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Hap2Gest: An Eyes-free Interaction Concept with Smartphones Using Gestures and Haptic Feedback

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Abstract. Smartphones are used in different contexts, including scenarios where visual and auditory modalities are limited (e.g., walking or driving). In this context, we introduce a new interaction concept, called *Hap2Gest*, that can give commands and retrieve information, both eyes-free. First, it uses a gesture as input for command invocation, and then output information is retrieved using haptic feedback perceived through an output gesture drawn by the user. We conducted an elicitation study with 12 participants to determine users' preferences for the aforementioned gestures and the vibration patterns for 25 referents. Our findings indicate that users tend to use the same gesture for input and output, and there is a clear relationship between the type of gestures and vibration patterns users suggest and the type of output information. We show that the gesture's speed profile agreement rate is significantly higher than the gesture's shape agreement rate, and it can be used by the recognizer when the gesture shape agreement rate is low. Finally, we present a complete set of user-defined gestures and vibration patterns and address the gesture recognition problem.

Keywords: Hap2Gest concept · Eyes-free interaction · Haptic · Gesture input · Gesture output · Elicitation study.

1 Introduction

Smartphones have become a necessity for many people throughout the world and offer a wide range of functions through their touchscreens. Touchscreen displays are the primary input modality supported by smartphones. A typical way of operating a smartphone is to first reach it and then operate it while looking at its display. This can draw the user's visual focus to the device, which is not desirable if the visual attention is needed elsewhere. For instance, checking directions on a navigation app while driving should cause the minimum distraction and be efficient to perform. Leaving users' visual attention free to perform additional tasks is one of the fundamental motivations for eyes-free interaction [5]. Several eyes-free interaction techniques have been developed that use gestures (*e.g.*, [23])

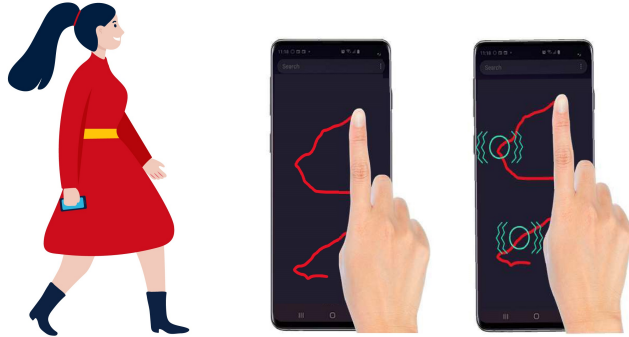


Fig. 1: *Hap2Gest* concept and context: (left) eyes-free context of use example, (center) command invocation by drawing the input gesture, and then (right) drawing the output gesture and receiving the haptic feedback that corresponds to the output information through this gesture.

or voice (*e.g.*, [9]) as input, along with various forms of output feedback (*e.g.*, audio [12] and/or tactile output [28]).

Both gestures and haptic feedback have been used intensively in many studies. Gesture interaction can offer a control interface that eliminates the need for reaching towards a device. Furthermore, haptic feedback can free up even more visual attention for other tasks. For instance, haptic feedback seems effective as a substitute for visual and audio feedback and tends to be quickly perceived when the user is engaged in another primary task [29, 6–8, 26, 10, 11]. However, technological means for creating tactile feedback remain very limited and not as developed as display technology. Most smartphones on the market are only equipped with a simple vibration motor to provide haptic feedback. Designing an interaction concept that can be achieved by a simple vibration motor will make that concept accessible to more people.

In this work, we introduce Hap2Gest, a novel interaction concept based on surface gestures and vibration motors, that permits command invocation and information recovery, both eyes-free. First, the user draws an eyes-free input gesture to ask the system to invoke a command, then the user draws an eyes-free output gesture through which the vibration patterns that constitute the output information are felt by the user (Figure 1). In the last fifteen years, in particular for input gesture, an impressive body of work has been published on elicitation studies: the design of intuitive gesture commands that are reflective of end-user behavior for controlling all kinds of interactive devices, applications, and systems. In this context, we conducted an elicitation study to determine user preferences for input gestures, output gestures, and the vibration patterns for interacting eyes-free with smartphones for the design of *Hap2Gest*. Unlike earlier elicitation studies, we studied user-defined gestures when haptic feedback is available to provide feedback, using a simple vibration motor, in the absence of visual cues.

To the best of our knowledge, this is the first study that investigates the elicitation gestures for eyes-free interaction with a smartphone in the presence of haptic feedback. The results of this study not only show which gestures users prefer for eyes-free interaction with smartphones but also show how they prefer to receive haptic feedback. We also report agreement rates in terms of gesture’s shape, gesture’s speed profile, and vibration pattern. Our understanding of agreement for user-defined gestures and user-defined vibration patterns allows the creation of more natural sets of user gestures and user vibration patterns. We finally discuss the implications of this research for the design of *Hap2Gest*, in particular, and more generally for eyes-free interaction on smartphones in twofold: (i) from the perspective of gesture design and recognition, and (ii) from the perspective of haptic design. We hope our results will prove useful to designers and practitioners interested on eyes-free gestures and haptic designs.

2 Related Work

Methodologies that involves users as part of the design process have gained popularity since the work of Wobbrock et al [39]. They created a set of user-defined gestures for touchscreens by showing participants the outcome of an action and asking them to make a gesture that would produce that action. After collecting the designs of all participants, experimenters quantified the degree of consensus among gestures proposed by participants using an agreement score. The gestures with the highest agreement rates were selected as the most appropriate for each action. Since then, the elicitation methodology has been widely used to create gestures for freehand TV control [18] and smart glasses [34], unmanned aerial vehicles [24], handheld objects [30], deformable displays [32], and blind people [13].

Besides the user preference for input gestures, several studies have recently adopted the elicitation methodology for user preferences for haptic outputs. Haptics have commonly been used as feedback or notifications. Lawrence et al. [3] studied the user preferences for mid-air haptic sensation to match gestures used for interacting with an augmented reality menu environment. Kim et al. [15] conducted an elicitation study on haptic patterns for social touch, generated by a haptic display called SwarmHaptics. Wei et al. [38] conducted a similar experiment for mediated social touch on touchscreens. In our work, users have to define the gestures and vibration patterns in order to give a command to the smartphone and then retrieve information, both eyes-free.

Researchers have proposed several new solutions in recent years to provide haptic feedback to touchscreens [1, 16, 40, 37, 27]. Vibrotactile actuators are the simplest and most common way to add haptic feedback to touchscreens. Zhao et al. [40] created the illusion of a moving tactile stimulus on a tablet by attaching several vibrators to the tablet. Variable friction displays are another way to provide haptic feedback on a touchscreen [1, 16, 37, 27]. The haptic feedback on touchscreens can also be achieved by using intermediate parts. Roudault et al. [28] built two prototypes that could move the finger on the screen to repro-

duce a given gesture, like a letter or a symbol, without the need to look at it. Our proposed concept makes use of the smartphone’s vibration motor instead.

Vibrotactile messages can be used to transfer non-visual information by different vibration patterns by changing the frequency, intensity, and duration of vibration [4, 6]. A recent review presents a comprehensive overview [14] of hands-free devices for transmitting speech and language with the tactile modality distinguishing between tactual language units and tactual words by encoding speech units and signal, phonemes, letters, and morse code. An inspiring work that aimed to find out the achievable throughput of the skin, the bandwidth of vibrotactile communication, is that of Novich et. al [22] who showed that vibrotactile patterns encoded in both the spatial and temporal dimension using a haptic vest exceed performance of spatially encoded patterns. Zhao et. al [41] showed how users were able to remember 20 haptic words under 30 minutes of training using 6 actuators on the forearm, while Tan et. al [31] succeeded in the acquisition of 500 words after 10 days of training.

On the application level, Marino et al. [17] developed WhatsHap, which helped two participants to have a conversation by mapping speech to tactile feedback on the arms. Wei et al. [38] applied mediated touch gestures in an instant messaging application as haptic icons. In this work, we introduce a new interaction concept called *Hap2Gest* that permits the users to have an eyes-free dialog with their smartphone devices while engaged in another primary task.

3 Hap2Gest Interaction Concept

On modern mobile phones, gestures are commonly used as input. When it’s combined with haptic feedback, it enables richer output (alongside the richness of multi-touch input), *i.e.*, a richer interactive experience (*e.g.*, [28]). Gestures and haptic feedback have been used in the context of eyes-free interaction. For instance, when the user is performing a primary task (*e.g.*, walking down the street [21, 10, 7] or working [7, 11]) and does not wish to be disturbed from an attention point of view but in the mean time wishes to check for new mails, text messages, or calls on the cellphone without looking at it.

In this context, we introduce *Hap2Gest*, a new eyes-free interaction concept that uses gestures both as the input modality and as part of the output modality, combined with haptic feedback. First, the user draws an eyes-free gesture on the touchscreen of the smartphone to give a command to the phone (input). Then, the user draws a second eyes-free gesture, the same or different from the first one, and can feel one or multiple vibrations on different parts of the gesture (Figure 1). The vibration pattern they feel—the number and locations of vibrations—through the output gesture are the vocabulary of this interaction concept for output. The output modality uses a combination of tactile and kinesthetic senses. The vibration created by the vibration motor of a smartphone creates the tactile sense, and the finger speed and position create the kinesthetic sense. Thus, Hap2Gest would enable a less obtrusive way to retrieve information from user’ phone, *i.e.*, without looking at the display or turning on his phone.

Our interaction design is similar to Roudaut et al., [28] as we both use gestures to give commands to the smartphone (input) and retrieve information with gestures and haptic feedback (output), in an eyes-free configuration. However, in their work, the output gesture is created by a force feedback system that moves the finger. Consequently, the haptic feedback is used to guide the user to draw the output gesture, while the output gesture constitutes the main output information. For example, if the drawn output gesture is “8”, the user understand that he received eight new messages. However, in our work, the output gesture is a predefined gesture drawn by the user, and the haptic feedback is created using the vibration motor at some points throughout the output gesture. Thus, the vibration patterns (their number and locations) constitute the main output information.

4 User Study

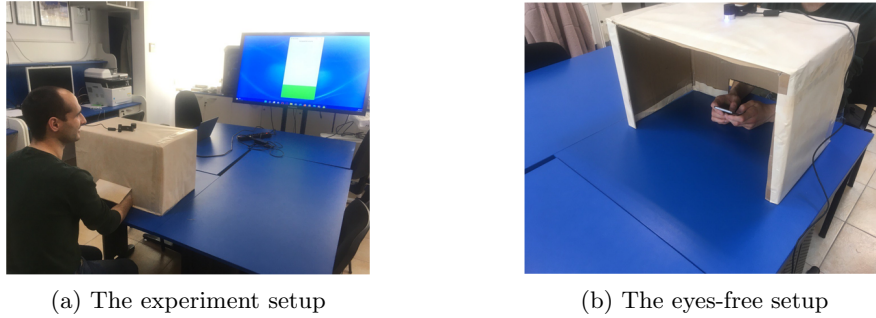


Fig. 2: The experiment setup. The participant manipulates the smartphone while their hands are inside a box to maintain eyes-free interaction. The user interface of the experiment was displayed on a monitor in front of participants.

We conducted an elicitation study to determine users’ preferences for the design of *Hap2Gest*: (i) eyes-free input gestures for command invocation on a smartphone in the absence of visual cues, (ii) eyes-free output gestures for receiving the output information, and (iii) vibration patterns to get eyes-free output information through the output gesture.

The main premises underlying this research are that (i) a good gesture-set needs to be easy to use and remember by the user, and (ii) vibration patterns need to be easy to understand, remember, and recognize by the user. Consequently, to support these main premises, we asked our participants to design gestures that are easier to remember and to come up with vibration patterns that take less time and effort to understand. In addition, in order to avoid compromising the system in differentiating between the different commands, we asked participants to try their best to avoid having exactly the same gestures for different commands.

Table 1: The five interaction scenarios and the different referents considered in each scenario.

A. Scenario in presence of auditory feedback	
R1. Accept call	R2. Reject call
B. Scenario with a yes/no response	
R3. Is it a call from my favorite contacts?	R4. Do I have any missed calls?
R5. Is my phone silent?	R6. Do I have new messages?
R7. Do I have new messages from a favorite contact?	R8. Do I have new notifications?
R9. Do I have a notification from Instagram?	R10. Do I have a notification from Facebook?
R11. Do I have a notification from Twitter?	R12. Do I have a notification from WhatsApp?
R13. Accept the call and tell me if it's from a favorite contact.	R14. Reject the call and tell me if it's from a favorite contact.
R15. Mute my phone with success feedback.	R16. Unmute my phone with success feedback.
C. Scenario with categorical responses	
R17. Which application do I have a notification from (Instagram or Facebook)?	R18. Which application do I have a notification from (Instagram, Facebook, or Twitter)?
R19. Which application do I have a notification from (Instagram, Facebook, Twitter, or WhatsApp)?	R20. Which application do I have a notification from (Instagram, Facebook, Twitter, WhatsApp, or Telegram)?
R21. How is the weather today? (sunny, cloudy, rainy, or snow)	R22. Which day of the week is it? (Monday, Tuesday, Wednesday, Thursday, Friday, Saturday, or Sunday)
R23. Which month is it? (January, February, March, April, May, June, July, August, September, October, November, or December)	
D. Scenario with numerical responses	
R24. How many new notifications do I have? (0, 1, 2, 3, 4, or 5)	
E. Scenario for time range	
R25. At which time today do I have a meeting?	

Similarly to previous gesture elicitation studies [39, 20, 25], we do not want participants to focus on recognizer issues for the defined gesture set. Consequently, we do not provide participants with recognition feedback during gesture production. We also asked participants to ignore recognition issues by considering the smartphone to be able to understand and recognize any gesture they might wish to perform. In addition, for vibration patterns, as we want to identify user preferences, we do not want participants to focus on tactile rendering issues. Consequently, no haptic feedback was provided to our participants during the task. We also encouraged participants to ignore haptic feedback issues by considering the smartphone to be able to render any vibration pattern they might wish to have.

4.1 Participants

12 participants (three females, and nine males) volunteered to take part in our experiment. Participants' ages were between 20 and 32 years ($mean = 22.9$, $SD = 3.7$). All participants were right-handed and had used smartphones for several years and were familiar with the vibration motors of smartphones.

4.2 Scenarios & Referents

We wanted to create a list of common smartphone commands that users frequently use when visual cues are not available. Moreover, we wanted to cover different types of data that can be provided to users: binary data, categorical data, numerical data, range, or assisted with auditory feedback. For this purpose, we considered five interaction scenarios in which users frequently need to execute such commands on the smartphone. Each scenario contains between one and 14 referents. Overall, the experiment included 25 referents. The list of the five interaction scenarios and associated referents are available in Table 1.

4.3 Procedure

First, participants watched a video, available as supplementary material, which explained our proposed interaction concept and the instructions for the experiment. The video served as *priming* [19] since it contained contexts of use and examples so that participants would think more generally about the proposed gestures. Written instructions were then handed out as printed forms, with 25 referents and possible responses for each referent. Participants were then asked to draw the gesture and vibration patterns for each interaction scenario on the paper forms. The participants were asked to pay attention to the following points while giving their answers:

- The participants will draw the gesture with one finger. They are allowed to hold the phone with the same hand or with the other hand.
- Try their best to avoid having the same gesture for different commands.
- Design gestures that are easier to remember.
- Come up with vibration patterns that take less time and effort to understand.

After finishing their designs on paper, participants moved to the next step in the experiment. In this step, participants were asked to enter the solutions they had just designed on paper to a smartphone in eyes-free configuration. For this purpose, the participants held the smartphone in a box to avoid having any visual cues. Five participants manipulated the phone with only one hand and the rest manipulated the phone with the dominant hand and hold it with other hand. Then, the papers on which they designed their solutions were given to them, and they were asked to copy their solutions from paper to smartphone one by one. An android application was developed to capture participants' responses in an eyes-free configuration. The screen of the smartphone was mirrored on a display in front of participants to guide them during the experiment and maintain the

eyes-free interaction with the smartphone itself, as shown in Figure 2. At the top of the screen, the interaction scenario and the answers were displayed one after another. The participants had to first draw the gesture for giving command, and then they had to specify vibration points one by one by drawing the gesture from the beginning to the point they wished to get the vibration. No visual cue was shown on the display about the touch point or gesture path, to ensure eyes-free condition. At the bottom of the screen, there was a green sliding button, which was used to approve the response by swiping right or return to previous steps by swiping left. A paper strap was glued on top of this virtual button, so participants could feel its position without seeing the phone. The average duration of the experiment for each participant was 50 minutes.

4.4 Apparatus

For the second stage of the study, we used a Samsung Galaxy S6 smartphone running Android 6.0.1. The phone’s dimensions were 5.65” × 2.78”. Display resolution was 1440 × 2560 pixels. We developed our application using Java to record the participants’ gestures and vibration patterns. Users’ hands were videotaped using a Microsoft LifeCAM Studio webcam. One author observed each session and took detailed notes.

5 Results

Our results include the agreement rate measures, user-defined gestures set, and the user-defined vibration patterns set.

5.1 Agreement rate measure

To evaluate the degree of consensus among our participants, we used AGATE (AGreement Analysis Toolkit) software [35] for calculating an agreement rate for each referent. An agreement rate, $AR(r)$, quantifies the magnitude of agreement among the gestures elicited from participants, where:

$$AR(r) = \frac{|P|}{|P| - 1} \sum_{P_i \subseteq P} \left(\frac{|P_i|}{|P|} \right)^2 - \frac{1}{|P| - 1} \quad (1)$$

In Equation 1, P is the set of all proposals for referent r , $|P|$ is the size of the set, and P_i is the subsets of identical proposals from P . The range for $AR(r)$ is $[0, 1]$. In our study, we used the formula above to calculate two agreement rates: (1) the gesture’s shape agreement rate and (2) the gesture’s speed profile agreement rate.

The gesture’s shape agreement rate is the same as the agreement rate in previous elicitation studies. In this study, participants propose two gestures for each referent (an input gesture and an output gesture). We assumed two designs were identical if they had identical input gestures and identical output gestures.

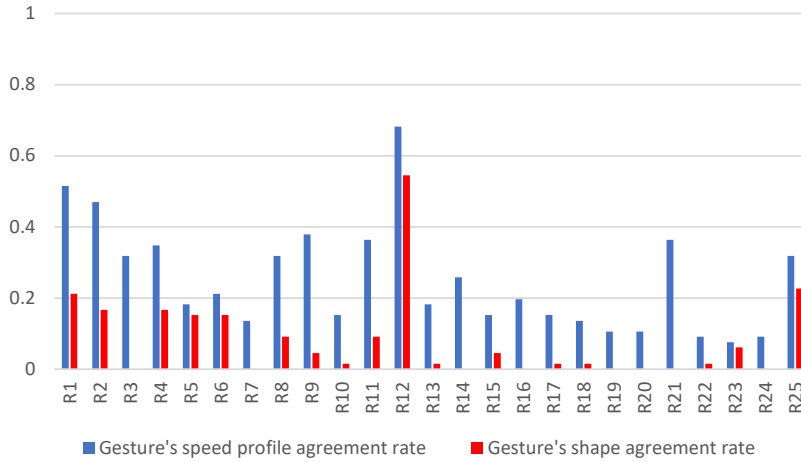


Fig. 3: The gesture’s shape agreement rates and the gesture’s speed profile agreement rates are shown for all scenarios.

After gathering all participants’ proposals, authors created a codebook [36] to evaluate the similarity of proposals. We considered two gestures identical if they were made from equal number of strokes and the deviation between stroke angles were less than 45 degrees, even if two gestures had differences between their absolute position on the screen, their overall shape size, or strokes’ lengths. Consequently, we calculate one gesture agreement rate for each design. However, in 96 percent of the designs, participants proposed the same gesture for input and output. Chance agreement [33, 36] was not considered and corrected since the user elicitation study was not conducted with a fixed set of nominal categories out of which participants chose their proposals.

In order to calculate gestures speed agreement rate, we derived the speed profile of gestures by taking the derivative of finger displacement with respect to time. The speed profile of all participants for each referent is available in supplementary materials. Then, we used the same formula above on the speed profile. The codebook used for evaluating the similarity of speed profiles were different than the one used for shape agreement rate. First, the peaks and lows in the speed profile was detected. Then, the speed profile was translated to series of peaks and lows, with the same order as they appear on time axis. Two speed profiles were considered identical if they had same number of lows and peaks in same order. To the best of our knowledge, we are the first gesture elicitation study that measures the speed profile agreement rate. The gesture set proposed by participants encouraged us to look at the agreement rate on the speed profile. We observed that the gesture shape proposed by participants for some referents had relatively low agreement, but the agreement rate among the speed profile of the same referent was significantly higher. So, it’s more likely to find consensus

by using gesture speed profile rather than gesture shape. Figure 3 shows the gesture agreement rates and speed profile agreement rates for all 25 referents.

A paired-samples t-test was conducted to compare the gesture agreement rate and speed profile agreement rate of the 25 referents. There was a significant difference between the gesture’s shape agreement rates ($mean = .081, SD = .122$) and gesture’s speed profile agreement rates ($mean = 0.252, SD = 0.153$); $t(24) = 8.545, p < 0.00001$. The gesture’s shape agreement rate is, in particular, low. Thus, to better understand the cause of this low rate and, in particular, if it depends on the scenario or not, we decided to calculate the gesture’s shape agreement rate by scenario. We also calculate the speed agreement rate for each scenario in order to determine if the gesture’s speed profile agreement rate compensates for the gesture’s shape agreement rate in cases where the latter is low.

Finally, the vibration pattern agreement rate VAR is calculated for each referent using the formula below:

$$VAR(r) = \frac{|V|}{|V| - 1} \sum_{V_i \subseteq P} \left(\frac{|V_i|}{|V|} \right)^2 - \frac{1}{|V| - 1} \quad (2)$$

where P is the set of all proposal vibration patterns for referent r , $|P|$ is the size of the set, and P_i is the subsets of identical vibration patterns from P . The range for VAR is $[0, 1]$. The criteria used to consider two vibration patterns identical for each scenario is explained in the next section.

5.2 User-defined eyes-free Gestures & vibration patterns sets

In the following, we present, for each scenario, the most used input gestures, output gestures, and vibration patterns, along with the agreement rates for gesture’s shapes, gesture’s speed profiles, and vibration patterns.

Interaction scenarios in the presence of auditory feedback The most common gesture suggested for accepting a call was a straight line drawn from left to right by seven participants, and for rejecting a call, a straight line drawn from right to left by six participants. The mean agreement rates for gesture shape and gesture speed profile are 0.190 and 0.493, respectively.

For accepting or rejecting call scenarios where auditory feedback is available, 75 percent of participants preferred not to have any haptic feedback for either of the referents. The rest of the participants all preferred to have a single vibration at the end of the output gestures, which were identical to the input gestures, for both referents. The vibration agreement rates for both accept and reject call referents were 0.591.

Interaction scenarios with yes/no response In this scenario, for eight of the referents the most agreed gestures were gestures with shape of a letter from referent. For instance “N” shaped gesture for “Do I have new notifications?” referent and “M” shaped gesture for “Do I have new messages?” referent. All

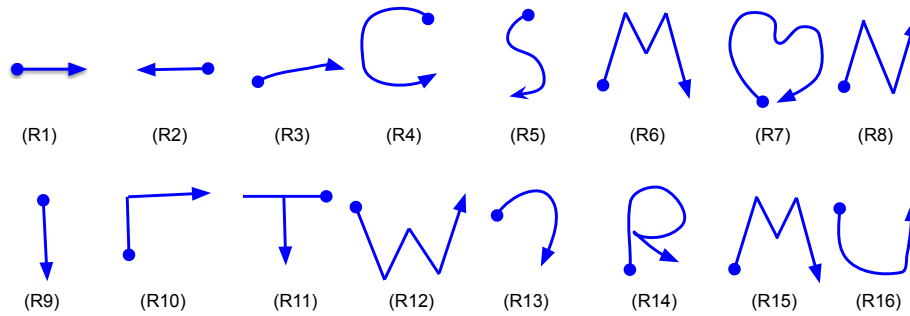


Fig. 4: The most suggested gestures referents R1 to R16. The filled circle shows the start point of the gesture. The arrow shows the ending point of the gesture.

participants suggested same gesture for input and output for every single referent. For this scenario, the mean agreement rate for gesture shape and gesture speed profile were 0.094 and 0.277, respectively. Figure 4 shows the most suggested gestures for yes/no feedback scenario referents.

The vibration patterns participants suggested can be categorized by three parameters. First, the number of locations on gestures where vibration is present. Figure 5a shows that the users suggested between zero and two vibration points for these interaction scenarios. 96 percent of users preferred to have a vibration at a single point for yes response and only four percent preferred to have vibrations at two points on a gesture for yes responses. For no response, most participants, 63 percent, again preferred to have vibration at one point on the gesture. However, contrary to the yes responses, 37 percent proposed not having any vibration for the no response.

Second, the vibration patterns can be categorized based on the number of vibrations proposed by participants. Figure 5b shows that participants suggested between zero and two vibrations for this interaction scenario. Most participants, 77 percent for yes responses and 64 percent for no responses, suggested one vibration on the gesture for the feedback. However, the rest of the participants proposed no vibration for no response and two vibrations for a yes response.

Third, the vibration patterns can be grouped based on the position of the vibrations. Figure 5c shows the distribution of vibrations on gestures by categorizing them into three groups: at the beginning of the gesture, at the end of the gesture, and in between. Our results show that most participants prefer to have a vibration at the end of gesture for yes response. However, for no response, the vibration is preferred both at the beginning and at the end of gesture.

Using the three criteria stated above for considering the vibration patterns identical, we calculated the vibration agreement rate for all 14 referents. Results indicate the mean vibration pattern agreement rate for “yes” answer was ($mean = 0.263, SD = 0.082$) and the mean vibration pattern agreement for “no” answer was ($mean = 0.242, SD = 0.046, t(13) = 3.802, p = 0.001$). Though most participants used similar vibration patterns for different referents of this

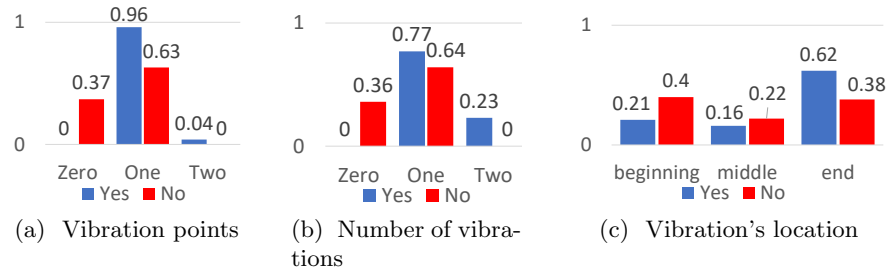


Fig. 5: The vibration patterns suggested by users for yes/no response scenarios. Figure (a) shows on how many points participants prefer to have vibration for each response. Figure (b) shows the number of vibrations they prefer to have for each response. Figure (c) shows where on the gesture they preferred to have the vibrations for each response.

scenario, no participant applied the same vibration pattern to every single referent of this scenario. The most suggested haptic feedback was one vibration at the beginning of the gesture for “no” response and one vibration at the end of the gesture for “yes” response.

Interaction scenario for categorical responses This interaction scenario includes seven referents. Four of these referents were analogues, R17 to R20, in the sense that the question asked was the same but the number of possible answers was different. In all these four referents, the question was “Which application do I have notification from” and the possible response was one application from two, three, four, or five applications. The most popular design was suggested by three participants. They differentiated the referents by adding an extra stroke to the end of the previous referent to increase the number of possible answers. Though the gesture shape they used was different, the speed profiles of those gestures were similar. For this set of designs, participants always assigned the vibration to the corners of the gestures. Figure 6 shows the most popular design for referents R17 to R20. Two participants used same gesture four all these analogues referents and assigned different vibration points for each referent. They always assigned the vibration to the same location for the same application in all referents. Two participants used the first letters of the applications for gestures. The next most common suggested gesture shape was drawing the letter from each possible response as both the input and the output gesture and feeling the vibration at the end of the corresponding letter, depending on the response. For instance, when the possible answers was “Instagram” or “Facebook”, they drew “IF” for this referent. When the possible answers was “Instagram”, or “Facebook”, or “Twitter”, or “WhatsApp” they drew “IFTW”. Referents R21, R22, and R23 were unrelated questions with four, seven, and 12 possible responses. For referents R21 and R22 with four and seven possible responses, respectively, 70 percent of participants proposed gestures with clear

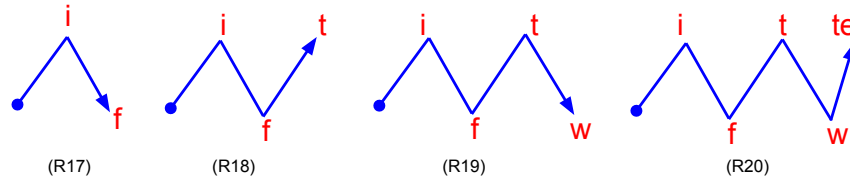


Fig. 6: The most suggested gestures for referents R17 to R20. The filled circle shows the beginning of the gesture. The arrow shows the ending point of the gesture. The red letters show the vibration point for each response. "i" for Instagram, "f" for Facebook, "t" for Twitter, "w" for WhatsApp, and "te" for Telegram.

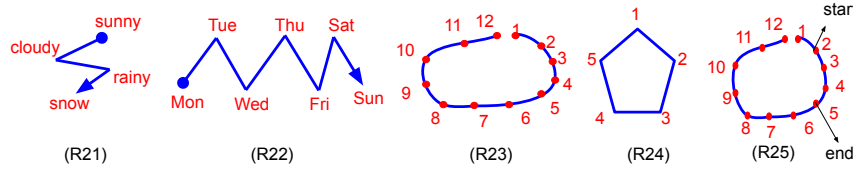


Fig. 7: The most suggested gestures for referents R21 to R25. (R23) numbers 1 to 12, represent the vibrations for month from January to December, respectively. (R24) shows participants suggest no vibration for number zero feedback and one vibration on the corners of the pentagon. (R25) The design suggested by half of the participants for a time range. They suggested feeling a vibration at the beginning of the time range (i.e. at 2 o'clock in the figure) and one at the end (i.e. at 5 o'clock in the figure) while they were drawing a circle.

corners and assigned the vibrations to the corners of the gesture. However, for referent R23, with 12 possible responses this percentage was 25 percent. Figure 7 shows the most suggested referents for these three referents.

This interaction scenario included referents with two to twelve possible responses. Our results show that the users prefer to have gestures with clear corners, such as zigzag patterns or geometric shapes such as rectangles, or hexagons, and assign the vibration to the corners of these shapes. The gesture shape agreement rate and gesture speed profile agreement rate were 0.015 and 0.147. The vibration agreement rate for this scenario was 0.056 ± 0.061 .

Interaction scenario for numerical responses from 0 to 5 For numerical responses, 75 percent of participants preferred gestures with clear corners, similar to categorical responses. The most suggested gesture for this referent was a pentagon, as shown in Figure 7. However, some other designs were also suggested, like having vibration at different places in a straight line (for the "1" response vibration at the beginning of a straight line and for the "5" at the end of the straight line) or varying the number of vibrations (one vibration for the

response "1" and five vibrations for the response "5"). In this case, the participant suggested a gesture shaped like the letter "N" as input gesture, and no gesture as the output gesture. The gesture's shape agreement rate was 0.000 and gesture's speed profile agreement rate was 0.091. The vibration agreement rate for this scenario was 0.106.

Interaction scenario for time range For this scenario, we had one referent that asks at what time range do I have a meeting today. For this referent, unlike other referents, participants didn't have access to possible responses when they designed their gestures on the paper. We asked them to devise a solution that covers all possible time spans. 50 percent of participants suggested a circular shape gesture, which corresponds to a clock, and they proposed to have one vibration at the beginning of the time range and one at the end. This design was the most popular one (an illustration is shown in Figure 7). The other participants suggested a similar idea but for shapes other than circles such as triangles. The gesture's shape agreement rate and gesture's speed profile agreement rate were both 0.439. The vibration agreement rate for this scenario was 0.439.

6 Discussion and Future Work

In our study, the overall average agreement rate for the gesture's shape was very low ($mean = 0.081$, $SD = 0.122$). The five scenarios in this study can be listed in descending order based on gesture shape agreement rate as follows: 1) scenario for time range ($mean = 0.227$), 2) scenario in presence of the auditory feedback ($mean = 0.190$), 3) scenario with yes/no responses ($mean = 0.094$), 4) scenario with categorical responses ($mean = 0.015$), and 5) scenario for numerical responses ($mean = 0.000$). The time range scenario has the highest agreement rate, though based on our participants' feedback, it was the most challenging scenario to design. However, at the end, half of the participants suggested the same design. Their design was based on a simple illustration of a clock's hours on a circle. The second scenario with the highest agreement rate was for accept and reject call referents. The gestures suggested by users are very similar to gestures used on many smartphones to accept and reject calls when visual cues are available. For the yes/no response scenario, though the gesture's shape agreement rate was low, the most popular design was to use a letter from the scenario. Among the other scenarios, the categorical and numerical responses scenarios had the lowest rate of agreement for gesture's shape. This can be due to the fact that they were difficult to illustrate with a simple, widely accepted gesture, and the required haptic feedback was more complicated. However, for these two scenarios, the mean agreement rate of gesture's speed profile were higher, 0.147 and 0.091, respectively. This findings suggests that for such scenarios, the gesture speed is more important to users than the gesture shape.

Based on our findings, in the following, we discuss the implications of our results for the design of the *Hap2Gest* concept in terms of gesture design, gesture recognition, and haptic design.

6.1 Gesture design and recognition implications

From our study, we recommend designers and researchers to **use the same gesture for input and output** to increase learnability and memorability. It also simplifies recognition. In our study, although we allowed participants to use different gestures for input and output, our user-designed sets emerged with 96 percent of the same gesture for input and output. This can be due to the fact that using the same gesture for input and output requires less memory effort for participants. Though participants decided this without considering the recognition problem, it is beneficial to the recognizer too. Since the two gestures drawn by users for input and output are quite similar to each other, the recognizer has a reference to compare the output gesture with. For instance, if a user wants to draw a circle as the gesture, it is a very challenging task to detect online where on the circle the touch point is, especially at the initial stages. But when the input gesture is already recorded, the recognizer can easily detect the position on the circle by comparing the incomplete output gesture with the input gesture, if there is not a significant difference between the input and output gestures.

Although we recommend the designers use the same gesture for input and output in most cases, we don't recommend it when the gesture is too long. Drawing two long gestures can be slow and exhausting. To solve this issue, we recommend excluding the output gesture and providing the information with only vibrotactile messages at the end of the input gesture, or using a shorter input gesture. For instance, for referent R22 and R23, where there were 7 and 12 possible responses, respectively, some participants used a short letter as the input gesture (*i.e.*, letter “Z” as input gesture and a longer zigzag as output gesture for referent R22).

Our findings show there is a clear relation between the type of gestures and vibration patterns users suggest and the type of output information. First, **stroke gestures with geometric patterns (like rectangle, zigzag, polygon, etc.) should be preferred over alphabetic gestures for commands that can provide the user with many output information**, like in the scenario with categorical responses. What is important in this case is that the number of strokes that make up the output gesture is significant to the participants: **the more strokes the gesture contains, the more corners there are, and the more output information the output gesture can provide the user.** However, when the size of output information is so large, drawing so many strokes can be exhausting. To resolve this problem, some participants suggested assigning multiple vibrations to a line or a curve, and not only on corners. In this way, the gesture becomes shorter and easier to draw. The agreement between the shapes of the geometries for such a referent, R23, was very low, but the majority of participants spread the vibrations on straight lines. However, the most popular design was spreading the 12 vibrations over a circle. Though this was the most popular suggestion, it doesn't show that it would work. Further experiments are required to determine if participants can accurately locate these 12 points on a circle while drawing gestures. If the circular gestures can't have high

accuracy, then the other design suggested by users can be used instead. Some participants, for example, proposed spreading the 12 points across a geometry with four edges, with three vibration points on each edge. The corners available in this geometry may result in higher accuracy for locating the vibration points.

In contrast, **alphabetic gestures are interesting to use when considering commands that provide the user with a binary response, like those in the scenario with a yes or no response.** In this case, the letter that corresponds to the first letter of the name of the application is a good choice for the input and output gestures. For example, to check if the user has received a message, the letter “M” can be used. This finding is correlated with the work of Roudaut et al. [28], where letters are used as output gesture accompanied with haptic feedback to notify the user that he received a message. Successive letter shapes can also be used, for example, in the case where the user wants to have different notifications from different applications.

For challenging scenarios like the time range, we recommend using gestures, which are simple illustrations of an object or act related to the scenario. For example, our participants used a circle to illustrate a clock’s hours. However, a commonly accepted illustration of every scenario is not possible. For instance, there is no common visual representation of months or weeks accepted by the public. Finally, **for scenarios where gestures are famously already used on smartphones, like to accept and reject calls, we recommend using these familiar gesture shapes.**

As Wobbrock et al. [39] we advocate gesture reuse to increase learnability and memorability. Our user-designed set emerged with reusable gestures for analogous operations. Interestingly, in order to exclude ambiguity between different referents, in addition to relying on the target of the gesture as observed by Wobbrock et al. [39], our participants rely on the location of the haptic feedback for the output information. Two participants used the same gesture for all four referents, which were asking which application they have notifications from. They just added new vibration locations to each additional application while keeping the same gesture for the four referents. **For the categorical and numerical response scenarios, the recognizer should be focused more on the speed profile and not on the geometry of the gesture,** as there is more agreement between the speed profiles. For example, for a majority of categorical referents, users draw a gesture with clear corners, such as a polygon or zigzag, and assign the vibration to the corners of the gesture. Although the gestures mean shape agreement rates for categorical and numerical scenarios were not high (0.015 and 0.000, respectively), the gestures mean speed profile agreement rates were significantly higher (0.147 and 0.091, respectively). This shows that the gestures participants suggested were quite different, but the speed pattern was much more similar. In this case, the speed profile of these gestures is formed from consecutive bumps where, at the corners of the geometry, the corresponding speed is close to zero, at the bottom of bumps in the speed profile, and that’s where most users prefer to have the vibrations.

6.2 Haptic design implications

Designers and researchers should privilege positioning the output vibration on the corner of the output gesture. For example, in the first scenario, accept and reject call, all the participants who decided to have haptic feedback chose to have it at the end of the gesture. In the second scenario, yes/no responses, 89 percent of participants assigned vibrations at the beginning, end, or in between but on the corners. In the third scenario, categorical responses, the preference of participants was for having gestures with clear corners and assigning the vibration to the corners. However, it was a function of the number of possible responses. The percentage of participants who decided to have shapes with clear corners such as a zigzag pattern increased from 50 percent to 75 percent when the number of responses increased from 2 to 6. However, for the number of responses greater than 6, this percentage was less, *i.e.*, 33 percent for 12 possible responses. For the numerical response scenario, there was also a high tendency to assign vibration to corners, 75 percent. These results show that participants find it easy to feel the vibration on corners and tend to focus on the speed pattern of the finger rather than the geometry of the gesture.

The number of successively perceived vibrations could be used to provide users with numerical output information. While this solution was not the most suggested, it is still an interesting way to receive the output information. After drawing the input gesture, the user will simply remain stationary and count the number of perceived separate vibrations. This method was suggested by one user for referents R22, R23, and R24. Referent R24's output is intrinsically a number. However, the outputs of referents R22 and R23 can have an order and can be numerated by the users, *i.e.*, one corresponds to the first month of the year and 12 corresponds to the last month of the year. Consequently, it is interesting to study in future work from both cognitive and precision points of view, for numerical output information, if it is better to perceive different vibrations through the gesture, each of which corresponds to a different number, or to stay stationary after drawing the input gesture while perceiving many successive vibrations (at the same location) such that their number corresponds to the output information.

When auditory feedback is available, haptic feedback can be excluded. For example, for accepting or rejecting call referents, most participants preferred not to have haptic feedback. However, as our study was made without a primary task, this implication can depend on the context of the interaction. For example, in [2], authors found that, after training with visual and auditory feedback, the use of haptic feedback permits users to reduce their attention to the touchscreen.

6.3 Limitations

Like any study, our study presents limitations. In this study, participants were younger than the population average, were right-handed, and were all students at the university. Undoubtedly, older people, children, or left-handed people would

behave differently. Moreover, the number of participants we recruited can be increased to draw more robust conclusions and derive a gesture set that is more generalizable. These issues are worthy of investigation, but are beyond the scope of the current work.

Unlike previous gesture elicitation studies on touchscreens, our study introduced the haptic channel to the equation. However, participants designed their solution without trying the haptic part. It’s possible some of the solutions participants designed may not be accurate or achievable in practice. We tried to minimize this problem by warning the participants in the instruction to try their best to come up with simple vibration patterns that are easier to remember and understand. Moreover, the solutions suggested by participants may not be necessarily the best solution in practice. In future, we plan to conduct psychophysical experiments on the solutions suggested by participants to evaluate them, in terms of accuracy, speed, and memory effort.

7 Conclusion

The nature of the haptic actuators used in smartphones makes the transmission of high-dimensional data difficult as they are limited to patterns such as intensity, duration, and frequency. In this work, we add one other dimension, kinesthetic perception of the finger, to human interaction with smartphones through haptic channel. We introduced *Hap2Gest*, a two-stage gesture-based, eyes-free interaction concept that leverages tactile and kinesthetic senses to retrieve information from a smartphone. We conducted the first elicitation study in the literature where gestures on touchscreens are selected not only by the task but also by considering the tactile channel for retrieving information. The results show that in more than 96 percent of the cases, participants prefer to have the same gesture for input and output, which is good news for designers as it makes recognition easier and online recognition possible. Our findings also show that there is a clear relationship between the type of gestures and vibration patterns suggested by users and the type of output information. Moreover, we showed that the gesture’s speed profile agreement rate is significantly higher than the gesture’s shape agreement rate, and it can be used by the recognizer when the gesture shape agreement rate is low. Finally, we highlight the implications of our work on the paradigm of gesture interaction design, gesture recognition, and haptic design. We hope that our results will prove useful to gesture and haptic interface designers, assisting them toward improved gesture and haptic designs that consider users’ behavior and preferences.

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