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A user-derived mapping for mid-air haptic experiences

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ABSTRACT

Mid-air haptic stimulation can enrich user experience during human-computer interaction. However, the design space of such stimuli is large due to the number and range of stimulation parameters. It therefore remains difficult for designers to select a stimulus to induce an intended experience. We derive a mapping for mid-air experiences based on two user studies. In the first study, participants rated 36 stimuli varied across three parameters (frequency, pattern, and repetitions). These ratings allowed us to determine a set of five experientially distinct stimuli. In the second study, participants vocalized their experiences with those five stimuli. This allows us to generate a mapping of 17 sensations and 23 experiences related to the stimuli. Finally, we discuss how the mapping can inform designers and researchers working with mid-air haptic technologies.

1. Introduction

Mid-air haptic devices can stimulate the skin without physical contact. Currently, the most common devices are based on ultrasound. However, the stimulation parameters of ultrasonic haptic devices differ from those with physical contact, such as vibration motors, in terms of force-feedback and spatial freedom. Therefore, the literature on designing haptic experiences (e.g., Kim and Schneider, 2020; Schneider et al., 2017) can only to a limited extent inform the selection of parameters of mid-air haptic stimuli and the consequences of those for user experience.

Ultrasonic mid-air haptic devices stimulate the sense of touch by emitting ultrasonic acoustic waves. The tactile focal point, created by these waves, causes vibrations on the skin that results in a haptics sensation and ultimately a haptic experience (Fig. 1). Previous work in mid-air haptics has focused mostly on the first step: how people *sense* changes in the stimulation parameters. For example, moving stimuli appear to have lower detection thresholds compared to static stimuli (Takahashi et al., 2018), and slower moving stimuli are perceived stronger compared to rapidly moving stimuli (Frier et al., 2019). Other studies show small or no effect of varying stimulation parameters when it comes to detection or recognition of mid-air haptic patterns (Long et al., 2014; Rutten et al., 2019). As previous work has so far covered only a small portion of the possible stimulation parameters, identifying those that people sense and thus possibly also experience differently is challenging.

Earlier work on mid-air haptic experiences roots their choice of stimulation parameters in neuropsychological properties of the human skin, such as the activation of mechanoreceptors (e.g., Hajas et al., 2020; Obrist et al., 2013). For example, Obrist et al. (2013) used this approach to relate one parameter of mid-air haptic stimulus, frequency (at 16 Hz and 250 Hz), to 14 distinct experiences. In a later work, they leveraged users' past experiences to define the best-fitting mid-air haptic stimuli for specific emotions (Obrist et al., 2015). However, it remains unclear how other stimulation parameters, such as spatial and temporal patterns, or combinations of these influence user experiences.

We conduct two studies (1) to find a set of experientially different stimuli and (2) to create a mapping of haptic experiences related to those stimuli. In the first study, we ask participants to rate stimuli on their experiential value. We base the experiential value on a subjective rating scheme. The possible parameter space is large with choices of any pattern and continuous values of frequency and repetitions. We vary the stimuli in 36 combinations of three frequencies, four patterns, and three repetitions. This allows us to choose a smaller set of combinations based on how they vary in experiential value. A smaller set of stimuli is necessary to study in-depth how each is experienced in the second study. The ratings also form our first contribution, linking three stimulation parameters to three dimensions of experiential value. In the second study, we employ a micro-phenomenological interview (Prpa et al., 2020) to encourage participants to describe their haptic experiences of five stimuli (from the first study) in depth. We analyse user descriptions by combining two approaches. First, we give an overall account of

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themes in the interviews and describe individual experiences in depth. Second, we do natural language analysis of the interviews to find keywords associated with particular stimuli. This forms our second contribution: A user-derived mapping for mid-air haptic experiences. As the mapping consists of five stimuli, it is not covering the full space of mid-air haptic stimuli. Nevertheless, we do cover a previously unexplored sample of stimuli with new spatial and temporal patterns, and can relate the five stimuli to 17 distinct sensations and 23 distinct experiences. We discuss how the ratings of stimulation parameters and the mapping can inform designers about the types of experiences they can induce with mid-air haptics.

2. Related work

The design space of mid-air haptic stimuli is large, and it remains unclear how mid-air haptic stimuli relate to user experiences. We first present some key prior research on how mid-air haptic stimuli induce changes in sensations. We then discuss approaches to support the design of mid-air haptic experiences.

2.1. Creating mid-air haptic sensations

Ultrasonic mid-air haptic devices stimulate the sense of touch by emitting ultrasonic acoustic waves, using an array of transducers. The waves collide in a focal point above the device, creating a field of high pressure. The focal point lets the skin vibrate when touched, resulting in a tactile sensation. By modulating the vibration intensity, frequency, position, and other parameters over time, designers can create a wide range of different stimuli.

In past research, three strategies have emerged to structure the modulation. With amplitude modulation, the first strategy, the vibration is modulated on a sinusoidal waveform, varying intensity over time (Hoshi et al., 2010). Takahashi et al. (2018) proposed lateral modulation, a second strategy for modulating the lateral position of the focal point. The third strategy is called spatiotemporal modulation, as it modulates the focal point position rapidly along a predefined path with fixed intensity, rendering tactile patterns on the skin (Frier et al., 2019). Although designers have access to these different modulation strategies, it remains unclear how to modulate parameters to induce specific sensations. This unclarity is due to the large space of parameters and the vast range of settings for these.

Previous work has identified spatiotemporal modulation of the focal point to be influential on detection thresholds (Takahashi et al., 2018) and on perceived strength (Frier et al., 2019). Frier et al. (2019) highlighted that the perceived strength of stimuli is dependent not only on the spatial pattern but also on the temporal parameters of rendering these on the skin (e.g., slow circular patterns are perceived as strong). Another body of work has investigated the recognizability of mid-air haptic patterns (Korres and Eid, 2016; Long et al., 2014; Rutten et al., 2019). Rutten et al. (2019), for instance, showed that it is hard for users to differentiate between similarly shaped patterns, and argued that this is due to the missing visual modality. While all these works show that each stimulation parameter has an effect on the perceived sensation, they cover only a small portion of possible parameters. Therefore, identifying those parameter settings that people sense and thus possibly also experience different is challenging.

We aim to tackle the large parameter space in our first study. We include three parameters: frequency, repetition, and pattern, which all have been shown to influence haptic sensation in the previous work above. We vary frequency in three levels within known perceptual limits, repetition of the stimulus in three levels, and use four distinct patterns. To assess whether these parameters can result in changes in sensations and possibly also experiences, we ask the participants to rate the stimuli in their experiential value based on the semantic differential created by Osgood et al. (1978). The ratings are given with polar adjectives “Pleasant” and “Unpleasant”, “Strong” and “Weak”, and “Excitable” and “Calm” (Osgood, 1962). These three sets of adjectives align with earlier work reporting on haptic user experiences (e.g., Frier et al., 2019; Obrist et al., 2013; Schneider et al., 2017), where pleasantness and strength of stimuli are measured. These ratings how the stimulation parameters play together in how distinct they are experienced. However, the three dimensions of experiential differences cannot provide insight into the nuances and variability of all that the users may experience about mid-air haptic stimuli. This insight is important for making decisions in designing stimuli.

2.2. Designing mid-air haptic experiences

Design of haptic experiences has been discussed in literature (e.g., Kim and Schneider, 2020; Schneider et al., 2017). For example, Schneider et al. (2017) identified prominent design challenges. They explain, for instance, that it is challenging to create consistent haptic

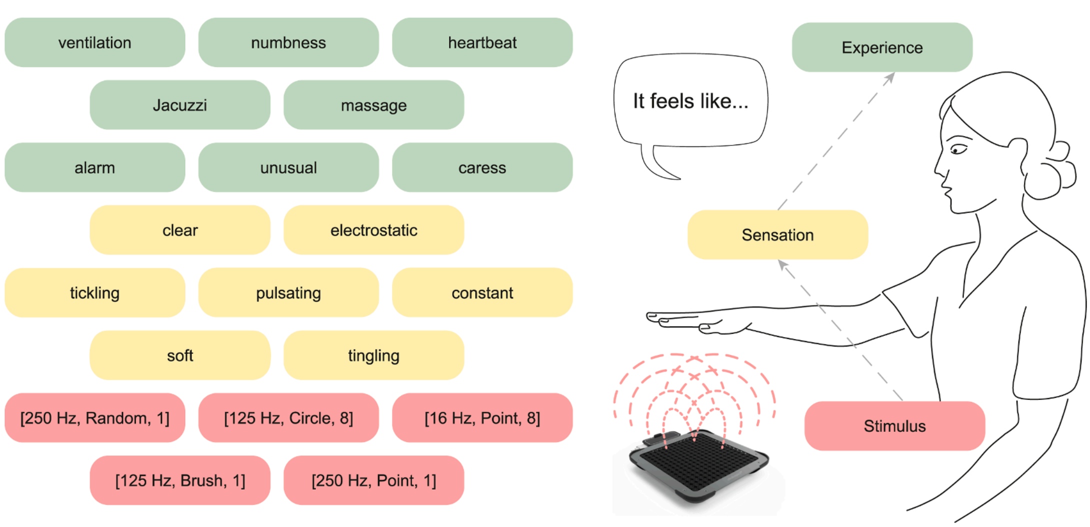


Fig. 1. A mid-air haptic device produces a *stimulus*. The stimulus is formed by the settings of device parameters. We selected five stimuli to generate a mapping. The settings of their three parameters, frequency, pattern, and repetitions, are presented on the left in the bottom cluster in red. The stimulus causes vibrations on the skin that results in a haptic *sensation*. The haptic sensation is based on the activation of the mechanoreceptors in the user’s skin. Some example connections from the stimuli to the sensations that the mapping includes are presented in the middle cluster in yellow. Through the sensation, the user *experiences* the mid-haptic stimulus. Examples of these are presented in the top cluster in green.

experiences across individual perceptions and to assess the quality of the designed experiences. Asking users to talk about haptic stimuli in their own language is one promising way of capturing related experiences (Hwang et al., 2011; Obrist et al., 2013).

Guidelines for designing mid-air haptic experiences for different domains have been proposed in recent years. Young et al. (2020) created a set of stimuli and hand gesture combinations, fitting car controls. In the AR domain, Van den Bogaert and Geerts (2020) employed user elicitation to create a set of stimuli and gesture combinations for input. Both works provide insights, guides, and hints to designing mid-air haptic experiences in their respective domains. Our work is different in the sense, that we aim to investigate the haptic stimuli, isolated from other modalities (i.e., we do not stimulate the visual or auditory system). We are also not looking to design haptic stimuli for specific functional uses (like car controls or AR input), as the aim is to generate descriptions of stimuli, independent of functional use.

Obrist et al. (2013) created a vocabulary for mid-air haptic stimuli, which relates two stimuli to 14 experiences. Although being limited to one stimulation parameter (frequency), this vocabulary solves the challenge of consistency and quality for the two explored stimuli, and thus serves as a guide for designers when creating mid-air haptic experiences by varying the frequency of the stimuli. Later work Obrist et al. (2015) showed that users can relate even complex experiences, such as emotions, to mid-air haptic stimuli.

Our work builds on the work of Obrist et al. (2013) by expanding the parameters of mid-air haptic stimuli as described above. Like Obrist et al. (2013), we also ask users to vocalise their experiences about mid-air haptics. We expand their approach by asking the participants to describe, relate, and interpret their experience with different mid-air haptic stimuli in a micro-phenomenological interview. Moreover, we combine the interview approach with both statement analysis and natural language analysis. Based on these, we present a mapping that connects haptic stimuli to conscious experiences.

3. Stimulation parameters

We investigate the relation between mid-air haptic stimuli and user experience by using an ultrasonic haptic device. Due to the large design space of stimuli the ultrasonic haptic device can produce, we have to limit our investigation to a set of stimulation parameters. Here we describe the design space and explain the set of parameters included in our studies.

Each stimulus induced by ultrasonic mid-air haptic devices consists of a set of primary and secondary parameters. The primary parameters are the focal point intensity and position. Intensity is in essence the amplitude of the wave emitted by the ultrasound speakers. In our study, the intensity of the focal point is modulated on a sinusoidal waveform, with a fixed amplitude of the highest possible setting for the used device, approximately 155 dB (Howard et al., 2020; Rutten et al., 2019). The focal point position can be modulated by emitting ultrasound from an array of speakers. Both the amplitude and the focal point can also be modulated over time. This brings us to a set of secondary parameters. For example, we can vary the frequency of the wave amplitude (how often the wave reaches its full amplitude) or the sequence and tempo in which the focal point is set onto a number of positions.

Because of this complexity of the stimuli, designing even seemingly simple stimuli requires many decisions. Let us take producing a circular pattern as an example. In this example, a designer has already decided on how to modulate the two primary parameters over time: they will use amplitude modulation to reach a certain intensity and a number of points are stimulated in such a sequence that they form a circle (i.e., taking the nearest point next and proceeding to a single, clockwise direction). Next, the designer needs to define settings for the secondary parameters. As intensity is modulated using amplitude modulation, the designer needs to define the appropriate waveform, and frequency of the modulation, and as the position is modulated as a circular pattern, the designer needs to define at least the radius, centre, and the number of points to stimulate along the circular path (i.e., resolution). This exemplifies that designing mid-air haptic experiences is difficult and not intuitive.

In our studies, we focus on three parameters: amplitude frequency, spatial pattern, and the number of repetitions. With these parameters, we can build stimuli that have the potential to trigger diverse sensations and experiences. The parameter settings presented reflect the current common use of mid-air haptic technology, such as feedback for button-presses and interaction with virtual objects (Rakkolainen et al., 2020). Additionally, these parameters are used often in previous work (e.g., Frier et al., 2019; Obrist et al., 2013, 2015; Rutten et al., 2019).

We vary the *frequency* of the wave amplitude, with values of 16 Hz, 125 Hz, and 250 Hz. With these frequencies, we target two sets of fast-adapting mechanoreceptors in the human skin, responding to vibrotactile sensations (Corniani and Saal, 2020; Vallbo and Johansson, 1984). The peak sensitivities of these receptors are around 16 Hz an 250 Hz respectively (Obrist et al., 2013), leading to the choice of these settings. A 125 Hz amplitude frequency has the potential to stimulate both sets of receptors, as the activation range of the receptors overlap (Corniani and Saal, 2020; Gescheider et al., 2001). Additionally, a 125 Hz frequency amplitude modulation was used in the experiments by Rutten et al. (2019).

We modulate the position in four different *patterns*. The patterns are inspired by the work of Frier et al. (2019) and Rutten et al. (2019). Fig. 2 shows the patterns. Except for the Point pattern, they are spatiotemporal patterns in the sense that they have a temporal sequence in which multiple locations are stimulated over time. The Point pattern (Fig. 2(a)) is a statically positioned focal point in the centre of the palm, with a diameter of approximately 0.8 cm (the focal point width). The Random pattern (Fig. 2(b)) is similar to the Point pattern, with the difference that the focal point is stimulating on random positions on the hand. Within one instance of the pattern, forty positions are randomly generated and the focal point is moved between these positions during the induction, such that the focal point is static at one position on the hand for a tenth of a second if the pattern is played for four seconds. The Circle pattern (Fig. 2(c)) describes a circular path for the focal point, with center in the centre of the palm, and a radius of 2 cm. The Brush pattern (Fig. 2(d)) is a 5 cm wide line moving from the wrist to the fingertips, where the illusion of a line is created by oscillating the focal point with a frequency of 100 Hz.

The stimulus length is fixed to four seconds. We vary the number of *repetitions* of the stimulus within this time frame, with values of one, four, and eight. In practice, this means that when the number of repetitions is four, the pattern is played four times within these four seconds. Thus, with four repetitions, the pattern is applied for 500 ms and paused for 500 ms, four times in a row. Patterns are completed exactly once every repetition (e.g., the focal point moves around the circular path once per repetition). We limit the stimulus length to keep the overall study duration short to counteract any fatigue during the study. With four seconds, the stimulus is long enough to repeat a pattern multiple times, while being short enough to not induce much fatigue during the overall study. The repetitions were chosen to represent a stimulus that is constantly on (when the repetition value is one), and a fast on-off stimulus (eight) which is still not that frequently repeated that it would be felt as being constantly on, as well as one value in between (four). The different number of repetitions are motivated by common uses of stimuli in haptic devices, such as for instance the vibration of mobile phones when an alarm is buzzing.

4. Study 1: evaluating experiential differences of stimuli

The purpose of this study is to identify a set of mid-air haptic stimuli that are experientially distinct. To do this, we ask participants to rate 36 stimuli based on their experiences. These ratings are used to cluster the stimuli based on experiential value using a*k*-means clustering algorithm.

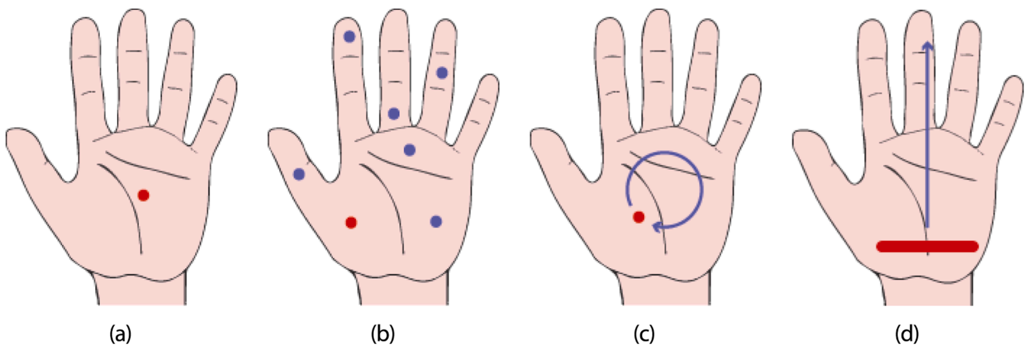


Fig. 2. Spatiotemporal patterns used to stimulate participants: (a) the Point pattern; (b) the Random pattern; (c) the Circular pattern; and (d) the Brush pattern.

The final set of experientially distinct stimuli is derived from the clusters. The ratings are available in an open repository (Dalsgaard et al., 2022).

4.1. Method

4.1.1. Participants

We recruited 19 participants to rate 36 mid-air haptic stimuli. The participants were aged between 25 and 57 (mean: 33.21, std: 8.66). Of the participants, five were female and 14 were male. None of the participants reported any sensory impairments in the hand, nor any prior experiences with mid-air haptics. It took 27 min on average for the participants to complete the experiment. All participants were rewarded with a gift valued at $15.

4.1.2. Design

The study followed a within-subject design with the three independent variables: frequency, pattern, and repetitions. The parameters are varied in 36 combinations of stimuli: three frequencies, four patterns, and three repetitions. The settings for these independent variables are listed in the previous section. We also add one zero-intensity stimulus, serving as an attention control condition. All stimuli were presented in an order randomized for each participant to avoid order effects.

4.1.3. Measures

The participants rated each stimulus on the three dimensions *evaluation, potency*, and *activity*, based on the semantic differential. Evaluation is rated with the polar adjectives “Pleasant” and “Unpleasant”, potency with “Strong” and “Weak”, and activity with “Excitable” and “Calm” on 7-point scales (Osgood, 1962). These three sets of adjectives align well with earlier work on haptic user experiences (e.g., Frier et al., 2019; Obrist et al., 2013; Schneider et al., 2017), where pleasantness and strength of stimuli are measured. These sets of adjectives also capture the valence and arousal dimensions of the Valence-Arousal model (Heise, 1987; Mehrabian, 1996; Russell, 1980) by measuring pleasantness and calmness.

4.1.4. Materials

The stimuli were given with the mid-air haptic device STRATOS Explore.[1] The device was placed on a table in front of the participant. An armrest was placed next to the participant, such that their dominant hand could be positioned consistently 20 cm above the haptic device. The distance of 20 cm between hand and device was shown to be best for stimulus perception by Obrist et al. (2013). The ratings were given with a desktop computer. Its 27” screen, mouse, and keyboard were placed on the table as depicted in Fig. 3. The study was conducted seated in a room with little visual and auditory distractions.

Fig. 3. The setup in the first study, consisting of (a) a screen, keyboard, mouse and headphones; (b) the mid-air haptics device STRATOS Explore and Leap Motion controller; (c) and an armrest.

4.1.5. Procedure

The participants were first introduced to the aim of the study, asked to sign an informed consent form, and fill out a demographics questionnaire. The participants were then instructed to wear a set of noise-cancelling headphones playing pink noise, so as to not become distracted by audible noise from the haptic device. A simple point stimulus was played before starting so that the participants had time to familiarise themselves with the sensation of mid-air haptic stimuli.

The mid-air haptic stimuli were applied to the dominant hand. To negate alignment issues, the dominant hand was tracked with a Leap Motion controller.[2] Stimuli were presented relative to the centre of the dominant hand. The participants were informed that they would not have to be very precise with the placement of the dominant hand during stimulus application, as the hand would be tracked automatically, as long as they placed their arm on the armrest and the hand over the device.

The study consisted of rating the 36 stimuli, each lasting four seconds. After a stimulus was played, a computer screen in front of them displayed the rating form for three dimensions of experiential value. The three ratings were given using the dominant hand and the mouse. Using the dominant hand to both controls the mouse and receive the stimuli ensured that the dominant hand was “distracted” between stimuli. The participants were allowed to take their time to rate the stimulus and to replay them. After submitting the three ratings, the participant had five seconds to place their dominant hand over the device, before the next stimulus was played. In addition to the three dimensions for ratings, participants had the option to indicate that they could not feel the induced stimulus and the option to be induced with stimuli again as

[1] https://www.ultraleap.com/product/stratos-explore/ (accessed February 14, 2022)

[2] https://www.ultraleap.com/product/leap-motion-controller/ (accessed February 14, 2022)

often as they wanted.

4.2. Results

The collected data consists of 684 ratings for 36 stimuli. In this section, we analyse the data using a*k*-means clustering algorithm. The clustered ratings are used to derive a set of stimuli that spans the experiential space, defined through the semantic differential ratings.

4.2.1. Stimulus ratings

All participants indicated not to be able to feel the attention control condition, such that no data points related to specific participants were excluded completely. The collected data contains 44 data points where participants reported the stimuli to be imperceivable. Most often, these stimuli were induced with frequency setting 16 Hz (97.77%), rendered as a Point pattern (52.23%) and/or for the full stimulation time (i.e., one repetition,52.23%). As these data points do not provide ratings, they are not included in further analysis.

The stimulus ratings were encoded to values between 0 and 6, such that low values indicate low evaluation, potency, and activity, and vice versa. Ratings were averaged per stimulus to yield an aggregate between participants. Averaging ratings lessens the influence of the novelty effect of mid-air haptics and potential rating inconsistencies within participant ratings. The variance between participants in ratings was 1.76 for evaluation, 1.41 for potency, and 1.59 for activity. Potency and activity ratings are strongly correlated ($r = 0.81$), evaluation and potency are moderately correlated ($r = 0.39$), and evaluation and activity are not correlated ($r = -0.11$). Table 1 shows the minimum, median, and maximum ratings for each of the dimensions and lists the stimulus resulting in these ratings.

4.2.2. Clustering stimuli

The ratings describe the experiential value of each stimulus. The aim of the study is to select experientially distinct stimuli, that can be used for further analysis. We do this by clustering experientially related stimuli into five clusters, using a*k*-means algorithm. The number of clusters was determined by scree analysis. All stimuli in the same cluster carry similar experiential values.

Fig. 4 shows all stimuli coloured by their respective clusters. Cluster #1 consists of the most pleasantly rated stimuli. All stimuli in this cluster are repeated once and Brush and Circle patterns (i.e., slowly moving patterns) are perceived as being pleasant. Cluster #2 groups together stimuli rated as very weak and it contains stimuli with Circle and Point patterns, all with an amplitude frequency setting of 16 Hz. Cluster #3 contains stimuli with Circle and Point patterns, high amplitude frequency (125 Hz and 250 Hz), and a high number of repetitions. These stimuli are rated around the middle of all three dimensions. Cluster #4 contains stimuli, that are rated high on potency and activity. All stimuli with Random patterns are found in this cluster, together with stimuli with Brush patterns and a high number of repetitions (four and eight). Cluster #5 contains stimuli with Point and Circle patterns and with high amplitude frequency and a low number of repetitions (one and four). These stimuli are rated pleasant, weak, and calm, in the middle ground between the other clusters.

We select one stimulus per cluster for further analysis. We do this by counting the number of each frequency, pattern, and repetition setting in a cluster. We select the stimulus that within a cluster has settings that occur most often. Thus, for each cluster, we find the most common amplitude frequency, pattern, and repetitions settings. The stimulus consisting of the commonly occurring settings was considered as representative of the cluster. In the case of equally common settings, we selected the stimulus that has a minimal distance to the cluster centroid. Table 2 lists the settings and ratings of the selected stimuli. The selected set is varied across stimuli settings, although the repetition setting four is not present. This is expected, as the selection process does not guarantee full coverage of stimuli settings but rather prioritises variance in the experiential values of the stimuli.

5. Study 2: generating a mapping of haptic experiences

The purpose of this study is to generate a mapping of experiences for mid-air haptic stimuli. To do this, we ask participants to vocalize their experiences in interviews with the set of five stimuli found in the first study. The participant statements are then used to form a mapping through thematic and natural language analyses. Interview transcriptions are available in the original language, Danish, and in the English translation in an open repository (Dalsgaard et al., 2022).

5.1. Method

5.1.1. Participants

We invited 11 participants to talk about their experiences with mid-air haptics. Of these six were females and five males. The participants were aged between 21 and 43 (mean: 27.6, std: 5.8). Three participants reported that they had tried mid-air haptics one or two times before. There was no overlap between participants participating in the first and second studies. Five participants currently studied or had completed an education within the STEM fields, three within Arts, two within Social Sciences, and one within Humanities. All participants spoke in their native language during the study. None of the participants reported any sensory impairments in the hand. Each participant was rewarded with a gift valued at $25.

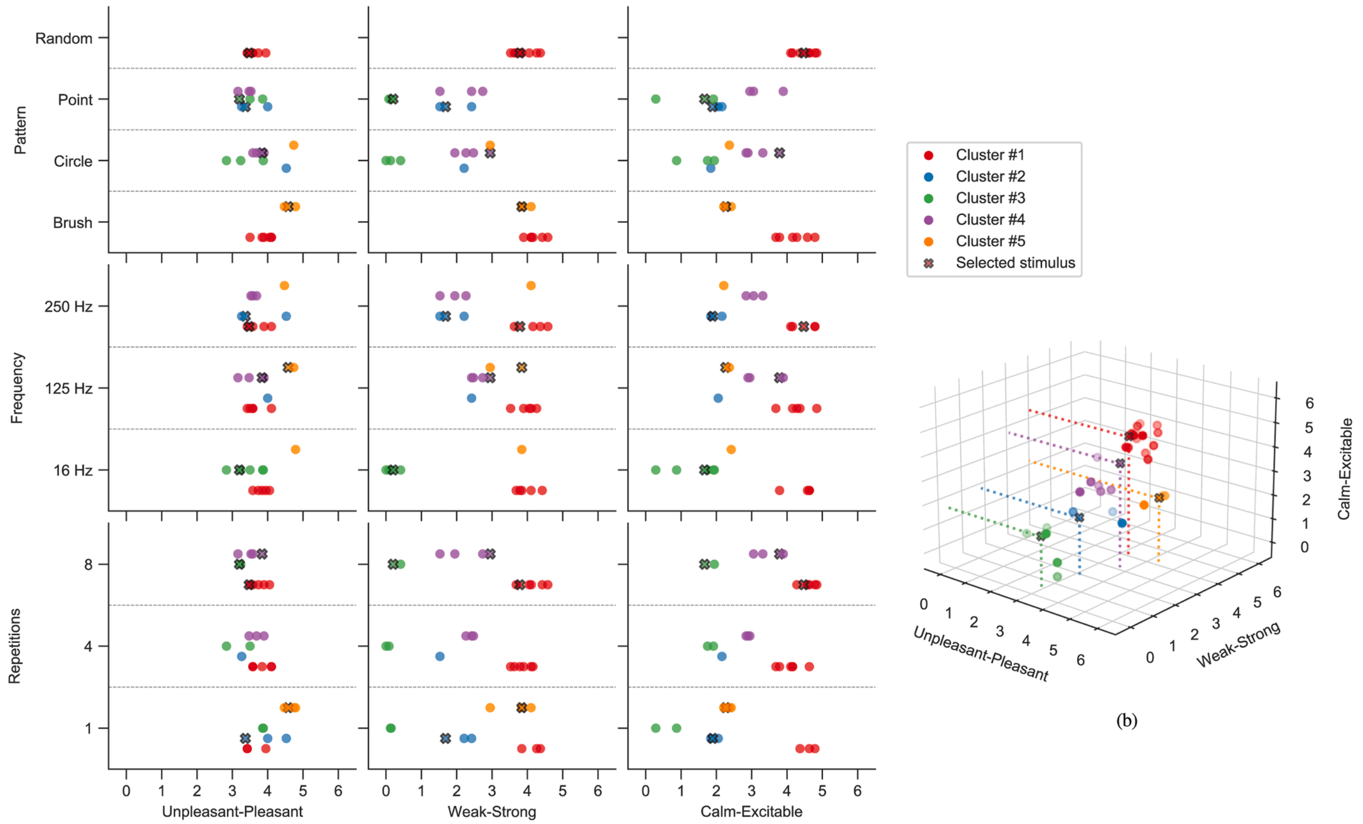
5.1.2. Approach

We use micro-phenomenological approach to conduct the interviews. Contrary to observational studies, micro-phenomenological studies do not rely on external observations of subjects experiences. This allows for in-depth questions about the subjective experience to generate rich and precise descriptions.

Petitmengin (2006) crafted the *micro-phenomenology interview*

Table 1
Minimal, median, and maximum ratings for evaluation, potency, and activity. Ratings range between 0 and 6.

		Rating	Frequency	Pattern	Repetitions
Evaluation	*min*	2.83	16 Hz	Circle	4
Unpleasant (0) - Pleasant (6)	*median*	3.68	250 Hz	Circle	4
	max	4.79	16 Hz	Brush	1
Potency	*min*	0.00	16 Hz	Circle	4
Weak (0) - Strong (6)	*median*	2.95	125 Hz	Circle	1
	max	4.58	250 Hz	Brush	8
Activity	*min*	2.29	16 Hz	Point	1
Calm (0) - Excitable (6)	*median*	3.05	250 Hz	Point	8
	max	4.84	125 Hz	Random	8



(a)

Fig. 4. Stimuli ranked by rating and coloured by clusters, found by *k*-means clustering. Selected, experientially different stimuli are marked with a cross. In (a) each plot shows a parameter against an experiential rating dimension, i.e., each plot contains all 36 stimuli positioned by parameter and rating. We can, for instance, derive that stimuli in cluster #2 are consistently rated as being weak, as all blue scatters are grouped close to zero on the Weak-Strong axis, and having a frequency of 16 Hz, as all blue scatters are found within the boundary marking the 16 Hz stimuli. (b) shows each stimulus coloured by cluster. Dotted guides mark the experiential rating of selected stimuli.

Table 2
Selected stimuli through *k*-means clustering of participant ratings.

Cluster	Frequency	Pattern	Repetitions	Evaluation	Potency	Activity
#1	125 Hz	Brush	1	4.58	3.84	2.26
#2	16 Hz	Point	8	3.20	0.20	1.67
#3	125 Hz	Circle	8	3.84	2.95	3.79
#4	250 Hz	Random	8	3.47	3.79	4.47
#5	250 Hz	Point	1	3.37	1.68	1.89

technique based on the work of Vermersch (1994, 2018). The micro-phenomenology interview is a technique for researchers to explore singular subjective experiences in depth. The interview is meant to focus the interviewee's attention on the experience, guiding them through the evocation of the experience, and directing their attention towards specific dimensions of the experience (Prpa et al., 2020). This structure invites interviewees to talk about the different sensory, cognitive, and affective inputs of a specific lived experience.

Recently, Prpa et al. (2020) described how the interview technique has been used by HCI researchers. They exemplify previous approaches to micro-phenomenology in HCI and provide guidance for researchers using this technique. In HCI, for instance, Knibbe et al. (2018b) used the micro-phenomenological interview to generate descriptions of the moment of exciting Virtual Reality and Hogan et al. (2016) explored information visualizations with the interview technique. Obrist et al. (2013) used the micro-phenomenology interview to generate a vocabulary for mid-air haptics.

In the interviews, we ask the participants to describe, relate, and interpret their experiences with different mid-air haptic stimuli. The analysis of interviews (described by Petitmengin et al., 2019), is not perfectly suited for our study, because here the experience of a haptic stimulus is relatively short in time. Therefore, we adapt the questions from Knibbe et al. (2018a); Obrist et al. (2014, 2013); Petitmengin (2006), and Prpa et al. (2020) to suit this type of experience. The aim of the questions was to uncover three underlying features of the experience: a subjective description, an experiential relation, and an interpretation. Examples of the questions asked are:

- "How would you describe the felt stimulus?"
- "What previous experience did the stimulus remind you of?"
- "How would you describe this to someone, who has not tried mid-air haptics at all?"
- "How was the first time you felt the stimulus different from the last?"

In addition to questions, we repeatedly reformulated descriptions given by the participants to stabilize their attention to the experience.

This technique allows the participant to refocus their attention and to correct misunderstandings during the interview (Petitmengin, 2006).

5.1.3. Procedure

The study was conducted in the same room as in the first study. The apparatus was also the same as in the first study, although the setup was re-arranged, such that participant and experimenter were sitting across from each other. This was done to focus the attention of the participant on the interview and stimulus, instead of the apparatus.

The participants were introduced to the aim of the study, signed an informed consent form, and filled out a demographics questionnaire. Afterwards, they were instructed to wear a set of noise-cancelling headphones playing pink noise during the time a stimulus was induced. A simple point stimulus was played before starting the interview on the set of selected stimuli so that the participants had time to familiarise themselves with the sensation of mid-air haptic stimuli.

During this second study, participants were presented with five stimuli selected in the first study (Table 2). The stimuli were presented one at a time in a randomized order to avoid order effects. Each trial was conducted in two phases: an induction and an interview phase. During the induction phase, participants felt the stimulus three times in a row with a 5 s delay between playbacks, such that the participant could get a firm impression of the stimulus. Participants were asked to wear a set of noise-cancelling headphones, playing pink noise, only during this phase. Immediately after the induction phase, the interview phase started; the interviews followed the micro-phenomenology interview protocol described above and lasted between 5 and 10 min for each stimulus. All interview sessions were audio-recorded. On average participants completed the full session in 46 min.

5.2. Data

We collected recordings of 11 interviews for each of the five selected stimuli, for a total of 55 stimuli-specific interviews. The interviews were transcribed for the qualitative analysis. The analysis was conducted on the transcriptions in the interviewee's native language. Translation to English was done by two of the authors.

We analyse the data with two approaches, qualitative analysis and natural language analysis. These analyses and the results are presented next.

5.3. Qualitative analysis

We do a qualitative analysis of the transcribed interviews, following the approaches taken in earlier uses of micro-phenomenology in HCI (e. g., Knibbe et al., 2018a; Obrist et al., 2013). This allows us to give an overall account of the themes in the interviews as well as participants' individual experiences in depth. The strength of this approach is to give rich, particular descriptions.

The analysis of the transcribed interviews shows five themes. Each theme spells out important aspects of participants' experience as captured by the interviews. In the following, we discuss those themes and use the notation [Participant, Frequency, Pattern, Repetitions] to indicate the participant identifier and felt stimulus (e.g., [P1, 125 Hz, Circle, 8]).

5.3.1. Sensations

Participants connect a variety of words to the sensation induced by the mid-air haptic stimuli. Table 3 shows an overview of these words. Words such as *vibration*, *mild*, and *soft* recur across stimuli, showing an overall positive sentiment towards the sensation. In general, many of the same words were used to describe the sensation across stimuli, with a few exceptions, for instance, *stuttering*: "*Like someone who blows, stuttering very much, while they are at it*" [P4, 125 Hz, Brush, 1]. Many participant stated that the sensation was "*not natural*" [P5, 125 Hz, Brush, 1] or "*unusual*" [P2, 250 Hz, Random, 8]. Some relate this to the fact, that the stimulus was produced by an artificial object:

> "*Everybody has tried, that someone is blowing on you. And you know that feeling well, but you have not tried a machine doing it before.*" [P2, 16 Hz, Point, 8]

Another participant clearly stated, that being touched involuntarily made the sensation unusual and unpredictable:

> "*Because it is rare that you come into contact with something new that you have not chosen yourself. It's more like that. It's unusual for me to sit here and feel a stimulus on my hand because I'm not used to my hands being exposed to things I do not expect to happen because it is often myself who decides what my hands [come in contact with].*" [P2, 16 Hz, Point, 8]

The linked words in Table 3 overlap with the previously generated vocabulary by Obrist et al. (2013), showing that the same sensations transcend to these more complex stimuli. For instance, do words like "tingling", "soft", "ticking", and "pulsating" recur in results of both studies.

5.3.2. Spatial movements

Here we compare the experiences of the patterns to the played patterns (Fig. 2), but do not consider the latter a "ground truth", as participants simply describe what they feel.

Both the [16 Hz, Point, 8] and [250 Hz, Point, 1] stimuli are described similar to: "*it felt like it was very specifically at one place*" [P4, 250 Hz, Point, 1] (in the middle of the hand). The descriptions differ in the number of times a "blow" was felt on the hand since the [250 Hz, Point, 1] stimulus was described as being continuously blowing, while the [16 Hz, Point, 8] stimulus is described as blowing multiple times on the same spot. These compare well to the pattern intended.

The [125 Hz, Brush, 1] stimulus was described consistently with the Brush pattern: "*[It] starts at the root of the hand, and then it moves up over the hand and over the fingers [...] in a fluid motion.*" [P9, 125 Hz, Brush, 1]

The descriptions of the [250 Hz, Random, 8] stimulus were less consistent. Many participants described the location of the focal point "*as if it were moving, to different places on the hand* " [P7, 250 Hz, Random, 8] or similar, but a smaller group of participants felt that the stimulus drew "*a pattern of what at least felt like linear movements in different directions over most of the palm*" [P8, 250 Hz, Random, 8] or similar descriptions of lines being drawn on the palm.

The movement of the [125 Hz, Circle, 8] stimulus is described in

Table 3
Described sensations associated with stimuli. Words unique to a stimulus are highlighted in italics. The number of participants (out of 11) using the word is indicated in parenthesis.

Stimulus	Sensations
[250 Hz, Random, 8]	vibrating (4), mild (3), tingling (3), pulsating (2), *stuttering* (2), electrostatic (1), soft (1)
[125 Hz, Circle, 8]	vibrating (4), constant (3), mild (3), *clear* (2), soft (1)
[16 Hz, Point, 8]	pulsating (4), tingling (4), vibrating (4), mild (3), electrostatic (2), soft (2), tickling (2)
[250 Hz, Point, 1]	*prickling* (2), trembling (2), vibrating (2), electrostatic (1), soft (1), tingling (1)
[125 Hz, Brush, 1]	vibrating (5), soft (3), tickling (3), electrostatic (2), tingling (2), trembling (2), mild (1)

various ways, from feeling like a door key touching the hand with a rotational movement, to movements in a C- or an O-like pattern. The latter examples compare relatively close to the intended movement pattern. One participant described the movement very thoroughly:

> "*Something starts down at the end of your hand and then goes a bit forward, or you get blown air on the hand a bit in front of that, which then blows back on down the hand, and then next time you feel something that is further up on the hand, which breaths back further down the hand.*" [P10, 125 Hz, Circle, 8]

It seems that it is hard for participants to identify the displayed pattern. Even patterns with little spatiotemporal complexity (such as those displayed here) are difficult to recognize consistently. This finding is consistent with that of Rutten et al. (2019), stating that the recognizability of mid-air haptic patterns is unreliable.

5.3.3. Experiences

Participants answered with a variety of earlier experiences that in different ways were thought to be similar to the sensation felt or that participants were reminded of based on the sensation.

A commonly mentioned relation was to an experience of blowing. One participant described how "*it's maybe a bit [like] a drunk man you would need to breathe into a breathalyzer, who just has to do it a few times before it gets a little random like that, well, that's the picture I get in my head*" [P2, 250 Hz, Random, 1]. Other participants emphasize the more localized experience of blowing, like through a straw (One participant had done so as part of practising to play the musical instrument Didgeridoo [P1, 250 Hz, Point, 1]), a weak bicycle pump [P3, 125 Hz, Circle, 8], a hand dryer [P10, 125 Hz, Brush, 1], or the ventilation in an aeroplane [P6, 250 Hz, Point, 1]. A few mentions emphasized that stimuli felt like blowing but non-localized, for instance like "*a small gust of wind*" [P11, 250 Hz, Point, 1].

Other relations were to technology. Participants frequently mentioned the similarity to the alarm in their phones or the vibrations from a pager. One said "*Okay, completely different experience. It's very funny. Well, it [makes me think of] the old Nokia 3310 when it rings, with, well, more like a blowing feeling [...]*" [P4, 16 Hz, Point, 8]. Three persons mentioned the feel of their phones ringing.

Participants also linked the stimuli to experiences with drawing, "*Yeah, so it might feel a bit like taking a pencil and then running lines across, but still just without touching...*" [P3, 250 Hz, Random, 8]. Similar comments were made about being touched with a feather and with a brush. The emphasis seems to be on the spatial analogies of the stimuli.

A final link was to the experience of touches on the body, in particular, to massage and caressing. One participant noted that the stroke was like being touched by another person.

> "*Yes, well, it was a lot...it was really funny, this feeling. It made me happy, that is. [...] it could also be a feeling, where my partner is running their hand down over my hand, or like..., it was very much like safe or fun, or something, that feeling...*" [P2, 125 Hz, Brush, 1]

Other participants spoke about massage, as in "*it's very chill...when you just sit and run your hand, like, back and forth, and the feeling, I get, is a little bit like you just sitting and getting a gentle massage, [on] the palm of your hand.*" [P7, 250 Hz, Point, 1] Although one person spoke about a massage chair [P1, 125 Hz, Brush, 1], the emphasis here is on the similarity to human touch.

Participants can relate rich and varying experiences to the stimuli. This shows the flexibility of mid-air haptic stimuli, both relating to simple notifications to complex interhuman interactions. One participant wrapped up the experiences: "*This is pretty magical*" [P1, 250 Hz, Random, 8].

5.3.4. Analogies

Not all participants could relate a previous experience to all felt stimuli, stating for instance that they had no visual feedback as a reason for it being difficult to relate the felt haptic stimuli to previous experiences.

> "*Well, I do not think you use, well, like this, with this "having to figure out what it is that could feel like this", of course, it requires thinking power in a completely different way than if you had something visual that could tell you what really happened, right?*" [P9, 250 Hz, Random, 8]

Other reasoned that the sensation felt "*very abstract*" ([P4, 250 Hz, Random, 8], [P7, 250 Hz, Point, 1], [P4, 250 Hz, Point, 1]) and that "*it does not feel natural, so it was not a feeling of, "now that experience is something [I] would naturally experience in everyday life"*" [P3, 125 Hz, Brush, 1]. Here, we will take a closer look at the strategies used by participants to explain the felt stimuli, that proved difficult to relate to actual previous experiences.

One strategy to explain a felt stimulus was to use an analogy of sounds. To some participants, it seemed that the haptic and auditory feedback modalities are connected due to the rhythm, created by the combination of Pattern and Repetition. All three selected stimuli with the number of repetitions set to eight were associated with rhythmic sounds (i.e., music, alarms, or sounds from vibrating objects). The stimulus with a Random pattern is described in terms of music, for instance as "*some tone, music like*" [P10, 250 Hz, Random, 8], "*a bass playing [...] and you can feel that "duf, duf, duf, duf"*" [P5, 250 Hz, Random, 8], and "*soccer battle cries, like "dudu dududu, let's win"-ish*" [P10, 250 Hz, Random, 8]. Next to music, sounds from real world objects were used to relate an experience to a stimulus, by for instance associating with "*a sound, [...] [when] a fire engine [is] going past you*" [P5, 16 Hz, Point, 8] or "*a sprinkler, [...] that goes like "prr prr prrr", as if it is rotating around*" [P5, 125 Hz, Circle, 8].

Despite being asked to relate to a previous experience, some participants related stimuli to imagined experiences. Inspiration for these experiences was gathered from, among others, Science Fiction movies, in which a character would get their hand, fingerprints or eyes scanned with a red laser to get through a secret door ([P7, 125 Hz, Brush, 1], [P10, 125 Hz, Brush, 1]). The analogy of a touchable laser was also used to relate a stimulus with a Point pattern to a "*laser light used to point at a blackboard*" [P1, 250 Hz, Point, 1]. At other times the stimulus with a Brush pattern was related to a "*lonely ocean wave*" [P8, 125 Hz, Brush, 1], that gave a "*soft, round feeling, [...and that] ran slowly [...] scanning the hand*" [P10, 125 Hz, Brush, 1]. Similarly the stimulus with a Circle pattern related to a constant soft wave ([P5, 125 Hz, Circle, 8], [P8, 125 Hz, Circle, 8]).

5.3.5. Temporal unfolding

During the interview, we asked the participants to recount the three repetitions of the stimulus induction at the beginning of the interview. We asked them to describe how their experience differed between the three repetitions of the played stimulus. Table 4 shows the timeline of the stimulus inductions and the identified themes for each time the stimulus was induced. Participants often reported that their related previous experience, or analogy, came to mind quickly, when first induced with a stimulus — "*It was in the first stimulus [...], that's what I associated it with right away*" [P7, 125 Hz, Circle, 8]. For others, the interpretation of stimulus came to mind during the second and third

Table 4
Participants were induced with a stimulus three times in a row before interviews. This timeline shows the common themes, participants talked about when asked to remember back to the moment of induction. Numbers in parenthesis indicate the number of participants (out of 11) talking about a particular theme.

1st induction	2nd induction	3rd induction
Analogy (5)	Analogy (1)	Intensity (3)
Movement (4)		Internalization (2)
Sensation (2)		Analogy (1)

induction. The movement of the stimulus appeared to be in the focus during the first induction, as participants reported: "*So, the first time, I just had to figure out where it hit [...]*" [P5, 250 Hz, Random, 8].

Although being induced with the exact same stimulus, participants felt differences in perceived strength of a stimulus between inductions: "*[...] I felt right there at the very end that it came, like, stronger than the first [...]*" [P5, 250 Hz, Random, 8]. The third stimulus induction is also used by some participants to internalize the stimulus and finalize their opinion of the stimulus.

> "*Well, I can not very well distinguish between the first two, but the last one, it was like a little more "Okay, this one is a little clearer", or, it feels stronger on your hand.*" [P3, 125 Hz, Brush, 1]

In general terms, at the first induction, intuition about the stimulus is formed. During the second and third induction, this intuition is consolidated and internalized.

5.4. Language analysis

Here we present a natural language analysis of the transcribed interviews. The strength of this approach is to find particular words associated with individual stimuli.

The research field of Natural Language Processing (NLP) has for many years concerned itself with the analysis of natural human language. We use NLP to extract keywords relevant to each stimulus from participant statements. In this analysis, we extract the nouns, verbs, and adjectives, to generate keywords from each of these different parts of speech. As "nouns name substances; verbs name processes; and adjectives name qualities" (Brown, 1957), we assume that the participant derived nouns refer to the objects relate to stimuli, that the verbs refer to the felt sensation, and adjectives refer to the qualities of stimuli. In the following, we describe our methodology to find keywords, ensure that their context is considered, and provide an overview of keywords.

5.4.1. Methods

In our analysis, we leverage two techniques from within NLP to find keywords in the participant interviews. Before applying these techniques, we filter the corpus to include participant statements (excluding interviewer questions) and to not include stopwords. We use the Term Frequency Inverse Document Frequency (TF-IDF) score (Havrlant and Kreinovich, 2017) to determine the importance of words within participant statements. TF-IDF scores words in a text document based on their frequency and on the inverse frequency within the document, where high scores imply a strong relation to the document. The technique is widely used for keyword selection (e.g., Havrlant and Kreinovich, 2017; Ramos, 2003), although it is application dependent to select a threshold for the scores to include. The second technique is based on adjusted residuals, following Knibbe et al. (2018a) and Sharpe (2019). The absolute value of the adjusted residuals implies how much actual occurrences of a word differ from the expected distribution. The sign of the adjusted residual indicates whether the number of occurrences was lower or higher than expected. As the adjusted residuals are$z$-values, we convert them to corresponding probabilities using a normal distribution. Since we are doing multiple testing, we adjust each probability using the Bonferroni correction.

Thus we compute the TF-IDF score and the adjusted residuals for each stimulus and part of speech, with the full corpus of interviews as reference. We threshold$\text{TF-IDF} > 0.5$, to highlight words to be found important, and$p < 0.05$, to remove words that are used across interviews to talk about stimuli. Scoring words with both techniques, we gain two sets of words. We find the intersection between the sets to determine keywords that are deemed to be important and not commonly used between stimuli. We analyse the keywords manually based on the context in which they appear, to ensure that singular keywords are not misinterpreted. We disambiguate keywords by adding context or removing keywords when deemed misleading.

5.4.2. Disambiguating keywords

Applying the methods above, we found 62 keywords, before filtering out 15, for a total of 47 contextually relevant keywords. We added contextual information to 14 keywords. All keywords are listed by the related stimulus in Table 5. We filtered words that are assigned the wrong part of speech due to word ambiguities in the origin language (e.g., "beating", as in "*a heart beating*" [P10, 125 Hz, Circle, 8] and "banks", the financial institution, use the same word) and words that relate to phrases in verbal language (e.g., *remember* as in "*[...] as far as I remember*" [P9, 250 Hz, Random, 8]). The language analysis results in a mix of keywords mentioned by only one participant (e.g., *pump air* [125 Hz, Circle, 8]) and a large number of participants (e.g., *movement* [125 Hz, Brush, 1]). This shows that the keywords not only reflect common words between participants, but also individual phrases. In the following, we mark keywords in italics, although they can be found in the aforementioned table.

5.4.3. Stimulus keywords

Each row in Table 5 shows how participants describe, related to and interpret haptic stimuli. The [250 Hz, Random, 8] stimulus is related to five nouns, that, in conjunction with five adjectives, describe the felt stimulus (*random pattern* moving in *lines* at *different* places on the hand), related experiences (e.g., "*[...feels] like putting your hand over the [...] air bubble tube for [...] a Jacuzzi*" [P9]), and what properties they attribute the stimulus (e.g., "*it sharpened the attention in various places of my hand*" [P1]).

Keywords found to describe the [125 Hz, Circle, 8] stimulus indicated that participants have difficulties relating previous experiences with the stimulus, as only the keywords *heartbeat* and *door key* were found. However, some participants described the stimulus, as if an object was dragged across their hand. The difficulty of relating to this stimulus is also reflected in a subset of the verb keywords, as participants can not *figure out* the purpose of the stimulus — "*Maybe because I do not have any associations to it, because I do not feel I can figure out what its purpose is*" [P10]. In any case, participants did report this stimulus to be

Table 5
Keywords found through TF-IDF and adjusted residual, grouped by the stimulus. Words added in italics provide context to the keywords and numbers in parenthesis indicate how many participants (out of 11) used the keyword. Keywords are sorted by their TF-IDF score.

Stimulus	Nouns	Verbs	Adjectives
[250 Hz, Random, 8]	feedback (1), Jacuzzi (2), pattern (6), *sharpen* attention (1), line (2)	exposed *to stimulus* (2)	different *places* (9), random (2), unusual (1), *missing* visual (2)
[125 Hz, Circle, 8]	heartbeat (1), door key (1)	surprising (3), *weak bike* pump (1), comb *hair* (1), figure out *[purpose]* (2), drag *across the hand* (3)	pleasant (3), not unpleasant (2)
[16 Hz, Point, 8]	alarm (3), bass (1), middle *of the hand* (3), video game (2)	pulsating (2), vibrating (4)	not negative (2)
[125 Hz, Brush, 1]	movement (7), wave (2), movie (2), feather (2), hand dryer (3), gust of wind (2), vibration (4)	move (5), choppy (1), tickling (3), scanning (2)	wide (3), damp *hand* (1), unusual (1), electrostatic (1)
[250 Hz, Point, 1]	point (2)	pointing *at something* (1), numbness (1), prickly (4)	not physical (2), long time (4), mild (3)

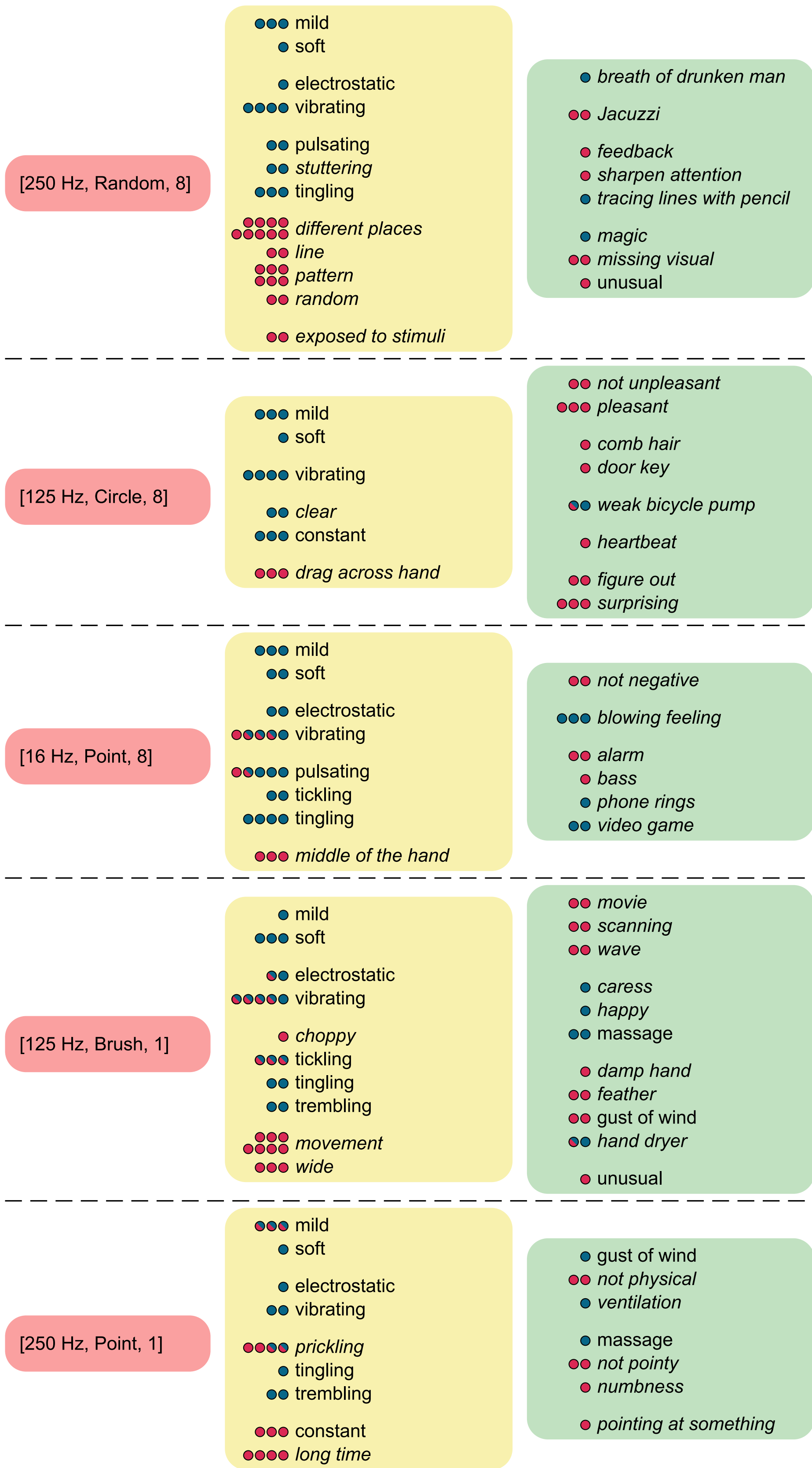


Fig. 5. The user-derived mapping, consisting stimuli in red on the left, sensations in yellow in the middle, and experiences in green on the right. Keywords highlighted in *italics* are unique to one stimulus and keywords are grouped together by semantic meaning. Each dot next to a keyword represents one participant and is colour coded by the analysis method used to find the keyword. Blue dots mark keywords found through thematic analysis, red dots keywords found through language analysis, and mixed dots keywords found throughout both methodologies.

pleasant or, at least, *not unpleasant*.

The [16 Hz, Point, 8] stimulus is typically described in terms of the position of the focal point at the *middle* of the hand). The resulting haptic experience is related to the vibrations and sounds of an *alarm* clock, the feeling of standing near a *bass* speaker at a concert, and vibrations emitted from *video game* controllers. The stimulus is sensed as *pulsating, vibrating*, or both, and it was "*[...] neither negative nor positive.*" [P7]

Also when describing the [125 Hz, Brush, 1] stimulus, participants focus on the pattern, specifically the *movement* of the pattern. The movement is described as a *wide wave, gust of wind*, or *feather*, touching and *moving* across the hand — "*[...] it is a static feather, to be very specific.*" [P4] The overall stimulation induced a *tickling* sensation, although the movement felt *choppy* or stuttering. Participants additionally related "*a slightly weak airblade [...] that you run your hand up and down through, but just holding your hand still instead.*" [P9] Similarly focusing on the movement of the stimulus, participants described feeling like a device *scanning* their hand, as they had seen in the *movies*.

The [250 Hz, Point, 1] stimulus is perceived as being a *mild, prickly point*, with a feeling when "*[...] one's foot sleeps or hand sleeps, the one there such a slightly stinging feeling [...].*" [P2] Similar to the other presented stimuli, this stimulus is described as being intangible, "*[b]ecause this feels more like such a gust of wind with vibrations, where physical touch feels more like such pressure and the feeling of skin to skin.*" [P3]

Overall, the stimuli are often spatially described by their pattern and as being *vibrating, tickling,* or *prickling*, although never as unpleasant nor as being tangible. Participants were reminded of a variety of previous experiences, most prominently an *gust of wind* blowing on their hand.

5.5. A user-derived mapping for mid-air haptic experiences

We generate a mapping linking the five selected stimuli and the found sensations and experiences from the insights gained through qualitative and language analyses. The mapping is presented in Fig. 5. It is based on the keywords listed in the qualitative analysis (Table 3 and Section 5.3.3) and language analysis (Table 5). We categorised the keywords as being sensation or experience by three authors and grouped them by semantic meaning. To categorise keywords, we define a sensation as a mental process resulting from an immediate stimulation of mechanoreceptors, while an experience is the conscious response of said sensation. These definitions are adapted from Kandel et al. (2013).

Fig. 5 shows the five stimuli adjacent to their related sensations and experiences. From the figure, it becomes clear that participants have a shared language of talking about sensations across stimuli, as they often use similar words to describe stimuli, both across different stimuli and within the same stimulus. For instance, the keywords *mild, soft*, and *vibrating* are omnipresent, repeating across stimuli. On the other hand, when a sensation is unique to one stimulus, it has been repeated often across participants (e.g., the keyword *movement* was related to [125 Hz, Brush, 1] and mentioned by seven distinct participants).

Experiences are less consistent compared to sensations across participants and stimuli. Participants deliver distinct descriptions of what experience a particular stimulus reminds them of. However, it is possible to group those associations. For instance, [16 Hz, Point, 8] does remind some participants of an *alarm*, a *bass* sound, a *phone ringing*, and *video games*, all with similar underlying sensations (*vibrating*, in this case).

This mapping can help designers in creating mid-air haptic experiences and in evaluating mid-air haptic stimuli. Let us exemplify how designers could leverage the mapping with two use cases.

In the first use case, a person living in a remote location would like to communicate a touch on their loved one's hand either during a live conversation or as part of a message. The designer could provide the [125 Hz, Brush, 1] stimulus as one option as that has been connected with experiences of caressing. Similar to emojis, the designer has chosen a stimulus to represent semantic meaning, directly augmenting the communicated words in a conversation or a message. In the second use case, a parent and a child play a haptically augmented pattern guessing game remotely. The designer of such a game could provide the [250 Hz, Random, 8] stimulus as one option to communicate the patterns as that has been connected to experiences of someone drawing on the hand, as this stimulus is related to such a game. This could leverage the feelings of social touch in the remote interactions between users.

6. Discussion

Mid-air haptics faces opportunities for creative, diverse and novel experiences; at the same time, it faces an enormous design space. Because mid-air haptics is a new technology, user experience in this space is not well understood. Nonetheless, novice participants proved able to provide in-depth insights into their experience with mid-air haptic stimuli.

In the first study, participants provided ratings of mid-air haptic stimuli, enabling us to select a set of diverse stimuli based on their experiential value. In the second study, we interviewed participants about their experience with the selected stimuli, ultimately resulting in a mapping for mid-air haptic experiences.

6.1. Informative and rich experiences

In the studies, participants felt the mid-air haptic stimulation to be pleasant (or, at least not unpleasant) and frequently commented on the lack of haptic force. When asked, participants in the second study commented that stimulation was created by somebody else than themselves or an artificial object (a "machine"). Participants related these stimuli created by a machine to their phone or alarm clock ringing or felt that the stimulus was conveying some sort of information, suggesting that artificial stimulation has been normalized through everyday use.

When participants thought somebody else initiated the stimulus, some vocalized social and interpersonal experiences. These ranged between someone drawing with fingers on the participants back, for them to guess a shape, getting their hand massaged, or their partner caressing their hand. The latter one shows that experiences, possibly related to a strong positive emotion come to mind when feeling certain mid-air haptic stimuli. Stimulating purely the sense of touch can affect the emotional state of users and convey complex interpersonal experiences. The fact that participants relate both bland informative and rich social experiences to mid-air haptic stimuli speaks for the experiential diversity of the technology. This finding mirrors the finding of Obrist et al. (2014), as they show that emotional meaning can be conveyed with mid-air haptics.

6.2. Talking about tactile experiences

Obrist et al. (2013) presented the human-experiential vocabulary, tying two stimuli to 14 word-categories, describing users tactile experiences. In our interviews and analysis, we can see many of the same themes emerging, for instance when participants comment that a stimulus feels "tickling" or like an "air-conditioner". The participants across both Obrist et al. (2013) and our studies even share analogies, when comparing the feeling of the stimulus with a feeling of numbness in their hand (i.e., "hand is going to sleep"). Distinct in our results, we found that users also can relate complex social interactions with mid-air haptic stimuli. This is probably due to the difference in stimulus pattern, as we present our participants with multiple patterns with varying complexity, compared to a point on the hand. In general, this shows that both the expert users, interviewed by Obrist et al., and the novices, interviewed by us, have a similar language when talking about mid-air haptic sensations and experiences.

6.3. Experience modelling

Kim and Schneider (2020) define the Haptic Experience Model, consisting of the different aspects to consider when designing haptic experiences. Part of the model are five experiential dimensions; *Harmony, Expressivity, Autotelics, Immersion*, and *Realism*. Participants talk about these dimensions without being prompted specifically, showing that these dimensions also apply to mid-air haptics. Harmony is an important issue for participants, as many state that they would like a visual reference to more easily be reminded of an experience. Some even mention related auditory experiences, indicating that stimulating the full range of sensory channels is promising to yield rich experiences. The Expressivity and Autotelics dimensions are satisfied, as participants report distinct relations to experiences between stimuli and that stimuli feel "pleasant". We do not measure Immersion, but as participants provide very colourful descriptions of their experience, indicating some degree of immersion, most likely limited by the lack of sensory harmony. This limit also applies to the Realism dimension, although participants through the provision of analogies give examples of realistic experiences. Overall, these stimuli alone do not target all of Kim and Schneider experiential dimensions, although they are able to influence experiential factors.

6.4. Methods for studying haptic experiences

We use a variety of techniques to first rate and cluster stimuli, to then be able to explore the haptic experiences produced by stimuli. As reported before, the results of two experiential ratings do correlate, showing that there is little distinct information to be gained from measuring both. On the other hand, it shows that users associate the strength and excitability of mid-air haptic stimuli.

Another technique we used is the micro-phenomenological interview, which in its essence focuses the interviewee's attention to a specific lived experience and facilitates generating descriptions of the very same. We quickly discovered that inducing the stimulus only once at the beginning of the interview makes it challenging for participants to talk about the experience in-depth, as one stimulus is limited to four seconds in total induction length. We thus opted to let participants experience the stimulus three times in a row, to gain a basis for the diachronic structure to unfold.

6.5. Limitations and future directions

The mapping is not exhaustive, due to the vast design space of mid-air haptics and limitations in the sample of participants. An exhaustive mapping was never the goal, as it is not feasible to search the full space, using the methodology presented. Instead, we aimed to cover a previously unexplored sample of stimuli and succeeded at generating distinct descriptions of these in this subspace. As we only investigate a small sample in-depth, we can not reliably provide insights into the effect of individual parameter settings (e.g., comparing 125 Hz against 250 Hz frequency settings). This would require a larger sample, evaluated for instance through crowdsourcing, once ultrasonic mid-air haptic devices gain increased entry into the objects of everyday life.

No matter the size of the sample, the resulting mapping should be validated. We propose two approaches for validation of vocabularies concerned with mid-air haptics: (a) invite participants to assign a phrase, from a carefully selected set of phrases to a haptic stimulus and then check whether the assigned phrase overlaps with the corresponding set of phrases in the mapping; or (b) invite participants to create a haptic stimulus that subjectively matches the experience in question and then check whether (or to what degree) it matches the corresponding stimulus related to the experience, according to the mapping. The latter approach is inspired by the work of Obrist et al. (2015), where participants are asked to create a mid-air haptic experience to mediate a specific emotion.

The results are also limited by the number of participants participating in the two studies. In the first study, the participants seem to agree on the ratings, as the reported standard deviations are low and the ratings cluster well. Assessing the consistency between participants in the second study, is more difficult, partly due to the nature of subjective reports and differences in tactile perception between humans. Although the set of participants interviewed in the seconds study is diverse in educational background, age, and sex, it would be meaningful to interview people with more diverse backgrounds, as tactile experiences can be individual. The naivety of the participants is also a limitation to our study, according to Rutten and Geerts (2020), as mid-air haptic sensations are generally perceived more positive, when novel to the participant.

7. Conclusion

We formed a user-derived mapping for mid-air haptic experiences, through two user studies. Using the results of the first study, we derived a set of representative stimuli. In the second study, we leverage the phenomenology interview technique to gather rich descriptions of the haptic experience related to the interview. The mapping is formed by a consensus of qualitative and quantitative methods applied to the interviews. With the mapping, designers gained a tool for creating mid-air haptic experiences and for evaluating mid-air haptic stimuli. We discuss design implications of the mapping and compare participant statements to existing haptic experience frameworks.

CRediT authorship contribution statement

Tor-Salve Dalsgaard: Conceptualization, Methodology, Software, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization. **Joanna Bergström:** Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Marianna Obrist:** Methodology, Validation, Writing – review & editing, Visualization, Supervision. **Kasper Hornbæk:** Conceptualization, Methodology, Formal analysis, Writing – review & editing, Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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