($F(2,44) = 3.47$, $p = 0.056$). However, the effect did not remain significant for any of the post hoc pairwise comparisons. No significant difference was observed in thresholds across repetitions, within a given AM frequency condition (see Figure 4). Thus, there is no indication of either short-term learning or desensitizing effects for participants between repetitions of a given condition. No significant differences were found between participants across modulation frequencies and repetitions. In the 50-Hz AM frequency condition, participants' mean thresholds varied from 17.5 to 45.8 mm (IQR: 15.41 mm). For the 125-Hz AM frequency condition, participants' mean thresholds varied from 17 to 45 mm (IQR: 16.25 mm). For the 200-Hz AM frequency condition, participants' mean thresholds varied from 15.4 to 47 mm (IQR: 14.27 mm) (see Figure 4). We estimate the mean thresholds for gap detection at 33.81 mm (SD = 8.66 mm), 32.36 mm (SD = 8.33 mm), and 30.78 mm (SD = 8.87 mm), respectively, for the 50-, 125-, and 200-Hz AM frequency conditions. Given the absence of significant differences between frequencies, repetitions or participants, we can estimate the overall mean gap detection threshold at 32.3 mm.

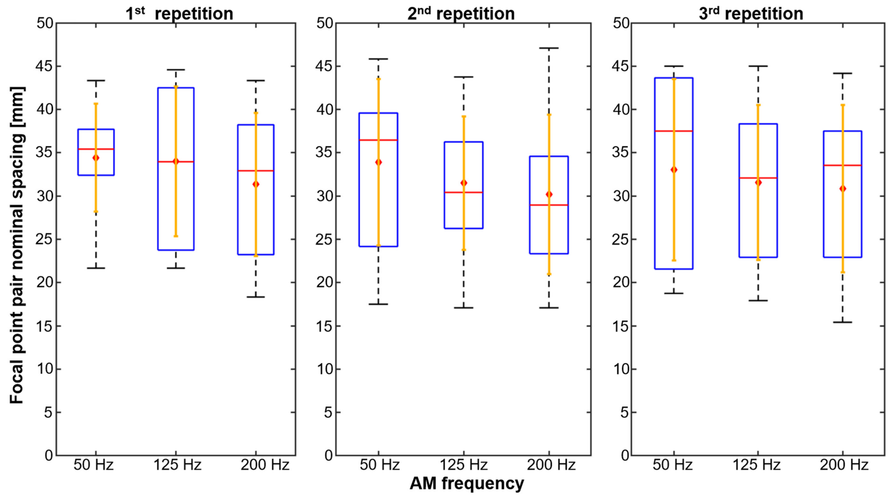

Fig. 4. Gap detection threshold (in mm) distributions plotted by AM frequency: 50 Hz (left), 125 Hz (center), 200 Hz (right) for each repetition. Solid red bars indicate the median threshold across participants, red diamonds show the mean and orange bars show the standard deviation.

These results confirm prior findings from the literature [4], indicating that pairs of focal points under 15 mm apart are consistently perceived as a single stimulus while pairs spaced more than 45 mm apart are consistently perceived as two distinct stimuli. However, the large variability in thresholds across participants does not allow us to draw any stronger conclusions on the exact distance at which two focal points become distinct, nor to infer any estimate of the perceived size of an individual focal point.

We performed an additional analysis of the same data set, this time considering trials within the staircase procedures as independent observations of gap detection for a given spacing, for each participant. From this, we calculated the probability of gap detection at each nominal spacing, per participant. Conclusions drawn from this analysis must be regarded as tentative given the differences in sample sizes for each spacing value. However, all samples were sufficiently large to obtain small 95%-**confidence intervals (CI)** when estimating the gap detection probability for each spacing for each participant. The 95%-CI ranged from 0.017 (15 mm spacing) to 0.07 (35 mm spacing). Shapiro–Wilk tests failed to reject the hypothesis according to which data were normally distributed; however, Bartlett's test showed that the assumption of homogeneity of variances was likely violated ($B = 317.02$, $p = 0$). A Kruskall–Wallis ANOVA failed to reject the null hypothesis according to which some gap detection probabilities differ from the rest at the 5% significance level ($\chi^2 = 26.11$, $p = 0.073$). Figure 5 shows the obtained mean probability of gap detection as a function of nominal focal point spacing.

Results once again show that participants tend to consistently detect no gap for focal points nominally spaced up to 15 mm, above which the mean probability of gap detection first steeply increases up to a nominal spacing of 25 mm and then linearly increases with a milder slope up to 45 mm nominal spacing. The observed mean probability of gap detection at 50 mm spacing then drops again (see Figure 5).

However, two sources of bias may affect the gap detection probability value at this spacing. First, the relatively large spacing places the focal points closer to the edges of the hand. If some interplay of imperfect hand positioning and poorer tactile sensitivity on one side of the palm led subjects to feel only one of the focal points, then they may inaccurately report "no gap". Second, it is possible that residual uncertainty about what they were feeling biased subjects toward responding "No" at the start of a set of trials due to and the phrasing of our question. Investigations over a wider range of focal point spacing values would, however, be necessary to confirm this.

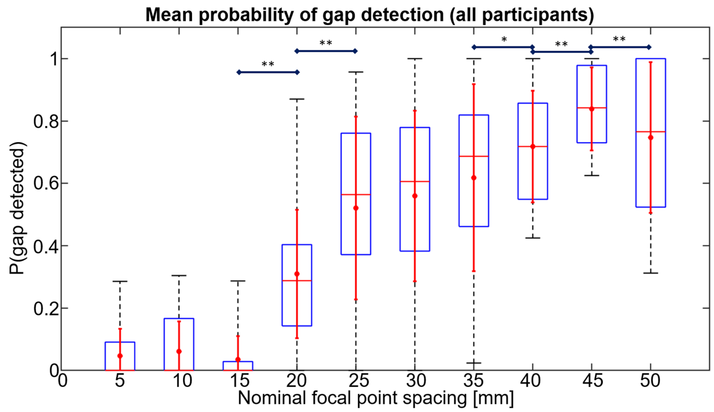

Fig. 5. Probability of detecting a gap between two stimuli as a function of nominal focal point spacing. Box plots show the distribution of probabilities across participants, with median values shown by a horizontal red bar. The mean and standard deviation are highlighted with a red diamond and vertical bar. Significant pairwise differences (Welch's t-test) between adjacent spacing values at respectively 5% (**) and 10% (*) significance levels are highlighted with black horizontal bars.

Before drawing any further conclusions, we performed an investigation into the pressure fields achieved when commanding the pairs of focal points, to determine whether any physical interactions played a role in the observed participant responses.

4 PHYSICAL SIMULATION OF FOCAL POINT PAIRS

An in-depth understanding of the behavior of the sound field around the generated pairs of focal points is required to accurately interpret participants' gap detection behavior. While it is possible to measure the generated sound field using one or several microphones, this option is impractical in the present case due to the high technical complexity and time required for such scanning measurements of the sound field. We therefore opted for a physical simulation of the sound fields generated by the stimuli from Section 3 (see Section 4.2 below).

We used a custom developed linear acoustic simulator for this. Transducers are represented as point source baffled pistons, and we apply Huygens' principle of superposition to construct the cross-sectional pressure profile of a focal point. The amplitude and directivity of each transducer are represented with a Bessel function, whose parameters have been adjusted to best match the real-world behavior of the Murata MA40S4S transducers built into our array [6]. The transducers assumed for this ideal phased array have a phase that can be continuously varied between 0 and 2π.

Simulations are an effective way of quickly obtaining high-resolution data on the generated sound fields; however, it is still necessary to ensure their validity by comparing them to real-world measurements. We therefore began by performing preliminary validation measurements to verify the fit between actual acoustic pressures and our simulation results.

4.1 Preliminary Validation of the Simulation Accuracy

To validate the accuracy of the simulated sound fields, we used a microphone (B&K 4138 1/8"microphone) to record the acoustic pressure at two positions of interest (see Figure 6). Data were acquired digitally using a B&K Type 3161 single-channel input/output acquisition module operating at 204.8 kHz [2] and the *Pulse* software.

Pairs of focal points were generated with an equal-phase 200Hz amplitude modulation applied to them, allowing easier alignment of the microphone with the focal point position. We recorded time-data of acoustic pressure levels for a few seconds at a time. We measured the acoustic pressure at the focal point nominal position for five

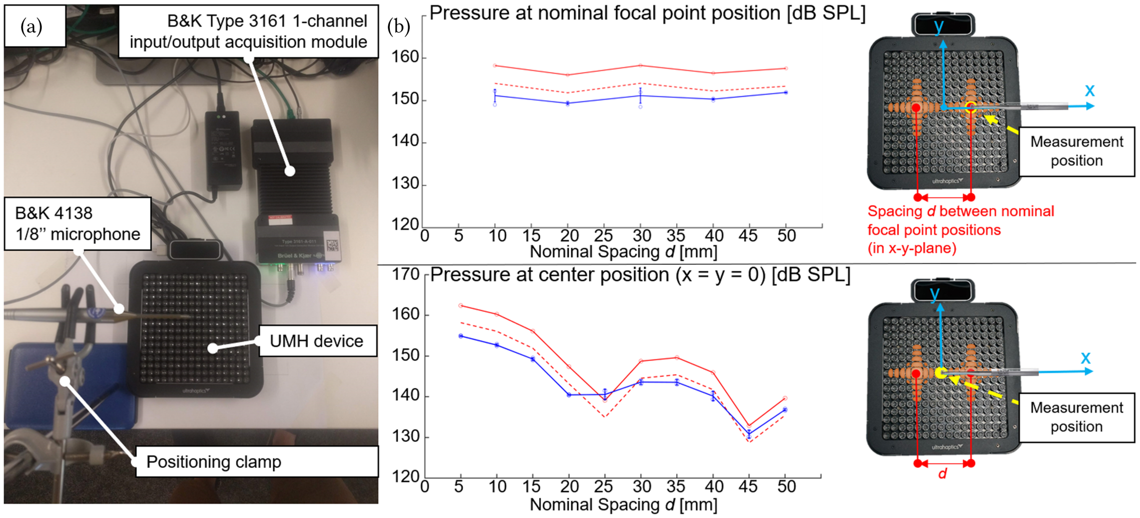

Fig. 6. (a) Microphone recording setup for validation measurements. (b) Plots showing the measured (blue) vs. simulated (red) pressure at the focal point nominal positions for five spacing values (top), as well as the mean pressure at the center position between both nominal positions ($x = 0$, $y = 0$ in the array coordinate system) (bottom). Circles indicate data points while lines show the mean and error bars show one standard deviation. The dashed red line shows the pressure expected for AM focal point pairs based on the simulation of unmodulated focal point pairs, i.e., with a −4.2-dB offset applied.

pairs of focal points (spaced respectively by 10, 20, 30, 40 and 50 mm). We also measured the acoustic pressure at the midpoint between both focal points ($x = 0$, $y = 0$ in the array coordinate system) for all 10 pairs of focal points from the previous experiment. Measurements were repeated 3 times for each of the three positions and for each focal point pair spacing. Analysing the time-recorded data, the peak-to-peak pressure was extracted using a lab-written python-script, and then converted to dB SPL (see Figure 6(b)).

Overall measured values were found to be very repeatable with standard deviations below 1.7-dB SPL for measurements at the focal points and below 1.3-dB SPL for measurements at the center position. We observed a consistent approximate 6-dB offset between the measured and simulated values at the focal point nominal positions. This is to be expected, since the simulation assumed non-modulated focal points and measurement were performed with a 200-Hz sinusoidal amplitude modulation applied to the focal point. In theory this modulation should introduce a 4.2-dB difference between the modulated and non-modulated acoustic radiation pressure. The remaining 1.4-dB offset could be due to three factors. First, some deviation from the nominal transducer output pressure used in the simulation is to be expected as the simulation assumed an ideal phased array and was not specifically calibrated with respect to the transducers used. Second, small inaccuracies in the microphone placement and angle with respect to the focal point may also introduce a constant offset. Finally the linear acoustic model assumed in the simulation would not account for non-linear acoustic effects that can occur at these high pressures. Since the offset between measured and simulated values is almost constant and small, we can conclude to a good match between the simulated and actual peak focal point pressures, confirming the validity of our simulation.

Regarding the measurements at the center position (Figure 6(b)), we also observe a strong correlation between simulated and measured values. Contrary to the measurements at the focal point nominal position, the pressure at the center position is highly dependent on focal point spacing as pressure at this point is a direct result of the interaction between the pressure fields generated for each of the two focal points. The offset measured at the focal point center position is not systematically observed in this case, although an approximately 5-dB offset

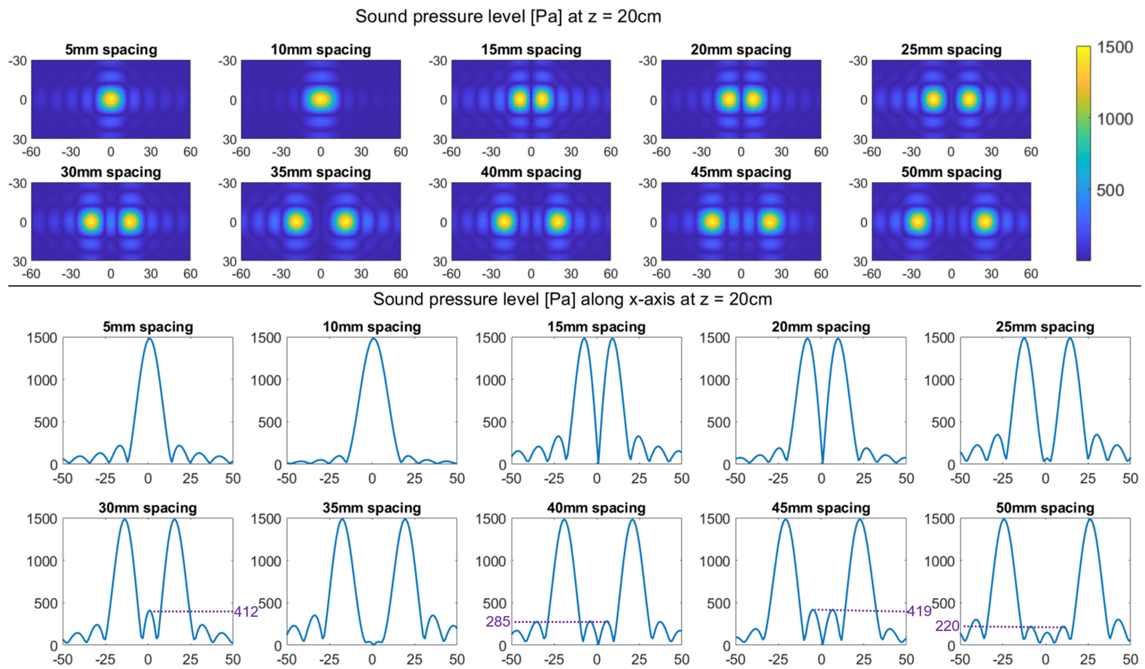

Fig. 7. (Top) Heat maps showing the sound pressure level in the plane at $z = 20$ cm above the array (in Pa). (Bottom) Sound pressure plots along the $y = 0$ axis in the same plane (in Pa). Notable pressure lobes occurring between the peaks around the focal points are annotated with their peak pressure value (in Pa) in purple.

is apparent for all spacing values except 25, 45, and 50 mm. This indicates some inaccuracy in the simulation of interference between focal points. However, for our purposes, the fact that the general trend in acoustic pressure is well predicted and that the actual acoustic pressure is either lower or equal to the simulated values in between focal points is sufficient.

4.2 Simulating Stimuli from the Human Participant Study

With the reliability of the focal point pair simulations established, we proceeded to fully simulate the pressure fields in the plane of the participants' palm for all 10 pairs of focal points used in the experiment from Section 3.

These simulations (see Figure 7) show that for nominal spacing values of 5 and 10 mm, the focal points completely merge, forming a wider main pressure lobe centered on the ($x = 0, y = 0$) position. This is in line with the very low gap detection probability at these nominal spacing values. This phenomenon also highlights the fact that physical interactions may cause the actual positions of pressure maxima to deviate significantly from the nominal positions commanded in the software. To understand to what extent this is the case, we simulated focal point pairs in 1-mm spacing increments between 1- and 50-mm spacing and plotted the actual versus nominal spacing between pressure maxima (see Figure 8(a)). Results show that at a height of $z = 20$ cm above the presently used array, it is physically impossible to achieve an actual focal point pair spacing below 15 mm. Furthermore, there is a non-linear relationship between actual spacing and nominal spacing, even above 15 mm, although the deviations are usually below 3 mm. It should be noted that these deviations are predicted by simulations based on an ideal phased array and thus are not the result of focusing inaccuracies of a real array. In light of these results, we corrected the plot of results initially shown in Figure 5 to instead reflect the probability of gap detection as a function of actual focal point spacing (see Figure 8(b)).

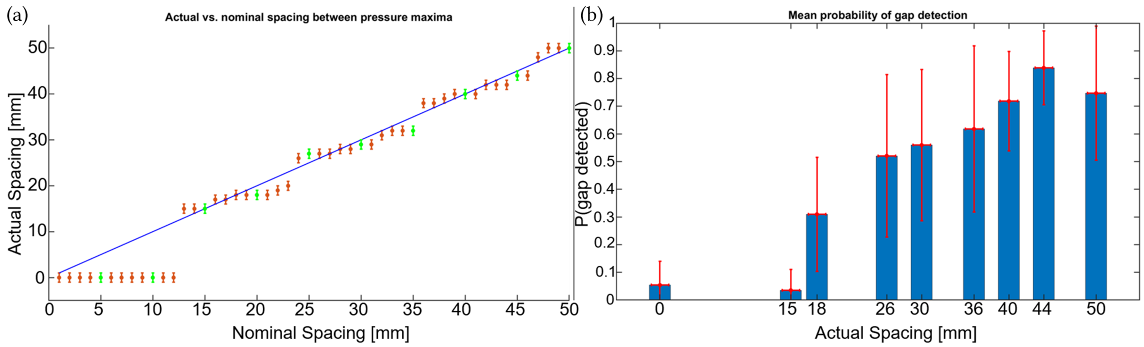

Fig. 8. (a) Plot of the actual distance between pressure maxima against the nominal focal point spacing compared to the $y = x$ reference line (in blue). Green points highlight the actual spacing achieved for the stimuli in the human participant study, while additional simulation results for 1-mm increments in nominal spacing are shown in red. Error bars show the uncertainty in actual spacing estimation due to the simulation's resolution. (b) Adjusted graph of probability of gap detection (from Figure 5) plotting the measured probabilities against the actual spacing between pressure maxima. Bar plots show the mean probability of gap detection (all participants). The standard deviation is shown with a red vertical bar, the red horizontal bar reflects the uncertainty in actual spacing estimation (corresponding to the vertical error bar in plot (a)).

This correction confirms that overall, the probability of gap detection is not a linear function of spacing. Gap detection probability seems to follow a pattern where it stays constant and close to 0 up until a threshold in pressure peak spacing between 15 and 18 mm. After this a sharp increase occurs, followed by a more or less linear increase in probability of gap detection as the focal points get further apart (between 18 and 45 mm). The seemingly linear relationship between spacing and gap detection probability for spacing values above 26 mm appears to be unaffected by the presence or intensity of secondary pressure lobes, regardless of their intensity (see Figure 7 (bottom) for spacing values of 30, 40, 45, and 50 mm).

5 DISCUSSION AND PERSPECTIVES

5.1 Effects of Hand Size, Age, or Gender

We found no correlation between participant hand size and the mean or standard deviation of thresholds, be it by frequency condition or averaged across frequency conditions. Women appeared to have lower thresholds than men; however, this could not be shown statistically given the small sample size. Similarly, younger participants also tended to achieve lower thresholds, though this effect was not significant and the sample size and age distribution do not allow any firm conclusions. Studies on a larger and more diverse population would likely be required to detect any effect of the participants on gap detection ability and perceived focal point diameter.

5.2 Limitations of the Present Study

One should keep in mind that because of the limited sample size and sample diversity, as well as the large uncertainty associated with the results of the human participant study (Section 3) and some imperfections in the simulation (Section 4.1), the conclusions presented here are tentative and require confirmation through additional studies. A more suitable experimental protocol for additional perception studies would be a method of constant stimuli to determine the probability of gap detection at each considered spacing value. Such studies should also take into account discrepancies between nominal and actual peak pressure positions from the start.

Also, the present study restricted the exploration region to the center of the plane above the array, guaranteeing that only the desired focal points were potentially perceived. Because of their design, UMH arrays produce so-called grating lobes at a distance from the nominal focal point position. These are usually not problematic but could, in the case of larger shapes, introduce additional unwanted stimuli that in turn could affect perceived continuity or discontinuity of UMH shapes. This issue can, however, be mitigated by using, e.g., hardware approaches such as appropriate array design, as proposed by Price et al. [30].

Despite these limitations, some interesting hypotheses about perception of focal points as well as basic guidelines for rendering can be derived from the present work and are discussed below.

5.3 Perceived Focal Point Diameter

When only one focal point is presented, there is a minimum peak pressure value below which focal points are never detected, and thus their perceived diameter is zero. Above this pressure threshold value, the probability of detecting the focal point (and thus of perceiving it to have a non-zero diameter) gradually increases until a minimum pressure threshold value where focal points are systematically detected (with a non-zero diameter). For a given probability x of detecting the focal point, the associated peak pressure is referred to as the *x%-detection threshold*. The 50%-detection threshold, which is usually considered to characterize stimulus detection in psychophysics, was found to be 560 Pa [15].

Alone, data from this perception study are insufficient to conclude on the relationship between pressure profile and perceived focal point diameter. However, they can provide some insights and serve as a basis for laying out hypotheses on the subject, especially when considering our observations for the 15 and 18 mm actual spacing.

The probability of gap detection at 18 mm actual spacing, where the pressure profile shows both main lobes to be tangent at the base, was found to differ significantly from zero. From this, we can conclude that the perceived focal point diameter is likely less than the base diameter of the focal point main pressure lobe (in this case <18 mm). Following a similar reasoning, the fact that the probability of gap detection at 15 mm actual spacing is close to zero could be construed as showing that the perceived focal point diameter is greater than 15 mm in that case, and that the perceived focal points thus overlap. However this would contradict the conclusion drawn from the observation at 18 mm spacing as the perceived focal point diameter would in one case be smaller and in the other larger than the base diameter of the main lobe. The more likely explanation is thus that at 15 mm spacing, the perceived focal point diameter is also smaller than 15 mm (a value that is coherent with prior literature results [17]), and that some other effect is at play (see Section 5.4).

If the diameter of the perceived focal point is less than that of the base diameter of the focal point main pressure lobe, then we may be able to model the perceived focal point diameter as the diameter of a cross section of said main pressure lobe, cut off at some pressure threshold that may relate to an x%-detection threshold discussed above.

This would suggest that secondary lobes have a negligible impact on the perceived focal point diameter, something that also matches observations from the present study. Indeed, above 30-mm nominal spacing, the different patterns of secondary lobes between the main lobes (see Figure 7) do not seem to affect the linear trend observed in the mean probability of gap detection.

5.4 Perceptual Interactions within Focal Point Pairs

The probability of gap detection increases with spacing, albeit in a non-linear manner. For spacing values below 15 mm, focal point pairs are perceived mostly as a single continuous stimulus, even though the largest spacing in this range is larger than previous literature estimates of the perceived diameter of focal points [4, 17, 18]. This is possibly indicative of spatial summation effects. Such effects are common in vibrotactile perception, occurring when a larger surface area is stimulated, and leading to a lowering of detection thresholds around the stimulation area [10]. In the case of UMH, a large skin surface area is subjected to continuously decreasing pressure the further one gets from the nominal focal point position, with only a fraction of this area centered on the nominal focal point position being perceived as a vibrotactile stimulus. A local decrease in detection threshold would thus result in a larger perceived stimulus area. Therefore, it appears plausible that two focal points in close proximity

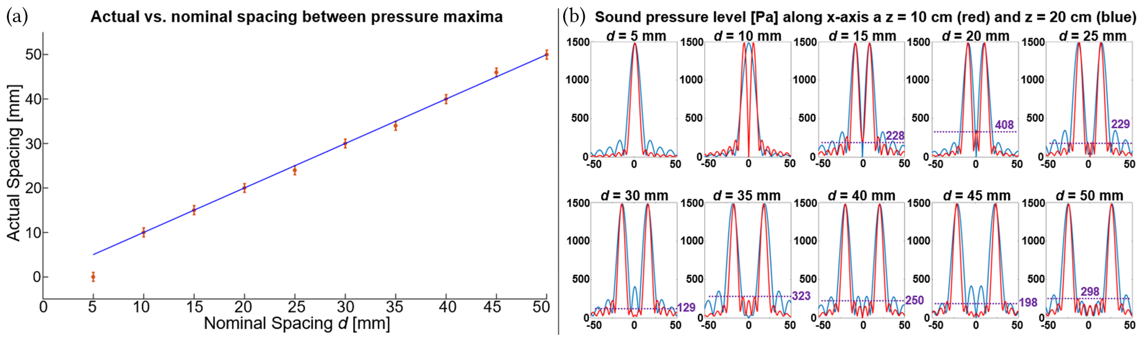

Fig. 9. Simulation of focal point pairs with identical spacing to those used in the human participant study, on the same array but at a height of $z = 10$ cm above the array. (a) The relationship between actual and nominal spacing. (b) Plots of the acoustic pressure along the x axis in red, overlaid on the plots from Figure 7 (at $z = 20$ cm) in blue.

may stimulate a sufficient area to cause spatial summation effects, increasing the perceived sizes of both focal points and thus lowering the probability of gap detection. These effects would, however, disappear beyond a threshold in spacing, which could help explain the gap detection probability between 15- and 18-mm spacing.

Prior results by Carter et al. [4] showed that pairs of focal points with different modulation frequencies are more readily discriminated than pairs with identical modulation frequencies. If spatial summation effects arise as suggested above, given the fact that the dimensions of focal point main pressure lobes are independent from the modulation frequency, then these would likely also depend upon frequency characteristics of the focal points.

Further investigation into the perceived size of focal points, alone and in pairs, are required to shed light the exact nature of perceptual interactions occurring within focal point pairs.

5.5 Influence of Array, Focal Point Height, Intensity, and Modulation Frequency on Gap Detection

Given our hypothesis according to which the perceived size of a focal point is directly linked to the dimensions of the focal point main pressure lobe, we propose an approach that could enable future investigations by changing the main pressure lobe shape in a controlled manner.

The minimum width w of the focal point main lobe is a function of ultrasound wavelength λ, focal point height above the array h and array aperture A (all in [m]) [17]:

$$w = 1.22 * \lambda * \frac{\sqrt{h^2 + (A/2)^2}}{A/2}. \tag{1}$$

We therefore hypothesize that changing the focal point height while keeping the same array aperture and carrier frequency could possibly impact the minimum achievable actual spacing between pressure maxima. To verify this, we conducted an additional series of simulations in identical conditions to those described in Section 4.2 for focal point pairs at $z = 10$ cm above the array (see Figure 9).

Results show that the achieved focal point main pressure lobes are indeed thinner by what appears to be a constant amount of 8 mm at the base. This also leads to focal point pairs merging at lower spacing values, in this case between 5 and 10 mm. On average the peak pressures of the secondary lobes in between the main pressure lobes also appear to be lower (mean of 257 Pa against a mean of 354 Pa for $z = 20$ cm). An unexpected side-effect is that the relationship between nominal and actual focal point spacing appears more linear with these rendering parameters. This hints to the fact that gap detection between focal points may be affected by array design and focal point height, although additional perceptual studies are required to validate this hypothesis.

In theory, scaling down the commanded focal point intensity (peak intensity) should scale down the pressures generated throughout the resulting pressure field by the same constant factor. Thus, assuming that the distance of some pressure threshold to the focal point center plays a role in the perceived focal point diameter, intensity could be used to vary said diameter. In turn, this could have an effect on gap detection. However, gap detection ability may also be affected by the pressure gradient within a perceived focal point, which would also be scaled down, counteracting or reinforcing the effects of intensity on perceived focal point diameter. Further investigations into gap detection behavior between pairs of equal- and unequal-intensity focal points at intensities different from the maximum could shed light on this aspect.

In our present work, we did not observe any influence of modulation frequency on gap detection ability. However, a previous preliminary study by Carter et al. [4] suggests that two focal points with large differences in AM frequency are more easily distinguished from one another. In future work, it may therefore be interesting to investigate whether small differences in AM frequency between neighboring focal points can reduce the gap detection threshold without both points being interpreted as independent stimuli. This could have interesting applications in finer discontinuous shape rendering using simultaneous or sequential AM.

5.6 Implications for Rendering

Our investigations allow some conclusions to be drawn with respect to the shape rendering methods presented in Figure 1. STM provides greater freedom than AM in terms of geometric shape sizes and number of spatial sampling points, yet it poses constraints in terms of draw frequency that may alter the perceived tactile properties of the shape, making AM preferable in certain cases. For simultaneous AM shape rendering, our results show that perception of continuous shapes is almost guaranteed for spatial sampling points spaced up to 15 mm apart. For the Ultraleap Stratos Explore device used in our studies, which allows rendering of only up to approx. 4 perceivable simultaneous focal points [4, 37], this implies that lines up to 60 mm in length might reliably be perceived as continuous, and that a surface stimulus up to 30 mm^2 may be achieved by arranging these points in a 15-mm-sided square pattern. These limits, however, vary depending on device design and could be increased by using devices with larger power output (e.g., Reference [13]). Larger continuous AM patterns may be achievable by using out-of-phase focal points that would allow better use of the device's full power output or by using more powerful arrays.

These findings also provide a starting point for further investigations into continuity of shapes for sequential AM shapes, although it remains to be seen to what extent these results hold true for this rendering scenario. Further investigations into the perception of gaps in sequential AM and STM shapes would be beneficial to better understand rendering requirements for mid-air haptic shapes.

6 CONCLUSION

We presented a human participant experiment investigating the perception of gaps or continuity between neighboring AM focal points generated by an UMH device. Gap detection thresholds were found to lie around 32.3 mm on average; however, a large within- and between-subject variability was observed during the task. Focal points spaced less than 15 mm apart were consistently perceived as a single continuous stimulus (>95% of the time), and focal points spaced 45 mm apart were consistently (84% of the time) perceived as two distinct stimuli.

Subsequent simulations of the acoustic pressure distribution generated by pairs of focal points show that at a height of 20 cm above the array used, focal points spaced less than 13 mm apart merge into a single wider focal point. Furthermore, there is a non-linear relationship between nominal focal point spacing and actual pressure peak spacing. By correlating the results from the human participant study with the simulation data, we find that both merging focal points (nominal spacing below 13 mm) and close pairs (nominal spacing of 15 mm) are consistently perceived as a single continuous stimulus. For pairs of focal points yielding pressure peaks actually spaced 18 mm apart or more, there appears to be a linear relationship between focal point spacing and probability of detecting a gap between the stimuli.

The present work provides initial guidelines for rendering continuous and discontinuous mid-air tactile shapes. It also provides insights into additional investigation required to draw strong conclusions about the perceived size of a focal point and the nature of perceptual interactions between neighboring focal points.

Our simulation study highlights the importance of validating the physical nature of the stimuli presented when running perception studies on ultrasound mid-air haptics, especially in situations involving complex shapes or multiple focal points. As we saw, significant deviations occur between the nominally commanded positions of pressure maxima and their actual positions, and interference between focal points can lead to unexpected interactions that may significantly modify the stimuli and bias results of perception experiments.

In the future, we plan to conduct investigations into the perceived diameters of focal points alone, in pairs and in complex patterns to gain further insight into perceptual interactions and to better predict perceived UMH shapes on the basis of physical pressure distributions. We hope this work will ultimately contribute toward a reliable model of mid-air haptic shape perception.

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