Invisible Touch: How Identifiable are Mid-Air Haptic Shapes?

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ABSTRACT

Mid-air haptic feedback constitutes a new means of system feedback in which tactile sensations are created without contact with an actuator. Though earlier research has already focused on its abilities to enhance our experiences, e.g. by increasing a sense of immersion during art exhibitions, an elaborate study investigating people's abilities to identify different mid-air haptic shapes has not yet been conducted. In this paper, we describe a user study involving 50 participants, with ages between 19 – 77 years old, who completed a mid-air haptic learning experiment involving eight different mid-air haptic shapes. Preliminary results showed no learning effect throughout the task. Age was found to be strongly related to a decline in performance, and interestingly, significant differences in accuracy rates were found for different types of mid-air haptic shapes.

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KEYWORDS

Mid-air haptic feedback; mid-air haptic shapes; identification; learning task

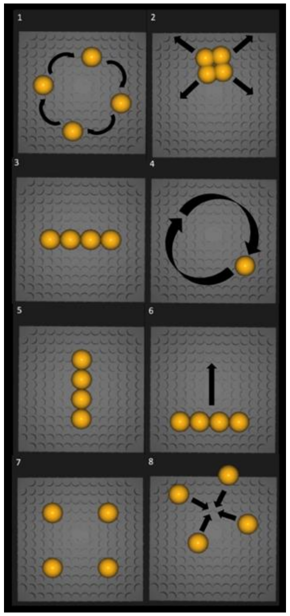

Figure 1: Screenshots of the visual representation of the eight different mid-air haptic shapes in the sensation editor©, figure included with permission of Ultrahaptics©. For each shape, we added an identification number, along with arrows showing the movement of the shapes. 1 = circle, 2 = open, 3 = horizontal line, 4 = dial, 5 = vertical line, 6 = hand scan, 7 = square, 8 = close. Some shapes are completely static (numbers 3, 5, 7). Shape 1 consists of four cycling focal points but is perceived as a static circle (based on a pilot study).

INTRODUCTION

Mid-air haptic feedback, involving tactile stimulation of the hand palm or fingers through ultrasound or air vortices, constitutes an exciting new means of system feedback for touchless interfaces [4][11]. As it constitutes a relatively new technology, research investigating human's ability to interact with mid-air haptic feedback is still largely unexplored, and its implementation in other technologies lags behind. Most studies on this topic focus on its myriad possibilities of enhancing our virtual and real-life environments, for example, by increasing our experience of immersion while watching movies [1] or during art exhibitions [12].

To our knowledge however, human's ability to efficiently interact with mid-air haptic technology, in the sense of quick identification of different shapes, has not yet been extensively investigated. Up until now, only small-scale usability studies, involving no more than 20 participants of mostly around 20 years old, reported some first accuracy scores regarding the identification of different mid-air haptic shapes. Korres & Eid [5], for example, observed a proportion of 59.44% correct answers in an identification task involving four 2-D mid-air haptic shapes, whereas Long et al. [7] obtained a general accuracy of 80% for five 3-D shapes. In these two studies, participants could familiarize with the shapes or with some of the shapes for as long as they wanted and all information regarding the training phase (e.g. accuracy scores, number of trials) was omitted [5][7]. Though these studies entailed some interesting first results, their lack of a controlled learning phase constitutes an important hiatus we aimed to counter with the current study, in which participants received a controlled period of learning, with accuracy scores carefully monitored from trial to trial.

This way, we could investigate people's learning abilities regarding the identification of eight different mid-air haptic shapes (see Figure 1 for a visualization of the shapes used in the current study). We considered a number of factors, both person-based as well as shape-based, that could potentially influence the identification accuracy. First, age was considered an important characteristic as increasing age has been repeatedly found to decrease tactile sensitivity [3]. Second, given that earlier studies showed divergent evidence regarding the effect of gender on tactile acuity [3][9][10], we tested whether sensitivity for mid-air haptic shapes would be different for male and female participants. Third, we explored whether the eight different mid-air haptic shapes were associated with different identification accuracies.

METHODS

Participants

As we aimed to obtain an equal amount of men and women, and a large variety in age, participants were selected based on these two criteria.

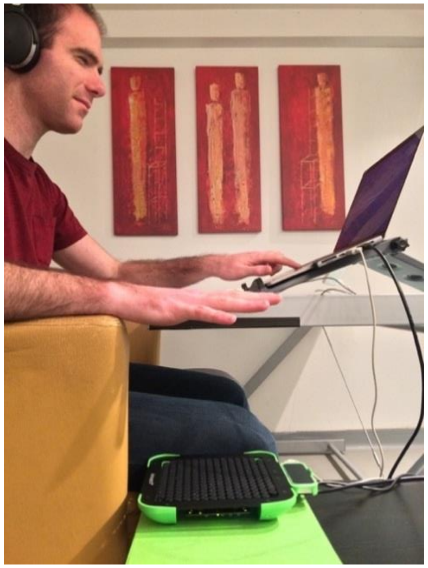

Figure 2: Example of the experimental set-up: participants were seated in a chair in front of a laptop, with their arms resting on armrests and their non-dominant hand in a stable position above the device at about 20 cm. The mid-air haptic shapes were projected fixed on participants' hand using hand-tracking technology. As the shapes were projected both on the palm of the hand and fingers, we could not fixate participants' hand without covering part of the projection surface. However, participants were asked not to move their hand during the task.

A total of 50 people, 25 men and 25 women participated in the study, with a mean age of 44.58 (SD = 15.93, range = 19 - 77), and 43 being right-handed, whereas 7 were left-handed. The mid-air haptic stimuli were always presented on their non-dominant hand. Exclusion criteria were: Previous experience with mid-air haptic feedback and touch deficits in the upper limbs. This study was approved by the social and societal ethics committee of the University of Leuven, Belgium (G-2018 10 1361), and participants received a voucher of 20 euro as incentive.

Experimental Stimuli

The mid-air haptic shapes were created using the sensation editor of the touch development kit, developed by Ultrahaptics© (https://www.ultrahaptics.com). Eight different mid-air haptic shapes were created: Four static shapes (see Figure 1, shapes 1, 3, 5, 7), and four dynamic or moving shapes (see Figure 1, shapes 2, 4, 6, 8). The speed of all dynamic shapes was fixed at one revolution per second, and the surface they could cover was limited to a 7.5x7.5cm box. The intensity of the shapes was fixed around 155 dB, and the modulation frequency was fixed at 125 Hz. Since our focus was on the identifiability of distinct shapes, we only selected the templates with the most pronounced shapes (from the touch development kit), whereas templates with a random or chaotic shape were excluded.

Experimental Task

The identification learning task was created using PsychoPy 3 [8] and was administered on a laptop. The task was divided into five blocks with all eight stimuli being presented once in each block in randomized order. The five blocks were not separated by any time interval. Each participant received a total of 40 trials (8 different stimuli in each of the 5 blocks), with each trial consisting of four phases. First, participants experienced a mid-air haptic stimulus on their hand (palm and fingers) during one second, next they had nine seconds to indicate (using the numbers on their keyboard) which stimulus they thought they felt by comparing their haptic experience with a visualization of the eight different shapes presented on their screen. This visualization was realized by recording the template representations in the sensation editor© and adding an identification number (1-8) to the video recordings. After answering or leaving blanc (not responding within nine seconds, what was considered as a wrong answer), they were asked to indicate how certain they were of their answer on a seven-point scale ranging from 1 (not sure at all), to 7 (very sure). Next, they received corrective feedback, including the correct answer if given the wrong one.

Procedure

Upon arrival in the lab, participants read and signed the informed consent, and answered some demographic questions. Next, they took place in front of the laptop and were asked to lay their non-dominant arm on the armrest.

Table 1: Proportion of correct response per block number

block	*p_corr*
0	.38
1	.42
2	.39
3	.45
4	.44

Note. p_corr = proportion correct responses.

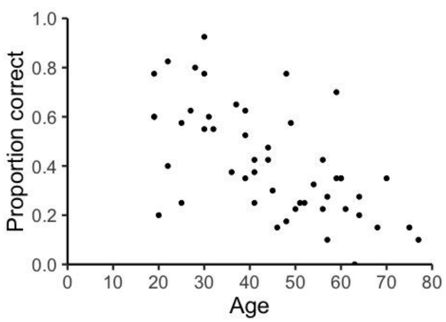

Figure 3: Scatterplot showing the relationship between proportion of correct responses and age.

In this way, the distance between their hand and the device was fixed at about 20 cm (see Figure 2). Before starting the identification learning task, they experienced a first mid-air haptic stimulus, as an example of what they could expect, during 10 seconds (a single focal point on the palm of their hand). Then, they could study the visual representation of the eight mid-air haptic stimuli (without the haptic sensations) during 15 seconds. Next, they completed the identification learning task, with a duration of about 15 minutes. During the entire task, participants wore a noise cancelling headphone playing white noise to mask the sound produced by the device. After finishing the task, participants' hand size was roughly estimated by measuring the length between the fingertip of their middle finger and their wrist crease, and the width of their hand along the distal palmar crease.

RESULTS AND DISCUSSION

Results

We first computed some descriptive statistics on the experimental results: Table 1 shows the proportion of correct responses in the different blocks of the learning task, Figure 3 presents a scatterplot showing the relationship between proportion of correct responses and age, and Table 2 shows a confusion matrix involving the eight different shape types.

Next, to test for the effects of block, gender, and age on predicting the accuracy scores (binary variable), we compared the goodness of fit of different logistic mixed effects models with random intercept (R package: *lme4* [2]). A full model including all predictors: block (within-person), gender (between-person), age (between-person), was compared to different more restricted models, each excluding one predictor of interest. As can be seen in Table 3, only age significantly improved the model's fit. More evidence for this age effect was found in a strong negative correlation of -.62 ($p <$ .0001) between age and proportion of correct responses. Block and gender did not improve the model's fit, meaning that participant's performance was equal across the different blocks of the learning task, implying the absence of a learning effect, and equal performance between male and female participants.

Lastly, we tested whether shape type (circle, open, ...) was a significant predictor of accuracy rate by comparing an intercept-only model with a model including shape as predictor[2]. The model including shape showed a significantly higher goodness of fit compared to the intercept-only model, $\chi^2(7) = 164.92$, $p < .0001$. This means that the accuracy scores were significantly different depending on shape type. Post-hoc pairwise comparisons (R package: *lsmeans* [6]) revealed that the shapes could be split into two groups based on the *p* values of the pairwise comparisons (see Table 4): circle, open, square, and close versus horizontal line, dial, vertical line, and hand scan.

[2] Both were logistic mixed effects models as accuracy rate was a binary variable and shape type was a within-person variable.

Table 2: Confusion matrix

	1	2	3	4	5	6	7	8
1	**.28**	.14	.04	.10	.04	.14	.11	.12
2	.13	**.35**	.05	.05	.04	.08	.06	.17
3	.05	.05	**.50**	.05	.08	.12	.07	.06
4	.15	.05	.01	**.54**	.03	.06	.04	.08
5	.04	.07	.13	.04	**.51**	.04	.05	.06
6	.08	.05	.04	.04	.10	**.60**	.03	.04
7	.08	.08	.19	.08	.16	.08	**.28**	.02
8	.11	.21	.07	.06	.08	.10	.08	**.26**

Note. 1 = circle, 2 = open, 3 = horizontal line, 4 = dial, 5 = vertical line, 6 = hand scan, 7 = square, 8 = close. The diagonal shows the proportion of correct responses per shape type.

Table 3: Results of model comparisons

Full vs.	X^2	*df*	*p*
-b	7.07	4	.13
-g	1.08	1	.30
-a	24.52	1	<.0001

Note. X^2 indicates the difference in goodness of fit of the full model versus the more restricted models, with -b = full model minus block, -g = full model minus gender, -a = full model minus age. The full model has a significantly higher goodness of fit only when compared to the model excluding age.

Within these groups, the shapes showed no significant differences in proportions of correct responses: e.g. the proportion correct of circle was equal to open, and the proportion correct of horizontal line was equal to dial. When comparing the shapes between these two groups however, horizontal line, dial, vertical line, and hand scan all had significantly higher proportions correct compared to circle, open, square, and close (see Table 4).

Discussion

Unexpectedly, participants showed no ability to learn identifying the different shapes as their performance was equal across the different blocks. However, the short stimulus presentation (1 second), combined with the limited number of presentations per stimulus (only five) might explain the absence of a learning effect. Future studies could investigate whether longer stimulus presentations and a greater amount of stimulus repetitions could stimulate learning in an identification task concerning mid-air haptic shapes.

Compared to the accuracy rate of 59.44% obtained by Korres & Eid [5] or the accuracy rate of 80% obtained by Long et al. [7], our observed accuracy rate of 44% in the last block of the learning task is remarkably low. The smaller amount of presented mid-air haptic shapes in the earlier studies (four or five versus eight in the current study), as well as the lower mean age of the sample (the mean age in Korres & Eid [5] was 26 years old[3], whereas in our study 44.58 years), might explain the discrepancy in results. Indeed, age is clearly associated with a decrease in general accuracy across all shapes (r = -.62, p < .0001). In future analyses, we will further investigate how age influences the shape-specific accuracies.

In contrast to earlier studies [3][9], no gender difference in tactile acuity was observed in the current study. However, in the study by Peter et al. [9] not gender as such, but fingertip size was actually related to tactile acuity. This might also be the case when considering hand size in general. As we roughly estimated participants' hand size (see Procedure), we will further explore this question in later, more elaborate analyses.

Most interestingly, participants appeared to be better at identifying shapes with a single focal point (dial) or shapes organized in a straight line (hand scan, horizontal line, vertical line), compared to shapes consisting of different focal points with a relatively large distance in between (square), or organized in a circular pattern (circle, open, & close). Given this discrepancy in accuracy rates, it could be possible that the learning effect is dependent on pattern type, something we will further explore in more elaborate analyses.

CONCLUSIONS

First, even after a short learning phase, mid-air haptic shapes do not appear to be easily identified.

[3] Long et al. [7] did not report the sample's mean age, but they did report the range, with 35 as maximum age.

Table 4: Pairwise comparisons (p values) of the proportions correct of the eight shapes

	1	2	3	4	5	6	7	8
1	-	.53	.00 **	.00 **	.00 **	.00 **	1	1
2	-	-	.01	.00 *	.00 *	.00 **	.60	.25
3	-	-	-	.97	1	.12	.00 **	.00 **
4	-	-	-	-	1	.67	.00 **	.00 **
5	-	-	-	-	-	.23	.00 **	.00 **
6	-	-	-	-	-	-	.00 **	.00 **
7	-	-	-	-	.-	-	-	1
8	-	-	-	-	-	-	-	-

Note. 1 = circle, 2 = open, 3 = horizontal line, 4 = dial, 5 = vertical line, 6 = hand scan, 7 = square, 8 = close. P values were adjusted for multiple comparisons using Tukey's method. * <.01 ** <.0001.

As a result, efficient interaction with mid-air haptic shapes might only be possible following a relatively extensive learning phase. Second, the strong decline in accuracy related to age points at an important hazard when implementing mid-air haptic technology in devices used by older audiences. Third, the observed discrepancy in identifiability of (mainly) line-based versus circular shapes is very informative. Simple line-based shapes resulted in convincingly higher identification accuracies compared to circular shapes, and consequently are easier to interact with. Thus, for the implementation of mid-air haptic technology, we recommend to focus on line-based as opposed to circular shapes.

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