Vibrotactile Stimulation of the Head Enables Faster Gaze Gestures

Jari Kangas*, Jussi Rantala, Deepak Akkil, Poika Isokoski, Päivi Majaranta, Roope Raisamo

Tampere Unit for Computer-Human Interaction, School of Information Sciences, University of Tampere, Finland

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Abstract

Gaze gestures are a promising input technology for wearable devices especially in the smart glasses form factor because gaze gesturing is unobtrusive and leaves the hands free for other tasks. We were interested in how gaze gestures can be enhanced with vibrotactile feedback. We studied the effects of haptic feedback on the head and haptic prompting on the speed of completing gaze gestures. The vibrotactile stimulation was given to the skin of the head through actuators in a sun glass frame. The haptic feedback enabled about 10% faster gaze gestures with more consistent completion times. Longer duration of haptic prompts tended to result in longer duration of gestures. However, the magnitude of the increase was marginal. Our results can inform the design of efficient gaze gesture user interfaces and recognition algorithms.

Keywords: Gaze tracking, gaze gestures, gaze interaction, haptic feedback

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1. Introduction

The widespread use of wearable devices such as smart glasses introduces the need fro new interaction techniques. For example, mobile users may have

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*Corresponding author

Email addresses: `jari.kangas@uta.fi` (Jari Kangas), `jussi.e.rantala@uta.fi` (Jussi Rantala), `deepak.akkil@uta.fi` (Deepak Akkil), `poika.isokoski@uta.fi` (Poika Isokoski), `paivi.majaranta@uta.fi` (Päivi Majaranta), `roope.raisamo@uta.fi` (Roope Raisamo)

difficulties operating small buttons on the glasses. One alternative could be to use hand gestures in front of a built-in camera, but this could attract unwanted interest or embarrass the user if used in a public place. Situational impairments (e.g., hands reserved) can make it impossible to use hands for input.

Spoken commands also have some limitations. Even though they are easy to use, in public settings they are not ideal because of the potential of eavesdropping by others or disturbing bystanders. Auditory feedback can also become useless if there are loud environmental sounds. To make smart glasses accessible in all situations, a range of different input and output modalities are needed.

In this work, we study the use of gaze for input and haptic stimulation for output with glasses. Gaze input is an unobtrusive method that leaves the hands free for other tasks. Furthermore, haptic stimulation is a discreet output method that is possible to sense even when mobile through haptic actuators in contact with the skin. We report two experiments where participants performed gaze gestures to provide input. Haptic feedback was presented to the skin of the head via two actuators in the temple bars of eye glasses and one in the front of glasses. Our results showed that the added haptic feedback made the use of gaze gestures faster.

2. Gaze Input

Gaze tracking is a promising and rapidly developing input technology that is based on following the user's gaze point with respect to the view that s/he sees, in most cases on a display in front of the user. The technology makes it possible to use the gaze point as an implicit pointer of a user's interest, and also explicitly as a pointing device. For example, the user could select an object by gazing it long enough.

To estimate the gaze point, most current gaze tracker devices utilize a camera (or cameras) looking at the user's eye and calculate from that image the gaze direction. Often a near-infrared light source is used to improve the tracking accuracy (please see Hansen and Ji (2010) for further details of tracking techniques). Camera-based tracking is suitable also for wearable devices. Eye glasses with gaze tracking capability are available both as research prototypes (Lukander et al., 2013) and commercial products (e.g., Tobii Glasses 2[1] and Dikablis Glasses[2]). It is also possible to augment virtual reality headsets with eye tracking[3]. Overall, technologies for gaze tracking are becoming more available and affordable [4].

The benefit of gaze input is that it conveys the points of interest in a very natural way. However, it is not as natural to use gaze for interaction because it lacks a natural activation function. One option is to use gaze for pointing and some other function, like a button press, for activation. For example, Salvucci and Anderson (2000) used a keyboard and Stellmach et al. (2011) used a keyboard and a mouse together with gaze based pointing to achieve a fluent work flow.

In some situations, purely gaze based methods for activation are preferred. This is the case, for example, for users with such disabilities that the gaze is the only interaction option. The dominant method of activation has been a dwell, i.e. assuming that if the user is gazing an object for longer than a threshold time (dwell time), his/her intention is to activate that object (Ware and Mikaelian, 1987). One typical application for dwell time has been gaze-based text input systems, which have been studied extensively (Majaranta and Räihä, 2002). Even though being widely used, dwell time is not optimal in mobile settings where gaze tracking accuracy is often reduced. This makes it difficult to point at a specific object long enough to activate it.

2.1. Gaze Gestures

A viable alternative to dwell time method is using gaze gestures, which are pre-defined sequences of gaze strokes (Drewes et al., 2007). In practice, certain eye movement patterns are interpreted as control commands that can be used, for example, to input characters. The eye movement patterns can be defined to be location independent or location dependent. A location independent gesture can start anywhere and the gesture components, strokes, only relate to each other, not to any fixed locations. Location dependent gestures, on the contrary, have fixed start and end points, often located in certain structures in an interface. If the gestures are defined location

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[1] http://www.tobii.com/en/eye-tracking-research/global/products

[2] http://www.ergoneers.com/en/hardware/eye-tracking/

[3] http://www.smivision.com/en/gaze-and-eye-tracking-systems/products/eye-tracking-hmd-upgrade.html

[4] For an overview of trackers, see http://wiki.cogain.org/index.php/Eye_Trackers

independent, the gaze tracker calibration is not nearly as critical as in dwell based methods because the exact gaze position is not needed.

A viable alternative to dwell time method is using gaze gestures, which are pre-defined sequences of gaze strokes (Drewes et al., 2007). In practice, certain eye movement patterns are interpreted as control commands that can be used, for example, to input characters. The eye movements patterns can be defined to be location independent or location dependent. A location independent gesture can start anywhere and the gesture components, strokes, only relate to each other, not to any fixed locations. Location dependent gestures, on the contrary, have fixed start and end points, often located in certain structures in an interface. If the gestures are defined location independent, the gaze tracker calibration is not nearly as critical as in dwell based methods because the exact gaze position is not needed.

Comparisons between dwell-based methods and gaze gestures have found that gaze gestures are preferred in settings with limited tracker accuracy. Dybdal et al. (2012) compared dwell and gaze gestures for an object selection task. Gaze gesture method was found more efficient than the dwell method as the target objects were shown on a small display and the gaze tracker had difficulties with the accuracy requirements. Hyrskykari et al. (2012) compared gaze gestures against dwell methods in a system for controlling a computer game. The results showed that gaze gestures were a robust interaction method when gaze tracker accuracy was reduced. Others have also found that gaze gestures are useful especially in mobile settings (Rozado et al., 2015; Drewes and Schmidt, 2007; Drewes et al., 2007; Kangas et al., 2014a). Dwell-based selection, on the contrary, was found faster for operating a soft-keyboard in desktop settings (Porta, 2015; Wobbrock et al., 2008).

Gaze gestures are suitable for occasional use in conditions where other modalities are not easily available. The intentional eye moves need to be learned, and using them for extended periods can be tiring (Kangas et al., 2014a). Learning can be made easier by using single stroke gestures (Mollenbach et al., 2009), but the downside is that single stroke gestures can be easily confused with natural gaze movements. This can happen, for example, when gaze gestures are used in natural environments where viewing of the surroundings may lead to unintentional triggering of gaze input. A possible solution is to impose constraints on the specific gaze movements (i.e. do something unusual with his/her gaze) to reduce the likelihood of false positives. More complicated gestures are recognized with higher accuracy than simple gestures, but can be more difficult to perform.

2.2. Feedback is Important in Gaze Interaction

The use of gaze gestures can be made easier by introducing appropriate feedback. In general, well timed feedback is useful and usually necessary for any interaction situation, to keep the interaction partners aware of the state of the dialogue (Nielsen, 1993). Majaranta et al. (2006) demonstrated how good feedback design improves the efficiency and experience of using a gaze based typing application. Heikkilä and Räihä (2009) also pointed out that a proper feedback design needs to be used with gaze gestures.

While visual and auditory modalities are the most common feedback channels in gaze-based interaction, they have some limitations. For example, in small devices a possible technique would be to extend the gazing area outside of the visual display (Isokoski, 2000), which would mean that visual feedback is not noticeable when looking at off-screen targets. In mobile situations, using a gaze based technique in public would discourage using audio feedback that may be disturbing to outsiders or difficult to notice in noisy environments (Brewster et al., 2007). Due to these reasons, we focus on haptics that would be private and easily noticeable. In a recent study, haptic feedback was preferred over visual feedback in interacting with a gaze-operated wrist device (Akkil et al., 2015).

3. Haptic Feedback

Haptic technology means using the sense of touch as an input or feedback channel (Hayward et al., 2004). Haptic sensations are created by actuators, often small motors, which generate movement, pressure or vibrations. The user of haptic devices then perceives the movement or pressure and associates it with a user interface action. Earlier research indicates that haptic stimulation used as feedback on mobile devices can improve user performance and subjective experience (Brewster et al., 2007; Hoggan et al., 2008; Koskinen et al., 2008; Pakkanen et al., 2010). Also other types of devices may benefit of the use of haptics. For example, in wrist devices haptic notification (Lee and Starner, 2010) and haptic feedback (Pasquero et al., 2011) improved the interaction experience and were found as easily perceivable.

For haptic feedback to be useful, it must be felt by the user in all situations. With handheld devices, this is typically achieved by directly touching the actuator or by perceiving stimulation through some (rigid) object. An example is the use of vibration alerts in mobile phones that work as intended when the mobile is held in hand, or in the pocket of tightly fitting trousers, but do not necessarily work in a coat pocket or in a handbag. Wearable devices, on the other hand, are designed to be in constant contact with the skin, and are therefore very suitable for providing feedback through haptics.

Head would be an ideal location to be used with eye tracking glasses because this would enable creating an all-in-one device with integrated gaze input and haptic output. Haptic stimulation needs to be designed carefully for the head because too strong stimulus can be uncomfortable and disliked by users (Myles and Kalb, 2010). By using short stimulus durations and intensities, Rantala et al. (2014) and Kangas et al. (2014b) showed that haptic feedback through glass frames was accepted by users. In the current paper, we continue this line of research by utilizing haptic stimulation on the head.

4. Haptic Feedback with Gaze Gestures

Earlier studies have indicated that haptic feedback can make the use of gaze gestures faster on a mobile phone. This was demonstrated by Kangas et al. (2014a) who instructed participants to use gaze gestures for controlling a simple list application shown own the phone display. A Tobii T60 gaze tracker was positioned behind the phone, and haptic stimulation was presented through the phone's built-in vibration motors. The used gestures consisted of two separate strokes and the haptic confirmation could either be given after the first stroke, after both strokes, or not at all.

The main result was that haptic feedback improved both the efficiency (the speed of accomplishing the tasks) and the subjective evaluations. The most effective haptic feedback was given already during the gesture making (after the first stroke) and not in the end of the gesture (after the second stroke). This finding supported the results of (Rubine, 1992) in that the most informative feedback for finalizing successfully the gesture should be available during the gesture making, not after.

Furthermore, the delay between a gaze gesture stroke and its corresponding haptic feedback affect how quickly users perform gaze gestures. Kangas et al. (2014c) studied this using a setup similar to (Kangas et al., 2014a) with the exception of an additional delay between gaze input and haptic output. The results showed that any delay in feeling the feedback will affect the gesture completion times. The participants were slower in completing the gestures with longer delays. A practical maximum delay between a gesture and feedback was shown to be around 200 ms (Kangas et al., 2014c). Also, in the subjective comments the participants mentioned how the gesture use became more difficult with longer delays.

4.1. Research Questions

The above discoveries led us to further study the effects of haptic feedback on gaze gestures. This time, we wanted to know if haptic feedback is beneficial also when it is presented to the user's head instead of hands. Furthermore, the earlier studies (Kangas et al., 2014a,c) used experimental tasks where participants had to perform multiple gaze gestures in a sequence. To be able to pinpoint how haptics affect the use of gaze gestures, we now focused on single gestures. We wanted to investigate these questions:

1. How does the vibrotactile feedback affect the efficiency of a single gaze gesture?
2. Are the effects of vibrotactile feedback to gaze gestures (if any) beneficial to the user?
3. Do the findings of different effects (if any) affect the design of interaction systems based on gaze gestures?
4. Does the effect of haptic feedback (if any) on gaze gesture making remain when the haptic feedback is turned off?

In the following sections we describe two experiments designed to answer these questions, their results, then we discuss the implications of the results, and finally our conclusions.

5. Experiment 1: Effects of Haptic Feedback to the Efficiency of Gaze Gestures

In the first experiment we wanted to see how the haptic feedback would affect the efficiency of gaze gestures, if at all. The expectation was that the feedback would make the gesture making easier. Easier tasks should be faster to complete (as indicated in, for example, by Kangas et al. (2014a)). To have more detailed results than those found in the earlier studies, we studied the user behaviour while doing isolated gestures in a simplified environment.

5.1. Participants and Apparatus

We recruited 30 volunteer participants (aged between 18 and 33 years, median 22 years; 22 males, 8 females) from the University community. All 30 participants had a normal (21) or corrected (9, 7 glasses, 1 contact lenses, 1 laser surgery) vision. Four of the participants were familiar with gaze tracking technology and all were unfamiliar with the gaze gestures. All participants were familiar with haptic feedback, in most cases from mobile devices but some had been using also gaming devices with haptic actuators.

We used a Tobii EyeX gaze tracker[5] to implement the interaction capability (see Figure 1). The EyeX gaze tracker is a robust, lightweight video-based tracker, targeted for gaming applications and can easily be utilized in real-time gaze based interaction experiments. The sampling frequency of the EyeX tracker is nominally 60 Hz, but it can momentarily decrease, depending on the processing load in the computer. We have found the sampling frequency adequate for our gaze gesture algorithms, however. Using a low-end consumer grade tracker rather than an expensive scientific instrument also improves the external validity of our results as such devices are the likely platform for future applications.

The distance of the participants to the display was between 50 and 70 cm, which is within the tracker manufacturer's recommended range (45-100 cm). The gaze data was processed on a Windows 7 PC where the application control logic was running.

Haptic feedback was given through three Minebea Linear Vibration Motors (LVM8, Matsushita Electric Industrial Co., Japan). The actuators were attached to the sunglass frame, see Figure 1. The actuators gave haptic stimulation through the temples of the glasses and through the front piece (similar to the device used by Rantala et al. (2014)). All the participants who wore glasses were asked to remove them to be able to wear the haptic glasses. We tested that the participants could comfortably see the display without their corrective glasses.

The vibrotactile pulses were generated by one of the actuators at a time. The actuators were driven using a 150 Hz sine wave, which is considered comfortable to the user (Myles and Kalb, 2010). The duration of the signal was set to 20 ms so that the perceived sensation would resemble a tap, and not felt as a vibration. The duration of the vibrotactile pulse was found

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[5] http://www.tobii.com/en/eye-experience/eyex/

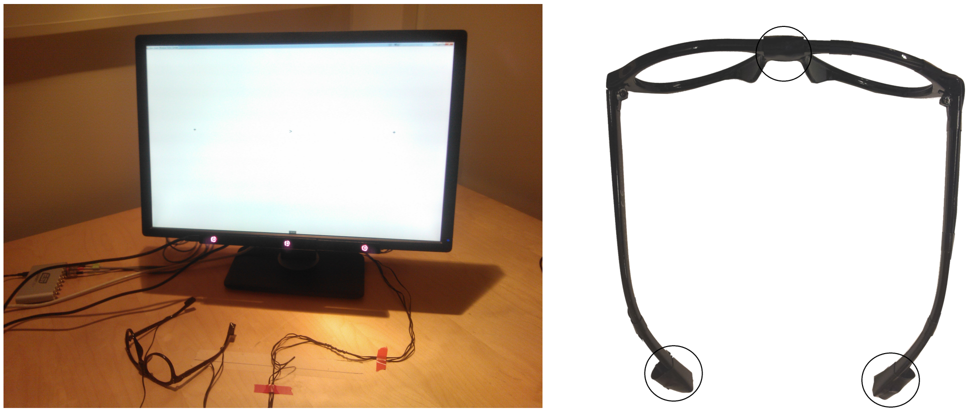

Figure 1: The Tobii EyeX gaze tracker attached to the bottom of the display (left). The glass frames with haptic actuators are shown on the table on the front of the display. The glass frames with two haptic actuators on the tips of the temples and one haptic actuator in the front (right).

long enough to be felt by all participants in pilot testing. The intensity of vibration was identical on all three locations and set to a level that was easy to notice and felt pleasant.

5.2. Procedure

In the beginning of the experiment the participant signed a consent form and filled in a pre-experimental questionnaire. The participant was then introduced to the equipment (the display with the gaze tracker and the glasses with actuators), followed by the calibration of the gaze tracker. The calibration was carried out using the tracker's own calibration software that asked participants to look at nine circles one at a time on the display. After that the participant tried the haptic feedback through the glasses to get used to the feeling. The familiarizing included single taps by one actuator and simple sequences of taps by two actuators.

In the experiment we asked the participants to do two-stroke gaze gestures similar to those used by Kangas et al. (2014a). In the beginning of each gesture the user was looking at the prompt in the middle of the display (see Figure 2, top). The first stroke of a gesture moved the gaze out from the central area to the side area, and the second stroke returned the gaze back. See Figure 2, bottom, for schematics of a gesture. The following two location dependent gestures were used:

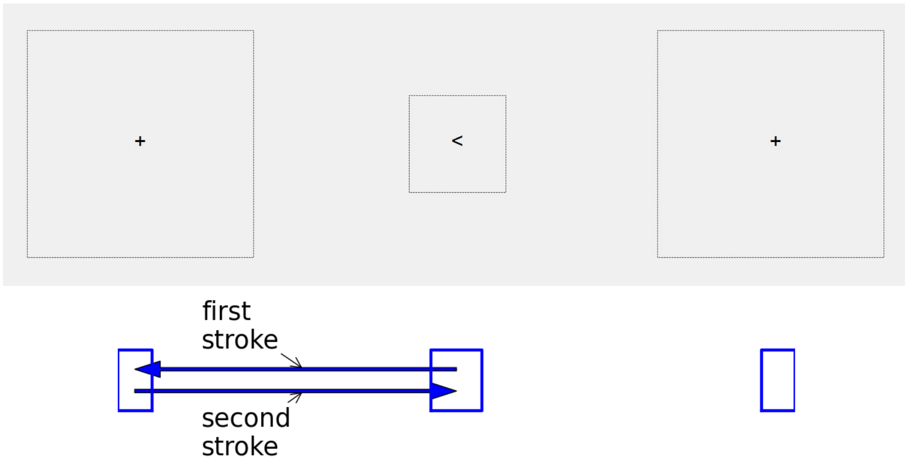

Figure 2: The display during the experiment is shown at the upper part. The participant was asked to look at the middle cross until it turned into a prompt (“<” for *Left* is shown) and then do a gaze gesture to the side that the prompt indicated. The squares with dotted lines marked the areas of gaze gesture recognition and were not visible during the experiment. The width of the middle square was between 3.5 and 4.5°of visual angle, depending on the viewing distance. The widths of the side squares were between 7.5 and 11°, and the distance between the visible symbols (the length of the gaze gesture, if the participant was looking the symbols exactly) was between 14 and 19°. A schematic illustration of a gaze gesture is shown at the lower part. The middle area was used to show the prompt indicating the gaze gesture direction. The arrows shown indicate a *Left* gesture between the middle area and the left area. That is, the participant was to visit the left area and return to the middle area.

- *Right* between the middle area and rightmost area.
- *Left* between the middle area and leftmost area.

The experiment consisted of four phases (see Table 1). During each phase the participant was asked to do 25 trials, i.e. 25 gaze gestures by the prompt of the system. A trial consisted of gazing into the middle area where a prompt was shown, and then moving the gaze onto the side target and back. The direction of the gesture was indicated by the direction of the arrowhead (“<” for *Left* or “>” for *Right*). When the participant had completed the correct gesture, the prompt disappeared and there was a three-second pause before the next prompt was shown. The completion time was measured from the moment of the participant’s gaze leaving the middle area to the moment when the participant’s gaze returned back to the middle area. The directions for each trial were given in a random order.

Table 1: The four phases of the experiment 1.

1^{st} phase	2^{nd} phase	3^{rd} phase	4^{th} phase
25 trials	25 trials	25 trials	25 trials
No haptic feedback	Conditional haptic feedback	Conditional haptic feedback	No haptic feedback

After the experiment the participant was given a post-experiment questionnaire where we asked for his/her subjective comments.

In the experiment we compared two different haptic conditions (see Table 2). First, half of the participants did the whole experiment (all four phases) without getting any haptic feedback (*NoHaptics* condition). Second, the other half of the participants were given haptic feedback during the 2nd and 3rd phases of the experiment (*Haptics* condition).

The start of the haptic feedback was linked to the gaze point location through the gaze gesture recognition. The first haptic feedback was activated as soon as the gaze point arrived to the side area completing the first stroke of the gaze gesture. Similarly, the second haptic feedback was activated when the gaze point returned to the center area completing the second stroke and the gesture. The first haptic feedback was always given on the temple actuator (of glasses) on the side where the gaze was moved, and the second haptic feedback was given in the middle actuator.

A delay between a recognized gaze stroke and its resulting haptic feedback was measured to be 185 ± 50 ms, which is just below the limit of 200 ms reported by Kangas et al. (2014c). The delay was caused by the experimental setting's different components such as eye tracker sample rate, eye tracker video processing, data transmission from the tracker to the main CPU of the device including network delay, processing time, transmission delay of the haptic pulse, as well as the rise time of the haptic actuator. There was some variability on the delay due to, for example, the varying processing load of the main CPU.

5.3. Results

We collected information of the gaze gesture completion times, i.e. the time that the participant used in completing the trials. For analysis pur-

Table 2: The two different haptic conditions used in the experiment 1.

NoHaptics	No haptic feedback during the experiment
Haptics	Haptic feedback during 2nd and 3rd phase of the experiment

poses we discarded the first two trials (of 25 trials) on each phase for each participant to avoid start problems[6]. I.e., in the end we had data of 23 trials for 4 phases for each participant.

5.3.1. General Trend in Gaze Gesture Completion Times

As the participants were unfamiliar with the gaze gestures one of the main questions was then to see how the participants start learning them, and if and how the gesture completion times will change. First we analysed the gaze gesture completion times for the 1st and 4th phase as these were similar to all participants. For that we computed the median completion times of each participant.

The results are illustrated in Figure 3, where the two median values for each participant are used as coordinates. In an ideal case, if the participants would all learn (the gaze gesture completion times would change) similarly in absolute or relative terms the markers would all be located on a single line. In the experiment the dots are not on a line, but there is a visible trend that the completion times on 4th phase are shorter than on 1st phase. Only 7 out of 30 participants were slower doing the 4th phase than the 1st phase. The multiplier of the best fit line in Figure 3 is 0.85, which means that the completion times on 4th phase are about 15% shorter than on 1st phase. We computed the best fit lines also separately for the two haptics conditions, and the multipliers are practically the same. The multiplier for the *Haptics* condition is 0.85 and for the *NoHaptics* condition it is 0.86. Those participants that had received haptic feedback during 2nd and 3rd phases were not learning differently than the participants that had not received any haptic feedback.

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[6] The participant was given some time to become more familiar with the system after a break to get the gesture making smooth.

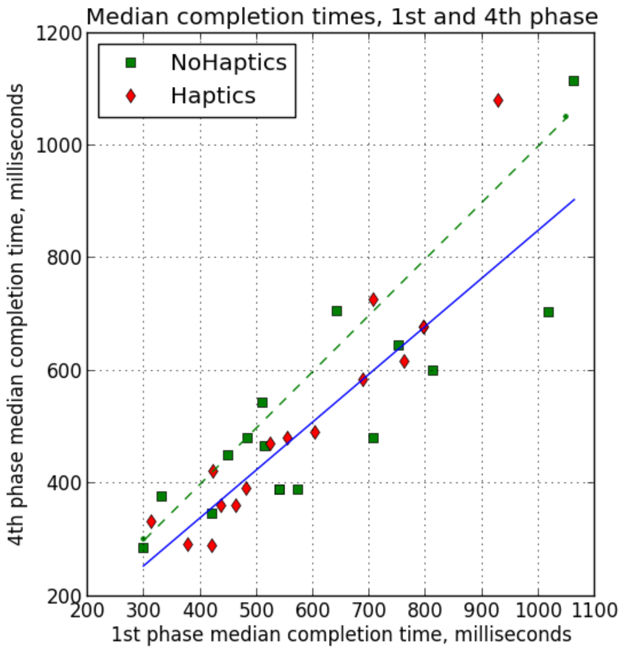

Figure 3: Median completion times of 1st phase and 4th phase of each participant are used as x- and y-coordinates. The boxes are for *NoHaptics* condition participants and the diamonds are for *Haptics* condition participants. The solid line is the linear best fit to these 30 points. The dotted line shows the locations which would indicate identical completion times from 1st phase to 4th phase. Only 7 of the participants were slower in the 4th phase than in the 1st phase.

5.3.2. Gaze Gesture Completion Times in Different Phases

To see the effect, if any, of the haptic feedback we computed the medians of gaze gesture completion times for all phases for all participants. The resulting numbers are illustrated in Figure 4.

While the general trend was downward from phase to phase there is an obvious dip in the median values for *Haptics* condition participants for 2nd and 3rd phase, where the haptic feedback was given. Even as the median values for most of the *Haptics* condition participants are smaller in 4th phase than in the 1st phase, in 10 out of 15 cases the median values for 4th phase are larger than either for 2nd or 3rd phase. The behaviour for the *NoHaptics* condition participants is different, the downward trend continues steadily to the 4th phase.

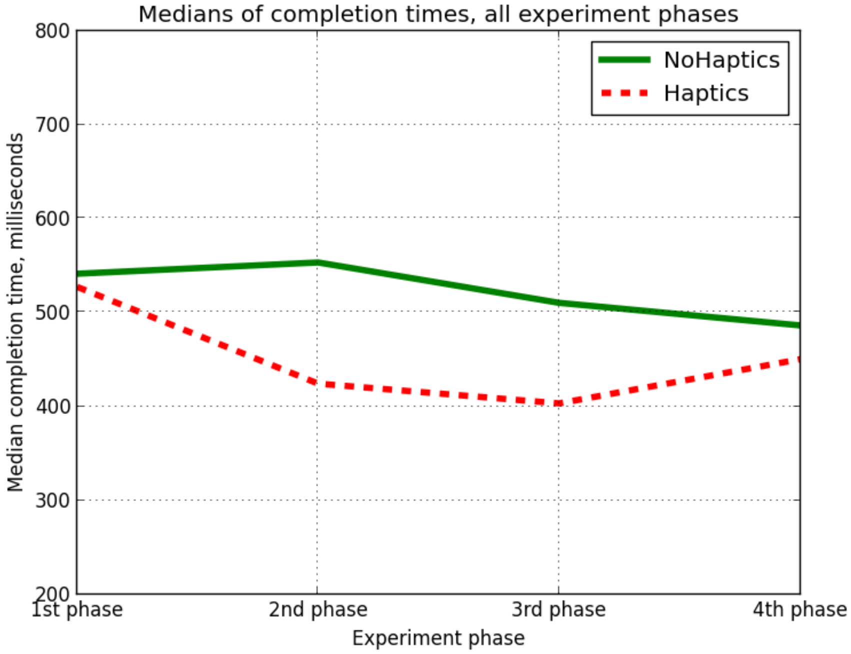

Figure 4: The median completion times of all experiment phases for all participants. The solid line is for all data of all participants in *NoHaptics* condition and the dotted line is for all data of all participants in *Haptics* condition. While the solid line has an overall downward trend from phase to phase, the dotted line has a clear dip during 2nd and 3rd phase, after which the completion times slightly rise for 4th phase.

We used a permutation method[7] to see if the completion times recorded in different conditions are statistically significantly different. For that purpose we collected the median values of the trial completion times of each participant. We used a Monte Carlo permutation test to do the significance tests (Nichols and Holmes, 2001; Edgington and Onghena, 2007; Dugard, 2014)(Howell, 2007, chapter 18). In the test an observed value of a mea-

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[7] We have used the permutation test as the method is not dependent on as many assumptions on the sample distribution as some other tests (Dugard, 2014). For example, the test sample need not be normally distributed while some other methods require that. Furthermore, we were able to use median values instead of mean as the test statistic, while some other methods are tied to using the mean value only. Median is more tolerant to outliers in data than mean value would be.

Table 3: The results of the permutation tests between the data sets collected from the two conditions *NoHaptics* and *Haptics*. The data sets consisted of the median values from each participant. The table shows analysis results of two different test statistics, the trial completion times (see Figure 4) and the median absolute deviations (see Figure 5).

	1^{st} phase	2^{nd} phase	3^{rd} phase	4^{th} phase
Trial completion times	$p = 1.00$	$p = 0.05$	$p = 0.03$	$p = 1.00$
Median absolute deviations	$p = 0.73$	$p = 0.08$	$p = 0.01$	$p = 0.46$

surement is compared against a distribution of measurements produced by resampling a large number of sample permutations assuming no difference between the sample sets (null hypothesis). The relevant p-value is given by the proportion of the distribution values that is more extreme or equal than the observed value. In this test we measured the median values of completion time medians per condition. To get the distribution of measurements assuming no difference between the conditions, we pooled the completion time medians from both conditions and resampled from that generating 10,000 permutations to be measured. The test results have been collected to Table 3. From the results we can see that there is a difference in trial completion times during the 2nd and 3rd phase, but not in the other phases.

5.3.3. Median Absolute Deviations in Gaze Gesture Completion Times

To analyse the stability of the gaze gesture completion times we computed the median absolute deviation (MAD) values for each participant and each phase. The results for all participants and all experiment phases are shown in Figure 5.

From the results one can see that the MAD values for the participants of *NoHaptics* condition are overall slightly decreasing throughout the experiment, while the MAD values for the participants of *Haptics* condition have a similar dip during the 2nd and 3rd phase as in the completion times (Figure 4) and then slightly rise again for 4th phase. That means that when a partictipant in the *Haptics* condition group was given haptic feedback the completion times of his/her gestures were slightly more similar to each other

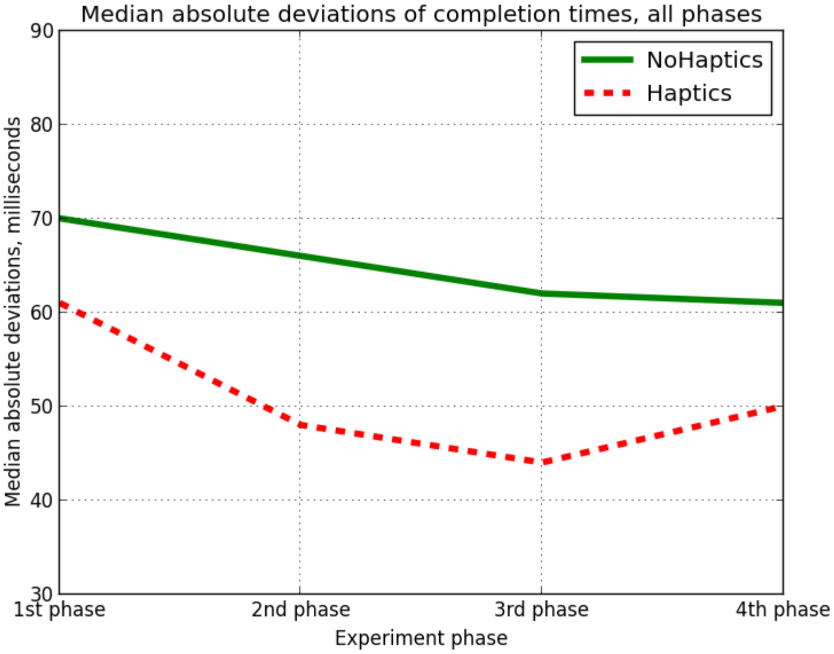

Figure 5: The median absolute deviations (MAD) of all experiment phases for all participants. The solid line is for all the *NoHaptics* condition participants and the dotted line is for all the *Haptics* condition participants. The dip in dotted line (*Haptics* condition) during 2nd and 3rd phase is as visible as in Figure 4.

than the completion times of gestures when the same participants were not given haptic feedback. For the *NoHaptics* group one can not notice any such difference between the phases. Instead, there was a slow overall downward trend as the participants were learning.

We used the permutation test to see if the MAD values calculated from data in different conditions are statistically significantly different. For that purpose we collected the MAD values of each participant. The test results have been collected to Table 3. From the results we can see that the MAD values differ statistically significantly during the 3rd phase, but not in the other phases.

5.3.4. Differences in Completion Times Between Consecutive Trials

To further analyse the stability of completion times we computed the sum S_p of completion times differences between consecutive trials of participant

p as follows:

$$S_p = \sum_{t=1}^{t=N-1} |T_t^p - T_{t+1}^p|, \tag{1}$$

where T_i^p is the gaze gesture completion time of trial i of participant p and N is the number of trials. That number will be small if the differences between consecutive completion times are small even if the completion times has a tendency to gradually change and are somewhat different between the beginning and the end of the experiment, as expected when the participants are still learning to do the gaze gestures.

The numbers shown in Figure 6 (left) were computed first for the 2nd and 3rd phases, where the participants were having different feedback conditions. The permutation test indicates a difference between the conditions ($p \approx 0.07$). For comparison purposes the same computation was done also for 1st and 4th phases (where the participants were all given same feedback). The results are shown in Figure 6 (right) and indicate less clear difference between the condition groups, which is a similar behaviour than what can be observed in Figure 5. The permutation test does not indicate a difference between the conditions ($p \approx 1.0$).

5.3.5. Relative Phase Completion Times Between Experiment Phases

An interesting relation between the phase completion times can be seen if we count how often the phase completion times in phase $n + 1$ are longer or shorter than in an earlier phase n. The transition behaviour is a good indicator in a sense that it takes into account only the participant's personal style, i.e. the measure does not suffer of a participant doing all gestures consistently a little faster/slower than some other participants. The phase completion time comparisons for both *NoHaptics* and *Haptics* conditions are collected in Table 4. All transitions from phase to phase are considered.

The comparison results for *NoHaptics* condition in Table 4 show that overall the phase completion times decrease from phase to phase. That is to be expected as the participants are gradually learning and, probably, find it easier to make the gestures, and make them faster.

In the *Haptics* condition the participants were given haptic feedback during phases 2 and 3. Therefore, the only data that can be compared directly to the *NoHaptics* condition is between the phases 1 and 4, and then again between the phases 2 and 3, when the system behaviour in *Haptics* condition

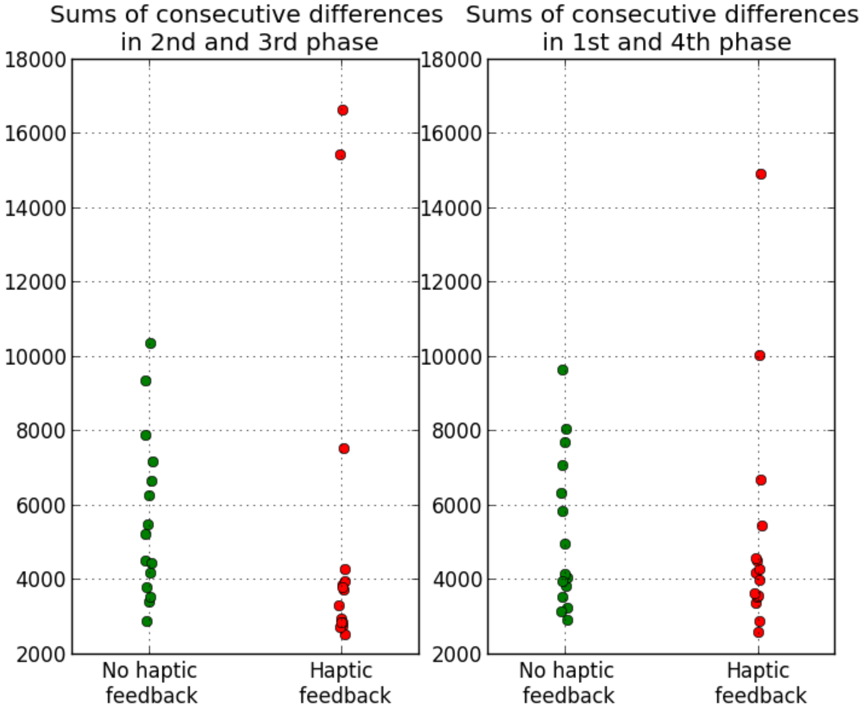

Figure 6: The sums of absolute differences between the consecutive trial completion times (in milliseconds), see Equation 1. The data from two phases for each participant is shown as a dot, different condition groups separately. The computation was done separately through the 2nd and 3rd phase (left) and the 1st and 4th phase (right).

is not changing. The data on those locations on Table 4 look very similar. Otherwise the two conditions differ considerably.

The most interesting phase changes happen in the *Haptics* condition from the phase 1 to phases 2 and 3 and then again from phases 2 and 3 to phase 4 where system behaviour was changed. In the first pair of transitions (from phase 1 to phases 2 and 3) the participants were not given haptic feedback in the first phase, while they were given haptic feedback in the latter phase. Our expectation was that the phase completion times are lower when haptic feedback is given, which was the case. There is, though, a confounding factor that overall the latter phases will be faster because of the expected learning effect. In that sense the second pair of transitions (from phases 2 and 3 to phase 4) where haptic feedback was given in the former phase and then was not given during the latter phase is more interesting. There the results show

Table 4: The phase completion time comparisons in both *NoHaptics* and *Haptics* condition. The numbers in the table show in how many cases the completion time was increasing/decreasing from phase to phase. "+" indicates an increasing phase completion time and "−" indicates a decreasing phase completion time in the later phase.

change \phase	1^{st} to 2^{nd}	2^{nd} to 3^{rd}	3^{rd} to 4^{th}
NoHaptics $+/-$	8 / 7	6 / 9	5 / 10
Haptics $+/-$	2 / 13	6 / 9	10 / 5
NoHaptics $+/-$	6 / 9		
Haptics $+/-$	2 / 13		
NoHaptics $+/-$		3 / 12	
Haptics $+/-$		10 / 5	
NoHaptics $+/-$	4 / 11		
Haptics $+/-$	3 / 12		

that majority of the participants, indeed, were using more time in phase completion without haptic feedback than with feedback, even as the phase without feedback was done last.

We used a permutation method to analyse the differences between conditions through all the single phase transitions (from phase 1 to phase 2, etc.). As a test statistics we used the following formula of the participant counts:

$$D_p = (NH_p^+ - NH_p^-) - (H_p^+ - H_p^-), \tag{2}$$

where NH_p^+ was the count of participants that increased the phase completion time in *NoHaptics* condition from phase p to the next phase, NH_p^- the participants that decreased the phase completion time in *NoHaptics* condition, and respectively for the *Haptics* condition. The results of the permutation test have been collected to Table 5. From the result we see that there is a rather strong difference between the conditions on transition from phase 1 to phase 2, no difference on the next transition (as expected) and some difference on transition from phase 3 to phase 4.

6. Experiment 2: Effects of Haptic Prompting to Gaze Gesture Duration

As the first study indicated that the haptic feedback would shorten the gesture completion times and also make them more stable, we were interested

Table 5: The results of the permutation tests between the data sets collected from the conditions *NoHaptics* and *Haptics*. The data sets consisted of the counts of participants with increase/decrease in phase completion times between test phases.

phase	1^{st} to 2^{nd}	2^{nd} to 3^{rd}	3^{rd} to 4^{th}
Phase completion time comparison	$p = 0.05$	$p \approx 1.00$	$p = 0.14$

to test if haptic prompts given before the gesture making might be used to shorten the completion times, as well. In the second experiment we measured how the time difference between two haptic prompts, two haptic stimulations one after the other preceding the gesture making, would affect the gaze gestures. We gave haptic prompts, two "taps", before the gaze gesture making was even started, and evaluated if varying the time span between the haptic stimulations would affect the gesture duration. Our expectation was that the participant would tend to mimic the rhythm of the haptic prompt to some extend, i.e. the gestures would take longer if the prompt duration would be longer.

The phenomenon, if we could find any, may have some effect, for example, in such situations where several gaze gestures are done one after the other, and the haptic feedback given to one gesture could be taken as haptic prompt for the next one. This could lead to three possible consequences depending on the duration of the gestures in between the haptic taps. 1) The prompting effect could further increase the pace of gesturing. 2) There would be no effect as the gesture length would match the prompt that encourages the same pace. 3) The prompting effect could slow down the gesturing.

6.1. Participants and Apparatus

For the second experiment we recruited 16 volunteer participants from the Experiment 1 (aged between 18 and 33 years, median age 22.5 years; 12 males, 4 females). 12 participants had normal vision, 4 participants had corrected vision. The glasses were removed for the duration of the experiment. The participants were all familiar with gaze tracking and, also, with gaze gestures. However, half of the participants were exposed to haptic feedback during the previous experiment, while the other half were not.

The apparatus used in the experiment was exactly the same as in the experiment 1, see Section 5.1. The vibrotactile pulses used in the haptic prompt were, as well, similar to the previous experiment. The duration of the pulse was 20 ms, which would resemble a tab.

6.2. Procedure

The participant was again introduced to the equipment (the display with the gaze tracker and the glasses with actuators), followed by the calibration of the gaze tracker. The participants then tried out the haptic feedback through the glasses to ensure that they were able to feel the stimulation. That step was needed for the other half of the group as they had not used haptic feedback in the previous experiment.

The experiment itself was very similar to the Experiment 1 as explained in Section 5.2, with the only exception that before seeing the visual prompt the participant was given a haptic prompt. Also, none of the participants was given any feedback of the gesture progress. In the experiment we asked the participants to do simple two-stroke gaze gestures as in the previous experiment. We did not instruct the participants to follow or mimic the prompt rhythm. In the beginning of each gesture the user was looking at the prompt in the middle of the display (see Figure 2, top). The haptic prompt was composed such that two of the haptic actuators, both sides of the head (see Figure 1), were giving a vibrotactile stimulus, a short vibrotactile tap, first once and then after a certain time (the haptic prompt duration) a second time (see Figure 7 for a timing diagram). Only after the second vibrotactile stimulus the middle visual prompt would change to indicate the direction of the gaze gesture and the participant was able to start making the gesture. The reason for using both sides of the head simultaneously was that the participant would not be given any cue of the gesture direction before the visual prompt, only the duration.

For the haptic prompt durations we selected seven different time spans from 150 ms to 750 ms with 100 ms intervals. The prompt test durations were given to the participant in a random order so that the experiment consisted of four groups of seven different durations each, and the order of the seven alternatives were independently randomized for each group. All together a test phase then consisted of 28 trials.

The first stroke of a gesture moved the gaze out from the central area to the side area, and the second stroke returned the gaze back. See Figure 2, right, for schematics of a gesture. The following two gestures were used:

- *Right* between the middle area and rightmost area.

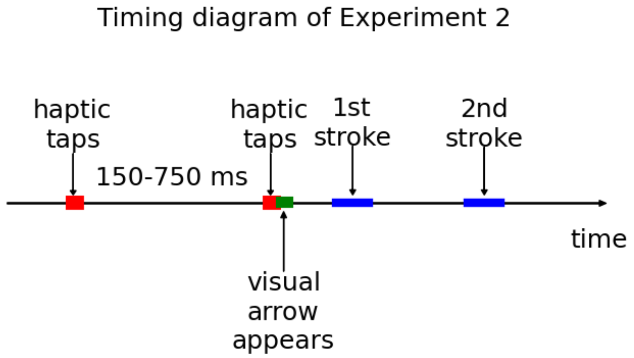

Figure 7: The haptic prompt consists of two haptic stimuli that were temporally separated by a variable time difference. The visual arrow appeared only after the latter haptic stimulus, after which the participant was able to do the gaze gesture (the two gaze strokes).

- *Left* between the middle area and leftmost area.

The experiment consisted of one phase, of 28 trials. A trial consisted of gazing into the middle area, getting the haptic prompt, seeing the visual prompt immediately after the latter vibrotactile stimulus of the haptic prompt, and then moving the gaze onto the side target and back. The direction of the gesture was indicated by the direction of the arrowhead ("<" for *Left* or ">" for *Right*). When the participant had completed the correct gesture, the prompt disappeared and there was a three-second pause before the next prompt was given. The completion time was measured from the moment of the participant's gaze leaving the middle area to the moment when the participant's gaze returned back to the middle area. The directions for each trial were given in a random order.

6.3. Results

We collected information of the gaze gesture completion times, i.e. the time that the participant used in completing each trial. For analysis purposes we discarded the two first trials to avoid phase start problems. I.e., in the end we had data of 26 trials for each participant.

6.3.1. Gaze Gesture Completion Times

The trial completion time data is shown in Figure 8. The two different groups of participants (those having previous experience of haptic feedback

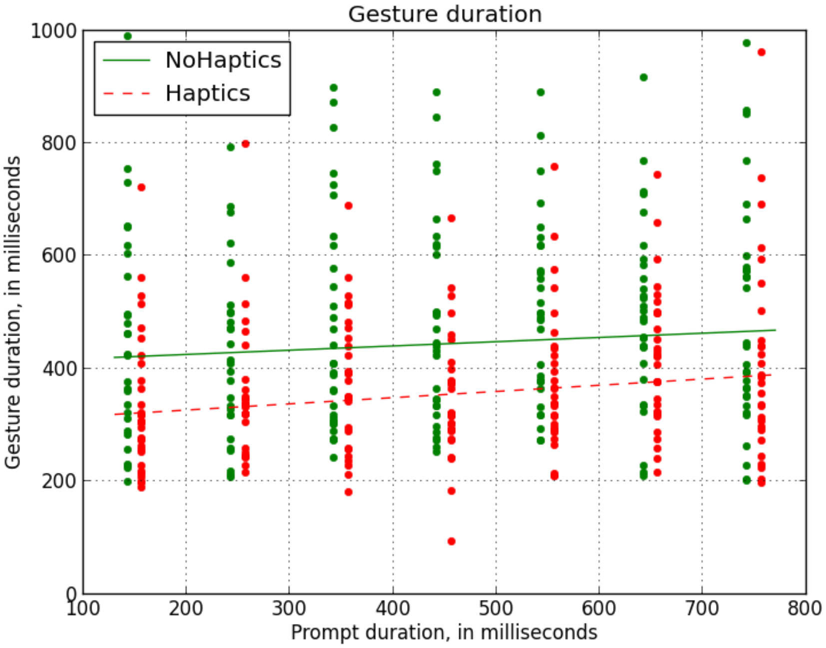

Figure 8: The gaze gesture completion times as a function of the prompt duration. Two different groups have been separated. First group consisted of those participants who had not received any haptic feedback in earlier tests of gaze gestures and second group consisted of those participants who had received haptic feedback. The (green) dots on left on each column belong to participants of *NoHaptics* condition and the (red) dots on right on each column belong to participants of *Haptics* condition. The prompt duration, the time between the haptic stimulations, is shown on the horizontal axis. The two lines are the best fitting lines of the respective data.

with gaze gestures and those having no such previous experience, see Table 2) have been separated in preparing the figure. The best fitting lines for the data are shown in the image. The lines show an increase in the gesture completion times, albeit rather weak one, from the faster prompts to the slower prompts, which would indicate that there may be an effect that longer haptic prompt durations lead to longer gaze gesture completion times. The gradients of the best fitting lines for *NoHaptics* group and for *Haptics* group are 0.08 and 0.11, respectively. Even as there is some difference in completion times between the conditions, the difference is not significant ($p = 0.20$). The significance was tested using the median values of trial completion times for

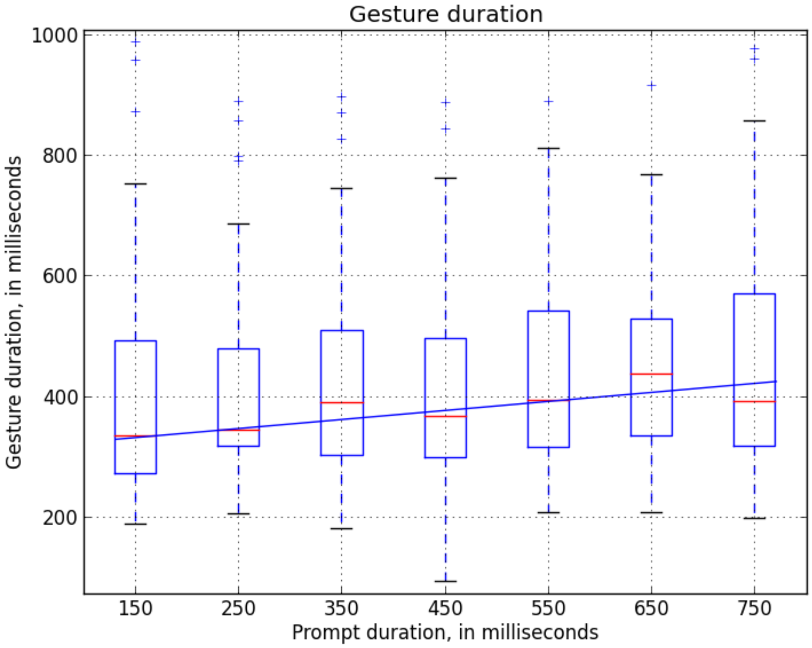

Figure 9: The gaze gesture completion times as a function of the prompt duration. All the participants have been included in the data. The prompt duration, the time between the haptic stimulations, is shown on the horizontal axis. The line shown is the best fitting line of all data.

each participant and a permutation test between the two conditions.

The gradient of the best fitting line, see Figure 9, is 0.15, which is only a fraction of the unity line (gradient of 1.0) that one would expect if the participants would really replicate the prompt duration. The fit still looks rather good and we tested the significance of the fitting, using a permutation method.

As the test logic is slightly different than in Section 5.3.2 we explain that in more details. As test statistic we used the F test. For every participant we had data of gaze gesture completion times (three to four samples) for every haptic prompt duration. We computed the mean values of completion times for every prompt duration and every participant. Assuming the null hypothesis that there is no effect of the prompt duration we were able to randomly rearrange the mean values of single participant to different prompt durations. Therefore, we used a factorial permutation test. Using the permutation test of 10,000 random rearrangements we got $p = 0.048$, which means that there is a weak link between the prompt durations and the gesture completion times.

7. Discussion

The results of both experiments indicate that there is a noticeable effect in the efficiency of gaze gesture depending on the arrangements of the haptic stimulus.

Returning back to the list of research questions proposed in Section 4.1 we will next go through them one-by-one. The first question was: **How does the vibrotactile feedback affect the efficiency of a single gaze gesture?** We can now answer that there are, at least, two different effects. One is on the time that it takes to complete the gesture itself, the completion time is shorter with haptic feedback. Another effect is decreased variability in gesture completion times, the times are more similar to each other with haptic feedback. Also, we separately found a related phenomena that varying the haptic prompt duration has an effect on the gaze gesture completion times.

It was shown by Kangas et al. (2014a) that the given task can be completed faster when having haptic feedback than without haptic feedback, which is superficially similar result than what we got in the current experiment. The experiment by Kangas et al. (2014a), however, was more complex and consisted of several phases and potentially quite many gaze gestures and it was difficult to separate the benefit given by the haptic feedback from other possible factors. The current experiments were about doing only a single gesture and measuring if there are differences. The results do show that there are differences on a single gesture level.

In some earlier studies about the use of gaze gestures the duration of gestures has been estimated and the results seem to vary considerably (Majaranta et al., 2011, p. 86). The duration of a single stroke in a (potentially multi-stroke) gaze gesture was estimated to vary from as low as 79 ms to as large as 1190 ms. The variation heavily depends on where to start the gesture length measurement, what kind of gestures are used, and how they are used in an interface. For example, Heikkilä and Räihä (2009) asked the participants to “draw” certain shapes (triangles, squares) by eye gestures, which led to rather long durations.

In our experiments the median gesture durations were mostly between 400 and 600 ms, i.e. between 200 and 300 ms per stroke (we always used two-stroke gestures). If we compare our results to the numbers from other studies we notice that our participants were doing the gestures rather fast, comparable to the experiments by Istance et al. (2010) and Møllenbach et al. (2010) who were also using rather simple gestures. More detailed comparison of the times between studies is useless as the implementations (gesture structures, interaction arrangements, etc.) were so different.

The second question was: **Are the effects of vibrotactile feedback to gaze gestures (if any) beneficial to the user?** We can now answer that the participants do benefit of the haptic feedback by being able to do the gestures faster, saving some time in interaction. Speculatively, the increased stability may indicate that the participants experience the gesture making with haptic feedback easier, they feel a little bit more confident and, therefore, the gesture instances are more similar from case to case. Even as the completion times were found to be shorter with haptic feedback the main benefit may, in fact, come up in the user experience. Kangas et al. (2014a) had reported, already, that the participants felt the conditions with haptic feedback more comfortable than the condition without haptic feedback.

The third question was: **Do the findings of different effects (if any) affect the design of interaction systems based on gaze gestures?** We can now answer that as the haptic feedback does improve the speed and stability of gaze gesture at least in some implementations, making such technology should be included in complete interaction systems whenever possible. In case some specific circumstances or environment prevents using the haptic feedback or the haptic feedback does not add any benefit the feedback system could always be switched off.

The fourth question was: **Does the effect of haptic feedback (if any) on gaze gesture making remain when the haptic feedback is turned off?** We can now answer that the results do not support the notion that the benefit of haptic feedback would last even if the feedback is no longer available. Seeing what happened between phases 3 and 4 in Experiment 1 when haptics was turned off for participants of *Haptics* condition (Table 4, between 3rd and 4th phases) one can say that the effect did not stay. Also, from Figure 3 one notices that the gaze gesture making was not affected by the haptic feedback after it was turned off.

Finally, our findings could also inform the implementations of gaze gesture recognition algorithms. When gaze gestures are used as an interaction modality in consumer devices, there are two issues that needs to be taken into account. Firstly, it is desirable from a user's perspective that the gestures are simple to perform and from the system's perspective that the involved eye movements are distinct, so as to distinguish the gaze gesture commands from normal eye movements. One way to do that is using upper and lower limits to the permissible duration of a gesture. Secondly, the users may forget the gesture or may not be aware of it during first time use. It could hence be beneficial if the devices reminded the users of the possible gestures and also guide users to successfully do the gesture.

Our results provides insights into how haptic feedback could influence the individual gesture duration. Haptics could help users make the gestures faster and more consistently. Also, the effect of haptics does not remain after the feedback is turned off. Taking these considerations into account allow interaction designers to set tighter limits for the gesture recognizer, reducing the potential false recognitions. However, one should note that there are also personal and situational differences that needs to be taken into account. The limits should be personalised and should also consider if the user has currently enabled haptic feedback for the interaction.

Secondly, it may be beneficial if the system could remind the users of the different gestures and guide the user to optimally perform these gestures. It is hence not difficult to imagine a smart glasses or virtual reality headset with gaze gesture based interaction with an initial training phase to allow users to identify and personalise different supported gestures. Haptic prompts could be an interesting way to guide the users to perform a gesture at an optimal pace. However, we need to keep in mind that the participants did not follow the prompt time difference exactly and the effect was small. For now we consider the prompt following an interesting indication of the effect of haptic stimulus on the participant behaviour.

7.1. Limitations on the Study

In our experiment we used only head haptics. Spakov et al. (2015) has shown that head and back can be used equally well for haptic cueing but more studies would be needed to study if the same applies to haptic feedback and also other body locations.

There are issues with the ecological validity of the experiments. The experiments were carried out using a desktop environment and would require validation in mobile environment.

The current experiments showed that haptic feedback has an effect for participants that started using gaze gestures. More studies are needed to understand the long term effects of haptic feedback. More studies are also needed to compare the haptic feedback to other modalities.

8. Conclusion

In general the results of the described two experiments were as expected. The gaze gestures are completed faster when the haptic feedback is given than without the haptic feedback. The result is, of course, dependent on a proposed implementation of the system. We ensured that the maximum delay of feedback was below the limit of 200 ms as stated by Kangas et al. (2014a). Haptic feedback reduces the variation in gaze gesture completion times. The gaze gesture completion times are more similar between them in presence of haptic feedback than without the haptic feedback. The duration of the haptic prompt has an effect on the duration of the following gaze gesture. The gaze gestures take longer to complete when preceded with longer haptic prompts.

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