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An Exploration of Just Noticeable Differences in Mid-Air Haptics

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***Abstract*—Mid-air haptic feedback technology produces tactile sensations that are felt without the need for physical interactions, wearables or controllers. When designing mid-air haptic stimuli, it is important that they are sufficiently different in terms of their perceived sensation. This paper presents the results of two user studies on mid-air haptic feedback technology, with a focus on the sensations of haptic strength and haptic roughness. More specifically, we used the acoustic pressure intensity and the rotation frequency of the mid-air haptic stimulus as proxies to the two sensations of interest and investigated their Just Noticeable Difference (JND) and Weber fractions. Our results indicate statistical significance in the JND for frequency, with a finer resolution compared to intensity. Moreover, correlations are observed in terms of participants' sensitivity to small changes across the different stimuli presented. We conclude that frequency and intensity are mid-air haptic dimensions of depth 5 and 3, respectively, that we can use for the design of distinct stimuli that convey perceptually different tactile information to the user.**

***Index Terms*—Mid-air haptic, JND.**

I. INTRODUCTION

Ultrasonic mid-air haptic feedback is a technology that enhances human-computer interaction by providing tactile sensations in a contactless manner [1], [2]. In recent years, there has been much research interest in advancing mid-air haptic technology to render points, lines, shapes, and textures in mid-air using a variety of modulation methods [3] and hardware platforms [4]. These research efforts are motivated by the common belief that, when combined with 3D hand-tracking and visual images, mid-air haptic feedback technology can enable and enhance natural hand-gesture input and user experiences in a variety of applications [5] such as automotive user interfaces [6], touchless displays [7], and AR/VR [8]. However, despite much progress, our understanding of mid-air haptic sensations lags behind other haptic displays such as wearables [9], surface [10], and grounded haptic interfaces [11].

While many previous studies on mid-air haptics have discussed the overall impact of haptic feedback on users interfaces, very few have delved deep into the specific design parameters used to create that haptic feedback. For instance, Martinez et al. [12] studied various methods of rendering 3D shapes by emphasizing salient features, and especially object corners. Howard et al. [13], [14] studied the recognition of local shapes and the gap detection thresholds between nearby mid-air haptic point stimuli. Hasegawa et al. [15] studied the detection threshold curve for different mid-air haptic stimuli. Mulot et al. [16] studied the influence of sampling strategies on a user's ability to differentiate arc curvatures. Ozkul et al. [17] studied how different auditory and mid-air haptic feedback combinations can change the emotional responses of users. Finally, Rutten et al. [18] studied people's ability in discriminating between different intensities and velocities of mid-air haptic sensations, i.e., their just noticeable differences (JND). The above papers are by no means exhaustive, however, to the best of our knowledge, no other JND study has been performed for mid-air haptics.

Knowing how much something must be changed in order for a difference to be noticeable is a well-known and important aspect of all of our senses and finds application in, *inter alia*, music production, speech perception, marketing, and haptics [19]. Specifically for mid-air haptic applications involving control interfaces, such as a holographic slider or button [20], it is important to not only know what is the minimum perceivable threshold but also to be able to sub-divide the *intensity* dynamic range into individually distinct sub-levels. Similarly, for mid-air haptic applications involving texture rendering [21], [22], it is important to be able to produce perceivably different levels of roughness.

In this paper, we study the JND that must exist between two similar mid-air haptic stimuli in order to be perceived as separate and distinct. Specifically, we evaluate the JND and Weber fraction for the parameters of frequency and intensity through two within-subject studies involving 15 and 19 participants respectively. Here, intensity refers to the amplitude of the acoustic pressure applied to the user's palm that is proportional to the perceived haptic strength. Meanwhile, frequency refers to the rotation rate that a mid-air haptic point moves around a circular path on a user's palm (see Figure 1), and is inversely proportional to the perceived haptic roughness [23]. Our results reveal a Weber fraction of 20% for frequency, and 28% for intensity. We also observe that older participants displayed a larger JND on average, and that participants with a larger Weber fraction in one condition (i.e., low sensitivity to change) typically also reported larger Weber fractions for other conditions as well, as one would expect. Overall, these findings provide new insights into the tactile resolution and information detail afforded by mid-air haptics in the dimensions studied (intensity and frequency) and are a step towards a more detailed and informed mid-air haptic design space.

Participants were asked to judge the roughness and intensity of a pair of stimuli presented in random order. The graphical user interface (GUI) for a pair of mid-air haptic stimuli for frequency is depicted in Figure 3. The results suggest that it might be possible to effectively combine the parameters of frequency and intensity for mid-air haptic feedback and translate them into a format that can be used to convey information to the user through mid-air haptic interfaces.

II. RELATED WORKS

A. *Mid-air haptic interfaces*

Mid-air haptic technology uses focused ultrasound to create high-pressure points that apply a small force onto the human skin [24]. Modulating the acoustic field in time and space enables one to induce contactless tactile sensations, a technology that has a wide range of potential applications in human-computer interaction (HCI), including automotive human-machine interfaces (HMIs), virtual reality, augmented reality, digital signage, and gestural interfaces [5]. These applications call for the ability to render a variety of stimuli with different geometric and temporal properties, which can be achieved through a deeper understanding of a user's ability to discriminate between these properties.

B. *Mid-air haptic rendering and modulation techniques*

There are several methods for the tactile rendering of mid-air haptics [3]. Modulation techniques currently available include amplitude modulation (AM), lateral modulation (LM) and spatio-temporal modulation (STM) each having different advantages and disadvantages. These techniques are being continuously studied, evaluated and improved through perceptual experiments, mostly targeting their capacity to increasing the perceived stimulus strength, or lowering the perceived minimum threshold, thereby widening the dynamic range available to the technology [25], [26]. Other research goals have been to improve 2D and 3D shape recognition [27] and the ability to evoke tactile sensation on different parts of the body, such as the face and arms [25], [28].

C. *Mid-air haptic perceptual studies and JND*

Many studies have investigated the perceptual dimensions of mid-air haptic stimuli. For example, Perquin et al. have looked at the discrimination of motion direction, and evidence of directional bias [29]. Wilson et al. studied the perception of localisation of a static point and the perception of motion [30]. Takahashi et al and Howard et al studied perceptual thresholds for points and local shapes respectively [14], [31]. Finally, Rutten et al studied JNDs and estimated people's abilities to discriminate between differences in the intensity and frequency of mid-air haptics patterns [18]. Their findings report JNDs of 12.12% for the intensity and 0.51 Hz for the frequency of the sensations displayed. In other words, to use mid-air haptic intensity and velocity as information channels, a minimum difference in intensity of at least 12.12%, and a minimum velocity difference of at least 0.51 Hz needs to occur from the reference output of 100% intensity and 2 Hz. However, Rutten's findings are limited to a moving (dial-like) stimulus with revolution frequencies in the range of 1-2 Hz which is amplitude modulated (AM) at 125 Hz.

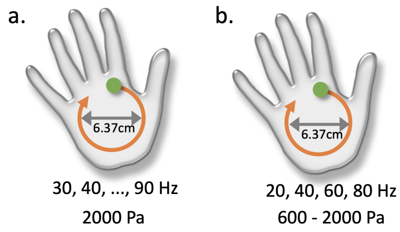

Fig. 1. Schematic of the STM mid-air haptic stimuli presented in study 1 (a.) and study 2 (b.). Both stimuli involved a mid-air haptic focal point (green) of different acoustic pressures ranging from 600 to 200 Pascals. The focal point is made to move around a circle (orange) of perimeter 20 cm centred at the user's palm, at different revolution frequencies ranging from 30 to 90 Hz. No further modulation is applied to the acoustic focus.

In contrast, our study involves a rapidly moving (STM) stimulus with revolution frequencies in the range of 20-90 Hz and is not amplitude modulated at all (see Figure 1). We chose this kind of mid-air haptic stimulus because it has also been studied by many authors including Frier et al. [26], [32], Alakhawand et al. [33], Romanus et al. [34], and Freeman et al. [35]. Moreover, the revolution frequency of the STM stimulus we study has been previously associated with the notion of roughness by Ablart et al. [23] and later used by Beattie et al. [36] to incorporate the perception of visual roughness into the design of mid-air haptic textures.

III. USER STUDIES

We designed two user studies to help us understand the JND in the frequency and intensity parameter space of mid-air haptics. Knowing these can help mid-air haptics designers discretize the dynamic range available in each of these dimensions and thus deliver sufficiently different haptic sensations to the user as required by the application at hand.

To that end, we describe below two within-subjects user studies corresponding to the following two haptic conditions:

- *Study 1* measured the responses to five pairs of haptic stimuli, each with a different *frequency* but the same intensity level of 1, which corresponds to a peak sound pressure level of 2000 Pa. The frequency pairs compared were $(30, 50), (40, 60), \ldots, (70, 90)$ Hz with the lower frequency acting as the reference value and the upper one being incrementally reduced by 2 Hz every time a user perceives the pair as different in terms of their *roughness*, or increased by $2/0.7393 = 2.7053$ Hz every time a user perceives the pair as similar.
- *Study 2* measured the responses to four pairs of haptic stimuli, each with a different *intensity* but the same frequency. The intensity pairs compared were $(0.3, 1)$ at frequencies $20, 40, 60,$ and 80 Hz with the upper intensity level acting as the reference value and the lower one being

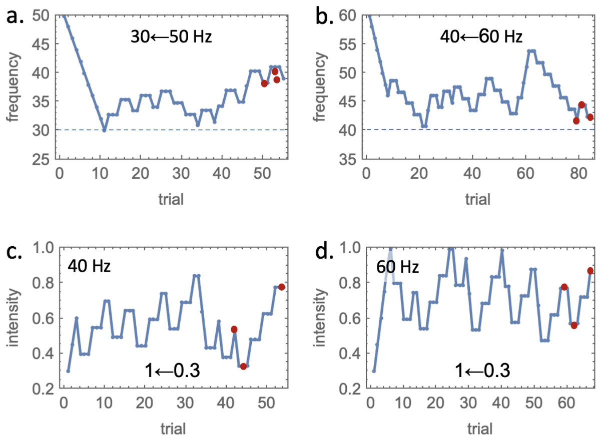

Fig. 2. Example JND staircases for frequency (a. and b.) and intensity (c. and d.). The red dots indicate the last three reversals in each case.

incrementally increased by 0.15 (or 300 Pa) every time a user perceives the pair as different in terms of their *strength*, or decreased by $0.15/0.7393 = 0.2029$ (or 405 Pa) every time a user perceives the pair as similar.

Through this process, we aimed to find out how close to the reference frequency (Condition 1) and reference intensity (Condition 2) we can get, and if these margins are a function of the frequency. Example staircases are provided in Figure 2. The procedures of the two studies were identical.

A. Participants

Two groups of participants were recruited for the intensity and frequency experiments. The JND frequency experiment included 15 participants aged 23 to 58 (mean age 32, SD = 8.5 years), 14 of whom identified as male and 1 as female. The JND intensity experiment included 19 participants aged 23 to 58 (mean age 32, SD = 8.5 years), with 16 identifying as male and 3 as female. Some participants from the first study overlapped with those in the second study. All participants, except for one left-handed participant, were right-handed and familiar with mid-air haptic technology. The participants came from diverse backgrounds and had a good grasp of the English language.

B. Haptic Stimuli

The mid-air haptic stimuli presented to the participants in the two studies differ only in terms of intensity and frequency of revolution as described in Figure 1. The revolution frequencies were chosen in the range studied by Ablart et al. [23]) whose results suggest that a lower frequency is associated with a rougher sensation. Meanwhile, a higher acoustic pressure is associated with a stronger sensation.

The stimuli presented lasted for 1 second each, with a pause of 0.5 seconds between pairs. After each pair, participants were asked a question about their self-perceived strength or roughness between the stimuli and given a forced-choice of two buttons for each haptic stimulus (see 3).

The stimuli were targeted at the center of the participant's palm using the Leap Motion hand tracking API, allowing the participants to move their hand freely within the device's tracking range while being advised to keep their hand relatively steady, centered, and approximately 20 cm above the haptic display for optimal performance.

C. Protocol

Both studies used a forced-choice staircase design. Namely, participants were presented with a pair of stimuli and were asked to choose the rougher (study 1) or stronger (study 2) one respectively. Each pair was presented up to three times in a controlled but random order. If all three participants answers were according to our existing knowledge (i.e., lower frequency = rougher sensation, and higher intensity = stronger sensation), then the frequency (study 1) or intensity (study 2) was adjusted in the direction of the reference stimulus. If a participant answered wrongly (i.e., not according to our knowledge) then the frequency or intensity was adjusted away from the reference stimulus.

Thus, the study design corresponded to 3 downs 1 up for study one (JND frequency) and 3 ups 1 down for study 2 (JND intensity) as can be seen in Figure 2. A reversal is said to occur when the direction of the staircase is reversed. Each participant block was allowed to carry on until 15 reversals were observed. Until the first reversal occurred, the study design was modified to follow a 1 up 1 down condition to accelerate convergence towards the JND. Finally, the mean frequency or intensity of the last 3 reversals was taken as the JND for each block and is later reported in the results section of the manuscript.

The ratio between the steps going up and down was chosen to be 0.7393 so that the convergence of percent-correctness is unaffected by the absolute size of the steps [37]. For example, in study 1, the initial condition of each comparison pairs were $(30 + 10i, 50 + 10i)$ Hz for $i = 0, \ldots 4$. For the case of $i = 0$, we used the 30 Hz stimulus as the reference value and the staircase began at 50 Hz and slowly decreased in steps of 2 Hz until its first reversal when it increased by 2.7053 Hz (see Figure 2 a.). In study 2, the initial condition of each comparison pairs were intensities $(0.3, 1)$ and frequencies $20, 40, 60,$ and 80 Hz. For the case of 40 Hz, the reference intensity was 1 and the staircase started at 0.3, slowly increasing in steps of 0.15 until its first reversal when it decreased by 0.2029 (see Figure 2 c.).

D. Procedure

The procedure was identical for both studies conducted. Due to Covid-19 social distancing restrictions, the studies were conducted independently by each participant using their own laptop/PC and an Ultraleap Stratos Explorer Device during a Zoom video call with the researcher. We obtained ethics approval from Ultraleap Ethics Committee and followed relevant guidelines to protect participant privacy and ensure ethical conduct. All participants provided informed consent, and data was collected and stored confidentially. During the call, the participants were provided with an information sheet

Which haptic felt rougher?

Which haptic felt stronger?

Fig. 3. Screenshot of the GUI used in the two experiments conducted.

which briefed them on the purpose of the study, and a consent form to sign. They were also given access to a Unity3D developed experimental GUI, which they loaded to play the JND demo shown in Figure 3.

A trial session was performed to familiarize participants with the Ultraleap device and the GUI. During the study, participants were asked to choose between "Haptic 1" or "Haptic 2" button, depending on which sensation that felt stronger (for the JND intensity experiment) or rougher (for the JND frequency experiment). Haptic 1 was always the one presented first. No corrective feedback was given.

Participants were advised to take breaks as needed to avoid hand exhaustion. The study consisted of 5 blocks of sensation pairs, with breaks in between each block. Also, participants were instructed to use earplugs to minimize distractions from the outside environment.

At the end of the study, participants were debriefed and the saved data was sent to the researcher to be stored securely, anonymized and prepared for post-processing and statistical analysis. The Zoom calls lasted approximately 50 minutes, with the experimental part lasting more than 30 minutes.

IV. RESULTS

To make sure the calculated JND for the study is accurate, we measured the mean of the last 3 reversals, assuming the last 3 reversals would provide us with the most accurate value, as the participant would hover around the JND threshold. We have validated our assumption by testing other options too, such as the last 5 reversals, or the middle 3 reversals of the staircase.

A. User study 1: Frequency

The results for the frequency JND and their corresponding Weber fraction (the ratio of the JND to the reference stimulus) are shown in Figure 4. We choose to show both box plots and violin plots to visually display the mean, quartiles, outliers, and their respective kernel densities; the latter can visually inform the normality of the data. The figures show that the JND above the reference frequency f_{ref} grows linearly. A linear regression returns a slope of $1.23 f_{\text{ref}}$. Outliers are observed for reference frequencies 50 and 60 Hz, which also seem to stretch upwards the respective distributions of the violin plots. The Weber fractions across the five reference frequencies tested have a mean of 20.7%.

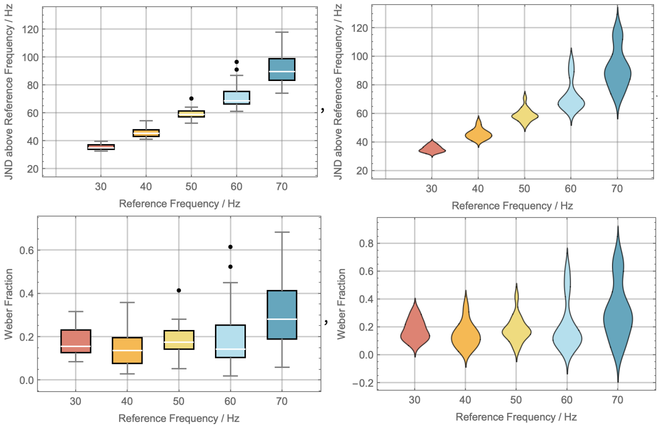

Fig. 4. Box (left) and violin (right) plots of the JND (top) and Weber fraction (bottom) relating to the frequency-related user study.

The Shapiro-Wilk Test violated the normal distribution of the calculated JND for each frequency. Therefore we used the Friedman test to look for statistical significance. There was a statistically significant difference between the JND values for each S_{freq} and R_{freq} pair $(\tilde{\chi}^2(2) = 25.137, (4, N = 14), p \leq 0.01)$. A further post hoc analysis with a Conover test was conducted with a Bonferroni correction applied resulting in a significance level set at $p \leq 0.01$, with statistical significance for two frequencies pairs - provided in Table I

group 1	**group 2**	***p-value***	**T-stat**
JND 40Hz	JND 70Hz	0.001	4.27
JND 30Hz	JND 70Hz	0.001	4.10

TABLE I
CONVENOR POST-HOC TESTS FOR EACH JND FOR ROUGHNESS IN FREQUENCY IN-BETWEEN PAIRS, WITH BONFERRONI CORRECTION.

The Weber fraction for the overall change required for JND is 20.7%, which falls within the range of 3-30% for the vibrotactile frequency of tactile and haptic stimuli based on the Weber range of stimulus intensities [38]. Overall, a significant regression equation was found with $R^2 = 0.92$, adjusted $R^2_{adjusted} = 0.84$), indicating that the change in frequency significantly predicts the change in JND $(B = 1.4, 95\% CI[1.26, 1.54])$.

B. User study 2: Intensity

The results for the intensity JND are shown in Figure 5. Again we choose to show both box plots and violin plots to visually display the mean, quartiles, outliers, and their respective kernel densities. However, we do not plot the Weber fraction, since the reference intensity is 1. The figures show that the JND below the reference intensity is basically flat, i.e., independent of the stimulus frequency. Outliers are observed for reference frequencies 60 and 80 Hz, which also seem to stretch downwards the respective distributions of the violin plots.

The Weber fractions across the four reference frequencies tested have a mean of 28.5%. This implies that for the stimulus (circle STM) and frequencies tested (20-80 Hz), there is a noticeable difference between intensity 1 (2000 Pa) and intensity 0.715 (1430 Pa). Note that the minimum detection threshold of these stimuli is around intensity 0.3 (600 Pa), however, the exact threshold has not been formally studied. Also, note that the force applied to the skin is proportional to the acoustic pressure squared. Therefore, the results of Figure 5 suggest that there may be several discrete and noticeable levels between 0.2 and 1, an investigation that we defer to future studies since one also needs to consider Fechner's law which asserts that subjective sensation is proportional to the logarithm of the stimulus intensity.

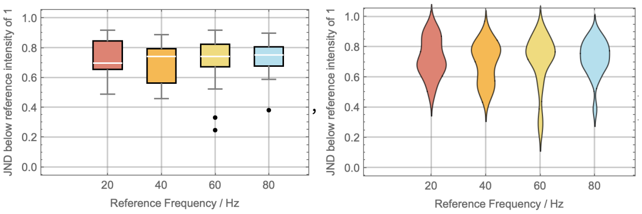

Fig. 5. Box (left) and violin (right) plots of the JND relating to the intensity-related user study.

A Shapiro-Wilk Test violated the normal distribution of the calculated JND for each frequency. Therefore, we used the Friedman test to look for statistical significance. There was no statistical significance in intensities JNDs across different frequencies, $\tilde{\chi}^2(2) = 0.3947(3, N = 19), p = 0.98$.

The Weber fraction for the overall change required for JND is 28.5%, which does not fall between 13 - 16% for the frequency of amplitude of tactile and haptic stimuli based on the Weber range of stimulus intensities [38]. As can be seen from Figure 5, the Weber fraction for each frequency is 20 Hz = 27.24%, 40 Hz = 30.39%, 60 Hz = 29.03%, 80 Hz = 27.31%.

C. Participant Weber fraction Correlations

Figure 6 shows matrix plots of the correlation matrix of the Weber fractions derived from the two user studies above. Namely, we look at the Weber fraction for each participant and for each reference stimulus and calculate the correlation coefficient between stimuli. This can inform us if participants with a low (high) Weber fraction for reference stimulus i also had a low (high) Weber fraction for reference stimulus j, where i and j are the rows and columns of the correlation matrix, respectively. The plots are of course symmetric with unit diagonals. Recall that a low Weber fraction implies that a participant can detect a small change in the stimulus. We observe that in user study 1 (see Figure 6a.) stimuli 50 and 60 Hz are moderately correlated with a Pearson's coefficient of 0.55. In user study 2 (see Figure 6b.) we observe that stimuli 20 and 60 Hz are moderately correlated with a Pearson's coefficient of 0.59, while stimuli 40 and 80 Hz are moderately correlated with a Pearson's coefficient of 0.63. We also observe that the overall mean correlation coefficient is positive at 0.2 and 0.28 for frequency and intensity, respectively.

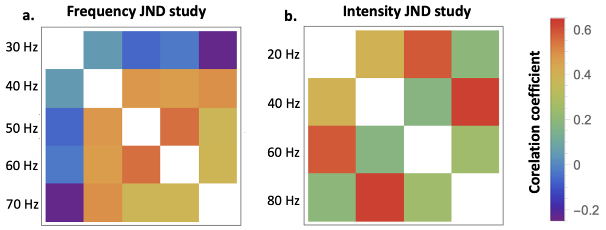

Fig. 6. Matrix plots of the Pearson's correlations between the Webber fractions of different reference stimuli in study 1 (a.) and 2 (b.).

V. DISCUSSION

The purpose of this JND study on mid-air haptic sensations is to bridge the gap in the current understanding of designing for mid-air haptic feedback and interfaces. JND studies, which examine the minimum noticeable difference of a stimulus, play a crucial role in design principles. Our JND study for frequency found statistical significance using a Friedman test for 2 pairs of JNDs. The calculated Weber fraction for the JND for frequency was 23.19%, which falls within the range of 3-30% for vibrotactile frequency of tactile and haptic stimuli. While not identical, these findings are consistent with previous studies on electro vibrations [39].

Our regression analysis showed a strong positive correlation between intercept values and predicted threshold frequency with an R2 of 0.84, indicating the effectiveness of the model in determining JNDs for varying frequencies and can be used for future predictions. In our frequency study, we recorded mean JNDs ranging from 5 Hz for lower reference frequencies (30 Hz), to 22 Hz for higher reference frequencies (70 Hz), suggesting that the step size should be higher for novice users. Further analysis of our results indicated that older participants (38 years or older) had higher mean JND values. When these participants were removed from the data set, JND at 70 Hz decreased significantly from 22 Hz to 14 Hz and the Weber fraction dropped from 31% to 17%, however, there was minimal change in the rest of the frequencies studied. We can therefore speculate that above a certain age group, JND could possibly differ, as it has been shown that sensitivity decreases with age [40]. However, our participants struggled to discriminate against high frequencies only, contradicting previous findings that discrimination decreases against all frequencies with age [41]. The randomization of stimuli makes it unlikely that the disparity is due to the length of exposure, but participant fatigue and overstimulation may have played a role. Prolonged exposure to tactile stimulus, and fine textures specifically, can reduce tactile sensitivity, as shown by previous research [42].

Our study found a consistent Weber fraction of 28.5% for intensity across the 20-80 Hz frequency range, suggesting no significant influence of frequency on intensity perception. The study's results differ from those of Rutten et al. [18] who found a Weber fraction of 12.12% for intensity. We can attribute the inconsistent findings to the significantly different stimuli used in their study.

The threshold for perceiving mid-air haptic intensities and frequencies has been shown to be 30% and 10 Hz, respectively [26]. Using the Weber fraction results from our study we can speculate that the reference intensity can be reduced by at least 2 levels without exceeding the threshold, and at least 5 levels for frequency, suggesting that people can distinguish 3 levels of intensity and 5 levels of frequency. Translating these levels into information bits, our findings suggest $\log_2(3) = 1.58$ bits of information can be obtained from the intensity dimension, and $\log_2(5) = 2.32$ bits from frequency. Since bits of information from these two dimensions can be summed up we have a maximum of 3.9 bits of information.

We have not studied diagonal JNDs in these two-dimensional parameter space. For example, we know that a stimulus with intensity and frequency (1,60 Hz) can be perceived noticeably differently from a stimulus that varies slightly in frequency (i.e., (1,72.5 Hz)), or slightly in intensity (i.e., (0.71, 60Hz)), but we do not know the mutual JND when making slight changes in both frequency and intensity simultaneously. One could imagine a combined Weber fraction that is a function of both frequency and intensity dimensions, e.g., something like $k = a\frac{\Delta f}{f} + (1-a)\frac{\Delta I}{I}$ $a \geq 0$ while $\frac{\Delta f}{f} = 20.7\%$ and $\frac{\Delta I}{I} = 28.5\%$ are respectively the frequency and intensity Weber fractions that we have evaluated in this paper.

Finally, we also looked at the correlation between participants' Weber fractions for certain haptic stimuli. The overall mean correlation coefficient was positive, indicating an overall positive relationship between participants' sensitivity to small changes. These findings suggest that individuals with high sensitivity to small changes in one stimulus are likely to have high sensitivity to small changes in other stimuli. These findings indicate that both frequency and intensity can be effectively used as channels of information to convey system feedback to the user when designing mid-air haptic sensations.

VI. Limitations

This study, conducted online due to COVID-19 restrictions, may have introduced biases in the results since it was not very well controlled. The results may not be applicable to lower or higher frequency ranges or other types of mid-haptic stimuli, such as AM, LM, and other STM shapes [3]. In fact, JNDs in mid-air haptic stimuli are probably not comparable to any other contact-based analogous stimulus like a brush or vibrotactile pin making it difficult to compare with other literature where Weber fractions can be stated in terms of physical units of skin displacement. The Friedman test was used to assess significance due to non-normal data, but non-parametric testing is less efficient. Participants had varying levels of experience with mid-air haptic technology, which may also have affected results. The number of participants tested was much smaller than that in other studies (e.g., Rutten et al. [18] had 50 participants) Finally, we did not study JNDs across the full dynamic range in intensity (03. to 1) and frequency (20-90 Hz).

A. Importance

Our study supports the role of STM frequency and acoustic pressure intensity in mid-air haptic stimuli design and highlights the importance of JNDs in the haptic experience design [43] for a variety of real-world applications. Namely, it highlights the existence of a palette of mid-air haptic sensations that can be designed to effectively convey discriminative tactile information to the user. For example, Harrington et al. [6] could have used sufficiently different intensity levels of mid-air haptic stimuli to indicate the value of their automotive HMI slider function, thereby improving UX and further reducing eyes-off-the-road time. Similarly, Beattie et al. [36] could have used sufficiently different STM frequency levels of to create perceptually different texture levels. Thus, our initial findings indicate the need for further investigation of Weber fractions for mid-air haptic parameters and the relationship between age and frequency range discrimination. Our results have important implications for improving user experience in mid-air haptic touchless interfaces through optimized JNDs.

VII. Conclusion

In conclusion, our study on mid-air haptic sensations has provided new insights into the perception of haptic intensity and frequency. The JND frequency experiment found significant differences and a positive correlation between predicted threshold frequency and intercept values. Results fell within the Weber fraction for vibrotactile stimuli. On the other hand, the JND intensity experiment showed consistent intensity perception across four frequencies and no connection between age and declining sensitivity. The correlation matrix of the Weber fractions indicated a moderate correlation between certain stimuli, suggesting a general consistency in participants' sensitivity to small changes in haptic stimuli. These findings provide valuable information for the design and development of mid-air haptic technology and systems. Additionally, the results from the JND frequency experiment suggest a potential link between age and sensitivity to mid-air haptic frequencies, but more research is required to confirm this connection

The field of mid-air haptic research is still largely undiscovered and offers vast potential for understanding the impact of haptic sensation on human touch, age, and perception. It presents significant challenges for designers looking to create immersive, fulfilling experiences using mid-air haptic technology.

Acknowledgments

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