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ORIGINAL PAPER

Gaze Cueing with a Vibrotactile Headband for a Visual Search Task

Jari Kangas[1] · **Jussi Rantala**[1] · **Roope Raisamo**[1]

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Abstract Augmented attention, assisting the user in noticing important things, is one of the ways human action can be enhanced with technologies. We investigated how vibrotactile stimulation given to the forehead could be used to cue gaze direction. We built a vibrotactile headband with an array of six actuators that presented short, tap-like cues. In the first experiment, the participant was instructed to look at the point on a horizontal line that they thought the vibrotactile cue was pointing to. Analysis of the participant's gaze points showed that for the majority there were statistically significant differences between cues from different actuators. This indicated that the six actuators could successfully direct the participant's gaze to different areas of the visual field. In addition, vibrotactile cueing of gaze direction could be used for directing visual attention and providing navigation cues with wearable headbands. To strengthen our findings, we investigated how effective the vibrotactile stimulation would be to cue gaze direction in a visual search task. Participant's were asked to find a deviant shape (a target) from a display full of simple shapes. The vibrotactile cueing implemented with the headband device was used to inform the participants of the approximate horizontal position of the target in three different experimental conditions. In the most informative condition, six actuators were used to inform the participant of the horizontal area where the target would be found, in the second condition two actuators were used to inform the participant of the target side on the display (left or right), and in the least informative condition no directional information was given. Analysis of the trial completion times showed that there were statistically significant differences between the least informative condition and the two other conditions. However, we did not find significant differences in trial completion times between the two conditions where information of the target location was given. This indicated that while the actuators could successfully direct the participant's attention to different areas of the visual field to help in the search task, the simple approach of just adding actuators and dividing the visual field to more sub-areas did not improve the results. The findings of this study showed that while there is potential in using vibrotactile cueing of gaze direction, more research is needed to fully exploit it.

Keywords Tactile cueing · Vibrotactile cueing · Vibrotactile actuators · Haptics · Tactile augmentation · Attention pointing · Visual search

Introduction

Humans can accurately localize the spatial point of touch on their body [30]. Upon sensing a touch, we typically shift our attention to that direction [3], which makes touch a suitable cue for egocentric orientation. With several vibrotactile actuators, it is possible to provide intuitive navigation information to users [18, 27, 29]. Other applications include motor skill learning in sports [24], helicopter landing [11], obstacle avoidance [1], visual search [14], and awareness of other people [20].

✉ Jari Kangas
jari.kangas@uta.fi

Jussi Rantala
jussi.e.rantala@uta.fi

Roope Raisamo
roope.raisamo@uta.fi

[1] Faculty of Communication Sciences, University of Tampere, Tampere, Finland

Vibrotactile stimulation in these applications has typically been presented to the user's torso [20, 27, 29], back [11], legs [24], hands [14], or shoulders [24]. Recently, researchers have started to consider the head as a potential body site. To stimulate the head, actuators can be attached, for example, to glasses [2, 18, 21], hats [1], helmets [15], headbands [4, 5, 7, 23], and head-mounted displays [6].

Even though the head is a highly touch sensitive body site, unpleasant perception can be avoided by using low stimulation frequencies [16] and short durations [12]. The sensitivity also varies between different areas of the head. Spatial discrimination of stimulus location is easiest on the forehead where a distance of 15 mm between actuators has been found to be sufficient to feel a difference between stimulation points [5].

Vibrotactile stimulation of the forehead has mainly been used to instruct users for head turns. de Jesus Oliveira et al. [4] built a vibrotactile headband for a study where the task was to face toward a virtual target given with either five or seven actuators. The results showed that users performed the task more accurately with seven actuators, and that up to five actuators can be used effectively on the forehead. Kaul and Rohs [13] built a system that used 17–24 small actuators around the head to study the virtual target pointing task and got good results compared to spatial audio use. With the dense actuator array in [4], it is likely that some of the actuators on the forehead are pointing to directions that are already in the user's field of view. That is, there is no need to turn ones head to see the point of interest. The effectiveness of vibrotactile cues could then be analyzed simply by measuring where the user moves his/her gaze after feeling a stimulus. Potential applications for such a technique could include, for example, vibrotactile warning systems where it would be time-consuming to confirm the directional cue by using head turns.

Finding visually an object from a complex environment can be a time-consuming task. Such a task could arise, for example, in shops with rows of similar looking merchandise or in traffic intersections with various signs. User needs to focus her gaze on one area at a time in a serial manner, which takes plenty of time. If an augmentation system already knows the location of an object relative to the seeker's egocentric orientation, the vibrotactile cueing system can be used to direct the user's gaze into the right area and speed up the search process. Lehtinen et al. [14] showed that presenting vibrotactile cues on hands helped in visual search task.

The benefit of using vibrotactile cues for presenting directional information is that the sense of touch is often an unoccupied modality. Direct visual pointers could be added in the egocentric view, but these pointers easily add visual clutter in an already packed view. Spatial audio cues can also be used, but may be difficult to observe in a noisy environment, and could possibly interfere with other audio signals.

Our goal in the current research was twofold. First, we investigated *if the vibrotactile cues on the forehead could be used to provide directional information of where to look*. To clarify that, we arranged an experiment where participants were given vibrotactile stimuli on the forehead and their gaze direction as a response to the stimuli was followed. Second, we investigated *if the vibrotactile cues on the forehead would be effective in a visual search task to shorten the search time*. To clarify that, we arranged another experiment where participants were given different amounts of directional information by vibrotactile cueing, and asked to find an object in a visual search task.

In the next section, we first describe the prototype vibrotactile headband that we developed for the experiments. In the following two sections, we then go through the two experiments. We will describe the experimental settings, explain the user studies and the data analysis methods, and describe the results in relation to the set research questions. In the very end, we discuss the results of both of the experiments and present conclusions of the main findings. The current work is an extension to the work by Rantala et al. [22] who describe the results of the first experiment in more detail.

Vibrotactile Headband for Gaze Cueing

Earlier studies on cueing gaze direction with vibrotactile stimulation have either stimulated the user's back [26] or used only two actuators on the head [23]. We designed a headband with six horizontally aligned vibrotactile actuators that were in contact with the skin of the forehead.

Prototype

The prototype device consisted of an array of six vibrotactile actuators (Precision Microdrives C10-100) that were fixed into a flexible headband with Velcro tape (see Fig. 1). The headband was worn on participant's forehead slightly above the eyebrows (see Fig. 2) so that the actuators would be situated symmetrically on both sides of the vertical

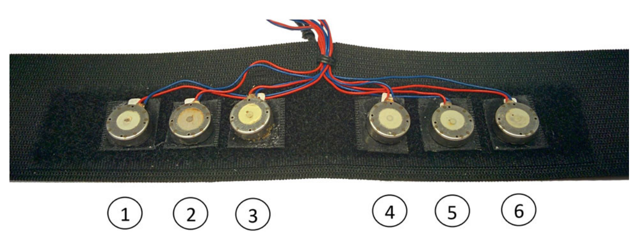

Fig. 1 Six vibrotactile actuators fixed into a flexible headband

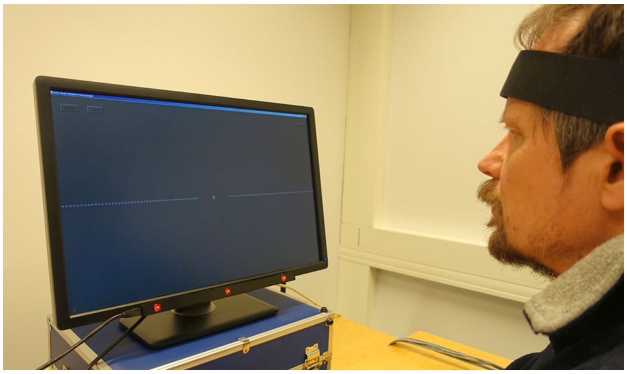

Fig. 2 In Experiment 1, the participants were looking at the start position in the center of the display while waiting for a vibrotactile cue. Upon sensing a cue, they looked at a suitable location on the *horizontal line* (i.e., to the left or right from the start position) and then moved the gaze back to the start position

midline of the body that is known to facilitate accurate spatial localization of vibrotactile stimuli [5]. The actuators were set in two groups of three actuators, on both sides of the midline. We did not position actuators on the body midline (i.e., above the nose) because it was used as a neutral start position for gaze before moving to the left or right. The distance between actuator centers on each group was set to 15 mm that should provide sufficient localization on the forehead [5]. The distance between the groups (i.e., actuators 3 and 4 in Fig. 1) was 30 mm.

Stimuli

A sine wave with a 160 Hz frequency was chosen for driving the actuators as a compromise between the resonant frequency of the actuator (175 Hz) and the recommended highest vibration frequency on the head area (150 Hz [16]). The stimulus duration was set to 30 ms so that the perceived sensation would resemble a short "tap" rather than prolonged vibration that can become irritating. A laptop computer running Pure Data (PD) audio synthesis software played the stimuli through a Gigaport HD USB sound card and IMG Stage Line STA-1508 eight-channel pro power amplifier.

Experiment 1: Directional Cueing of Gaze

In the first experiment, the vibrotactile headband actuators provided short cues, and the participant's task was to glance to the direction of the cue by moving his/her gaze accordingly on a display. We measured where participants would naturally look after sensing a cue by not providing any markers on the display to guide gaze direction. A remote eye tracker was used to measure the gaze direction (i.e., the gaze angle).

Research Questions

In an ideal case, gaze angles as responses to vibrotactile cues would reflect the actuator array's spatial configuration. That is, the gaze angles for a given cue would remain the same over several trials, and cues provided with different actuators would result in different gaze angles. As we did not know how people would respond to the cues, we defined the following research questions:

RQ1 Do participants look in different directions when the location of vibrotactile cue changes? This will be analyzed by comparing possible differences between gaze angle sample sets.

RQ2 Is the horizontal order of vibrotactile actuators and corresponding gaze angles consistent? This will be analyzed by checking whether actuators from left to right are mapped to gaze angles from left to right.

RQ3 Do the gaze angles of each vibrotactile actuator remain consistent from trial to trial? This will be analyzed by looking at the widths of the collected gaze angle sample sets.

RQ4 Are the gaze angles of vibrotactile cues evenly distributed in the visual space? This will be analyzed by looking at the distances between gaze angle sample sets.

RQ5 Can participants localize the vibrotactile actuators, and are the localization rates similar for all actuators? This will be analyzed by asking participants to indicate which actuator presented the cue.

Participants

Ten participants took part in the study (mean age 28, age range 20–42 years). Three of the participants were female, and five wore eyeglasses during the study. All were students or staff members at a local university.

Procedure

The participant was seated in front of a 24 in. display at a distance of 55 cm (see Fig. 2). The visual angle from the display's left border to right border was approximately 50°. This covered the typical 45° range of human eye movement that can be performed without a need to turn the head [19, 25]. The eye tracker attached to the bottom border of the display was calibrated to detect the participant's eye movements. The headband was fastened so that it stayed in place, but did not apply unnecessary pressure. Each actuator was then played twice to ensure that the participant felt the stimuli.

The experimental application showed a start position in the center of the display and a horizontal line in two parts, both sides of the center (see Fig. 2). When a trial was initiated, the participant was instructed to look at the start position with the head oriented straight ahead. After five seconds, a vibrotactile stimulus was felt on one of the six actuators. The participant's task was to glance to the direction of the vibration by looking at a suitable location on one of the horizontal lines without moving the head. The eye tracker recorded data of how far (horizontally) the participant glanced from the center of the display. After a brief glance, the participant moved the gaze back to the start position. The participant was then asked to localize the felt actuator. A verbal answer was given using numbers between 1 and 6 (see Fig. 1). The experimenter used a keyboard to record the answer, but did not tell whether it was correct. The next trial was automatically initiated after a few seconds.

A practice session was first carried out to introduce the experimental application and procedure to the participant. In the practice session, each actuator was activated twice in a random order. This was followed by an actual test session that consisted of two blocks. In both blocks, each actuator was played eight times (6 × 8 trials) in a random order. Thus, there were a total of 96 trials per participant. Conducting the whole study took approximately 40 min.

Data Analysis

We used a Monte Carlo permutation test [8–10, 17] to analyze possible statistically significant differences between gaze angle data sets. The permutation test is not dependent on as many assumptions on the sample distribution as some other tests such as ANOVA [8], especially as the test sample need not be normally distributed. Also, we were using median values as the test statistic, while some other methods can only use the mean. Compared to the mean, median is more tolerant to outliers in data.

In all tests, an observed value of a measurement 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 then given by the proportion of the distribution values that is more extreme or equal than the observed value. To get the distribution of measurements assuming no difference between the conditions, we pooled the sample set values from both conditions and resampled from that generating 10,000 permutations to be measured.

We excluded data of one trial in Experiment 1 due to environmental disturbance during the experiment. Thus, data of 959 trials out of possible 960 were used in the analyses.

Results

In the following, we briefly go through the main results of the first experiment. The results are described in more detail by Rantala et al. in [22].

Total Width of the Used Visual Area

After sensing a vibrotactile cue, the participants chose the corresponding gaze angles that would feel "correct" to them. As expected, the participants utilized different visual angles. The median total width of the sample sets was 30.9°, with median of absolute deviations (MAD) value of 7.4°. As the display was around 50° wide, the participants were using a little bit more than a half of the display width, on average.

Distributions of Gaze Angles (RQ1, RQ2)

All participants were consistent in their use of vibrotactile cues from different actuators in that the horizontal order of median gaze angles from left to right corresponded with the order of actuators from left to right. We conducted a simple permutation test ("Data Analysis" section) separately for the data of each participant. For five out of ten participants, the results showed statistically significant differences between all adjacent actuator pairs. For the other participants, two to four actuator pairs were significantly different. Over all participants, 40 out of 50 actuator pair comparisons (80%) showed statistically significant differences.

The differences between participants are evident in the gaze angles recorded from different participants. In Fig. 3

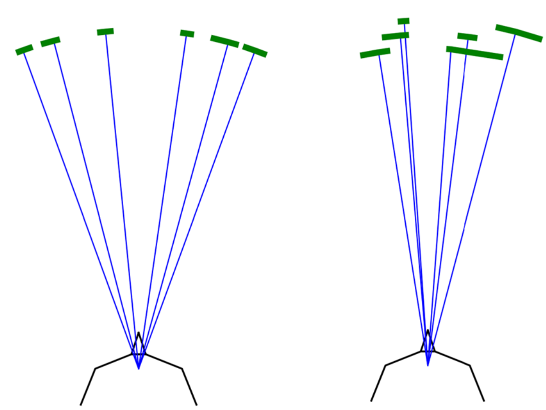

Fig. 3 Median gaze directions per actuator for two participants in Experiment 1. On the *left*, the gaze angles were well separated with quite even distances between them, while on the *right* some gaze angles are very close to each other. The *narrow blue lines* show the median gaze angles, and the *thick green bars* close to the ends show the distribution of second and third quartile of the gaze angles per actuator

(left), the participant responded to the cues accurately as he/she was consistently looking in the same directions and the angles were distributed evenly over the used visual space. In Fig. 3 (right), the participant was more inconsistent in the use of gaze for the same cues. The gaze angles of two actuator pairs, 2–3 and 4–5, overlap heavily, indicating that the participant looked almost in the same direction regardless of differences in the cue locations.

Gaze Angle Widths per Actuator (RQ3)

The width of the gaze angle set collected for each vibrotactile cue reflected how consistently participants used their gaze directions. The widths of the sample sets varied between the actuators. The two middlemost actuators, 3 and 4, have narrower gaze direction distributions than the other actuators.

Distances Between the Gaze Angle Medians (RQ4)

To analyze how evenly the gaze angles were distributed, we measured the distances between the sample set medians of different actuators (e.g., the angle difference between the medians of actuators 1 and 2). Because the total width of used visual area varied between participants, we normalized the data so that the total width calculated from the median angle of actuator 1 to the median angle of actuator 6 was 1.0 for each participant. The difference between actuators 3 and 4 was adjusted because the physical distance between the actuators was twice the distance of the other actuator pairs, and we expected that this would be visible also in the visual distance of the vibrotactile cues. Therefore, we divided the distance between the sample set medians of actuators 3 and 4 by 2.0.

The observed median distances do not differ much from the expected normalized average of $1.0/6 = 0.167$. This is the case, especially for the two middlemost actuators, 3 and 4, while there is more variation in the distances for the actuator pairs 2–3 and 5–6.

Actuator Localization (RQ5)

We asked the participants to localize the actuator. The median identification rate of all participants was 59.4%. The rates varied between participants from 41.1 to 88.5% (with MAD value of 7.8%). In addition, the variance between actuators was high. The two middlemost actuators, 3 and 4, were easiest to localize.

To analyze the errors, we collected a confusion matrix of participants' identifications (see Fig. 4). The two middlemost actuators, 3 and 4, are accurately localized, with only a few errors to the left or right of the correct one. For actuators 2 and 5, the errors happened mostly toward the midline of the body. That is, the participants felt that the vibrating actuator was closer to the nose than it actually was. It was six times more probable to err toward the midline than away from it when trying to localize actuators 2 and 5.

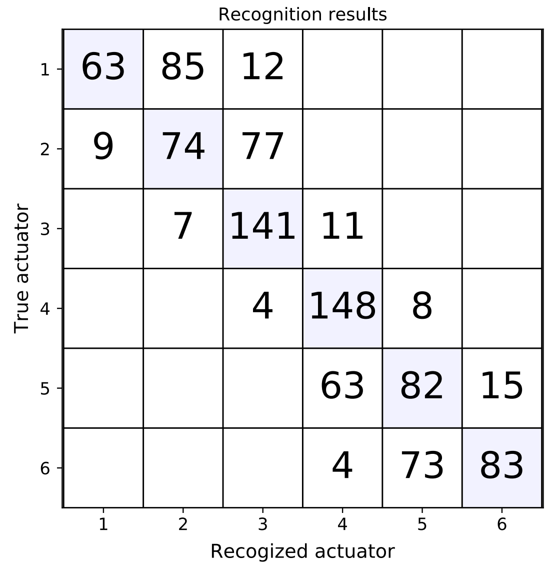

Fig. 4 Confusion matrix of actuator identifications. Each *row* represents one actuator, and the *columns* show which actuator the participants thought was active. Actuators 3 and 4 are localized accurately, and the errors happened to both directions, left and right. The errors in localizing actuators 2 and 5, however, were strongly biased toward the midline of the body

Discussion

The goal of our first experiment was to investigate how well vibrotactile cues on the forehead can direct users where to look. The results indicated that half of the participants directed their gaze to an area of the display that was always consistent with the order of the vibrotactile cue location (RQ1 and RQ4). The other half of participants had at least one adjacent actuator pair where gaze directions could not be consistently separated from each other. Overall, however, participants' gaze directions for two adjacent actuators were significantly different in 80% of cases. This supports the idea of using vibrotactile cues to direct gaze.

In the experiment, we demonstrated that a functional vibrotactile headband-based gaze cueing system could be developed. The results of the vibrotactile cueing were not, however, all consistent. For example, the results demonstrated that the participants usually made quite many identification errors between neighboring actuators, especially when cue was given farther from the body midline. The results of the localization rates between different actuators showed that participants were more accurate in localizing actuators 3 and 4 that were closest to the midline of the body (RQ5). This enhanced spatial localization of vibrotactile stimuli close to the midline has earlier been demonstrated on the head [5], back, and abdomen [28]. In addition, in our study, the relative widths of gaze angles for the middlemost actuators tended to be more focused than the ones on the sides even though no statistically significant differences were found (RQ3). It seems possible that because localization of stimuli close to the midline is accurate, also gaze direction cues given close to the midline result in more consistent gaze movements.

Experiment 2: Gaze Cueing for a Visual Search Task

Our next goal was to investigate *if the vibrotactile cues on the forehead could be used to provide effective directional information of where to look for in a visual search task*. We designed an experiment where the participant's task was to find a deviant shape among a large number of shapes. We varied the vibrotactile cue type used to guide the gaze to the search area. We were interested in measuring if participants would find the target shape faster when more accurate vibrotactile cueing was used.

Research Questions

Our expectation was that the search task would be completed faster when the participant is given more accurate information of the location of the target shape, which effectively decreases the search area size that needs to be checked. However, we also observed in the previous study some difficulties in identifying the indicated segments (see "Actuator Localization (RQ5)" section), and wrong identifications might lead to delays in finding the target as erroneous search areas were used. It was evident that the two sides of the display (left/right) could be rather easily and reliably identified, but there were some difficulties in separating certain pairs of neighboring actuators on each side. To study these issues, we defined the following research questions:

RQ6 Does the use of vibrotactile cueing speed up the visual search task compared to not using vibrotactile cueing? This will be analyzed by comparing the trial completion times between the conditions without location-specific vibrotactile cueing (*One_Area*) and with location-specific vibrotactile cueing (*Two_Areas* and *Six_Areas*) (see the definitions of the vibrotactile conditions in "Vibrotactile Conditions" section).

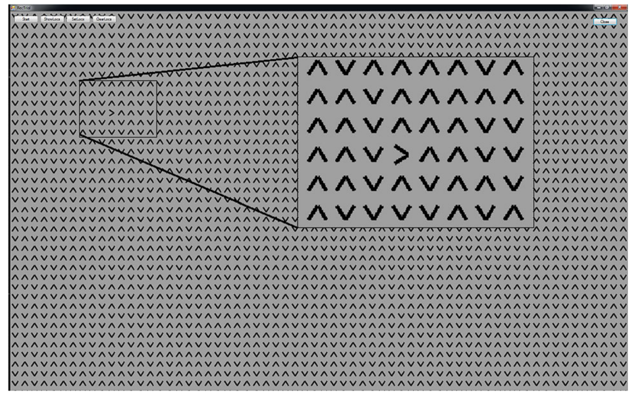

Fig. 5 Display view of the experiment, containing 64 columns times 39 rows of simple corner shapes. All but one of the shapes point either *up* or *down*. A *closeup* of a portion of the display has been included containing the target, the deviant corner shape, which is pointing to right in this example

RQ7 Does the number of vibrotactile actuators have an effect on the trial completion times in the visual search task? This will be analyzed by comparing the trial completion times between the conditions with two and six actuators (two actuators in *Two_Areas* and six actuators in *Six_Areas*).

RQ8 Are the trial completion times the same for all search areas related to different actuators in the "Six_Areas" condition where the participant is informed separately of all segments? This will be analyzed by comparing the trial completion times by different search areas only in the most informative vibrotactile condition (*Six_Areas*).

Search Task

In the search task, the participant was asked to locate the target from the display as fast as possible and indicate the direction of the target by a key press. The display contained about 2500 simple corner shapes (see Fig. 5). All but one of the corner shapes were pointing either up or down. The target shape was pointing either left or right. For each search trial, the location of the target shape and the orientation (left/right) was randomly selected, and the task of the participant was to press one of two dedicated keys to indicate the direction of the deviant corner shape.[1]

For the conditional gaze cueing, the display was divided into seven segments (see Fig. 6). The middle segment was

[1] The direction key was used for confirmation to be able to discover such situations where the participant would not actually search for the deviant shape, but would just confirm the trial in random to speed up the test. In such a situation, we would naturally expect around half of the confirmations to show an erroneous direction. If such behavior would be noticed, we would be able to remove the measurements from the data.

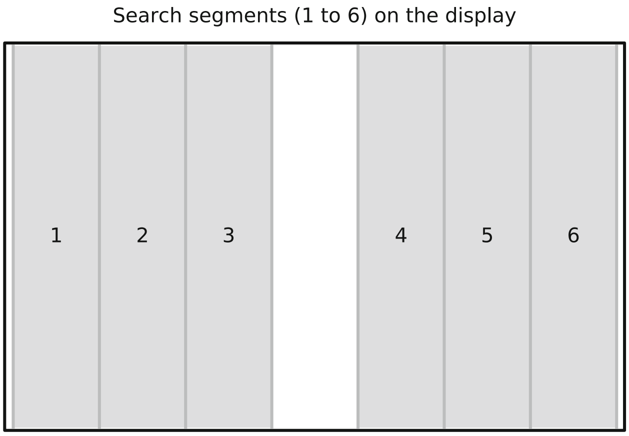

Fig. 6 Six rectangular search segments, numbered 1 to 6 respective to the vibrotactile actuators as shown in Fig. 1. The *top* and *bottom rows* and the *leftmost* and *rightmost columns* are not used. The search segments cover all the rest of display area (except the middle segment). In some experiment conditions, several segments are combined to bigger areas

not used for search task, while all the other segments were each associated with one of the actuators in the headband in a natural order. For each search trial, one of the six search segments was first randomly selected, and the exact location of the deviant corner shape on the segment was then randomly chosen with equal distribution. All the search segments were used equally often, but in a random order.

Vibrotactile Conditions

We were studying three different vibrotactile conditions which would each provide different amount of spatial information of the location of the search target. In the least informative condition (*One_Area* in Table 1), the participant was given a simultaneous cue on both sides of the forehead, using actuators 1 and 6 (see Fig. 1). Therefore, the participant was only aware that the trial had started, but was not given any information of the target location, i.e., there was only one search area that covered the whole display (except the middle segment). In the next informative condition (*Two_Areas*), the same two actuators were used, but only the one that was on the target side was used. For example, if the target was on the left side of the display (one of the segments 1 to 3, see Fig. 6), only the actuator number 1 was used. Therefore, the participant was able to limit the search area to half of the display, to three adjacent segments. In the most informative condition (*Six_Areas*), each actuator was separately used to inform if the search target was located in the corresponding search segment. For example, if the target was located in search segment 5, then only actuator number 5 was giving the vibrotactile cue.

Participants

Altogether, 18 participants took part in the study (median age 34, age range from 19 to 49 years); seven of the participants were female. Six participants wore eyeglasses, and all were students or staff members at the local university.

Procedure

The participant was seated in front of a 24 in. display at a distance of 55 cm, similar to the first experiment (see "Procedure" section). The headband was fastened, and each actuator was played twice to ensure that the participant felt the stimuli.

In the beginning, the experimental application showed the display full of corner shapes (see Fig. 5). The participant was explained how the regular corner shapes looked like and how the deviant corner shape differed from the regular ones. The participant was also explained the search task arrangement, and the six search segments were shown on a separate paper (as shown in Fig. 6). The participant was instructed on how to press the corresponding key (see Fig. 7) to indicate the direction of the corner shape once it was found.

At the beginning of each trial, the display was redrawn with random corner shape orientations. At the same time, the participant was given the vibrotactile cue to signal the start of the search. As soon as the participant had found the target shape, he/she was expected to press the corresponding key. A short beep sound was given to confirm the key press.[2] After a three-second pause, a new trial started automatically, with redrawn corner shapes and a new vibrotactile cue.

Three short practice sessions were run first, one for each vibrotactile condition. In each practice session, each of the six search areas was used twice, which resulted in 12 trials in a random order. The order of the vibrotactile conditions was counterbalanced between participants.

After the three practice sessions, the actual data collection sessions were run in the same condition order as the practice sessions. Each test session consisted of 48 trials, where each of the six search areas was used eight times. Thus, there were a total of 144 trials per participant. The order of the segment use was randomized over a session. There was a short break between sessions. Conducting the whole study took on average 35 min.

[2] In early pilots, some participants expressed frustration as they were not sure if the key press was registered or not, and we decided to add an aural confirmation. We decided not to use visual or haptic confirmation so that we don't interfere with the main task.

Table 1 Three vibrotactile conditions that informed the participant in different amounts of the search target location

One_Area, least informative	Vibrotactile stimuli on both actuators 1 and 6, no location information
Two_Areas, somewhat informative	Vibrotactile stimuli on one side, either actuator 1 or 6, indicating the display side
Six_Areas, most informative	Vibrotactile stimuli on the exact actuator that corresponds to the segment that contains the search target

Fig. 7 Dedicated corner shape keys for Experiment 2 trial confirmation

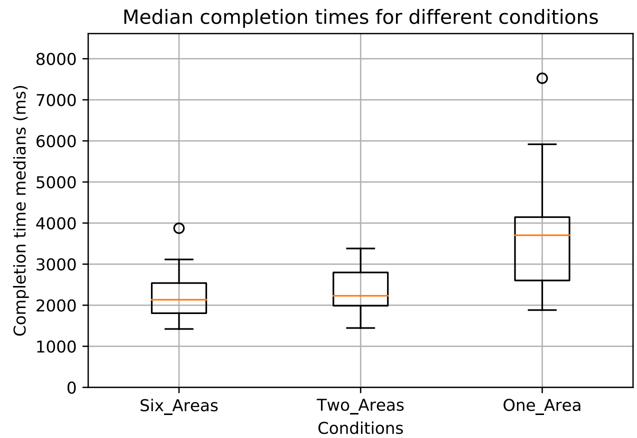

Fig. 8 Median trial completion times for all participants in different conditions. There are clear differences between some of the conditions in median values and in the spread of the median values

Data Analysis

We used a Monte Carlo permutation test to analyze possible statistically significant differences between trial completion time sets for different conditions, as described in "Data Analysis" section.

Before the experiments, we decided to exclude all data of sessions where the participant made at least eight mistakes in 48 trials when indicating the direction of the corner shape. In the end, we didn't exclude any sessions, as the maximum number of errors in a session was only 2.

Results

Effect of Vibrotactile Cueing for the Search Completion Time (RQ6)

Our expectation before the experiment was that vibrotactile cues would make the target search easier and trial completion times shorter than without the vibrotactile cues. As shown in Fig. 8, there is a clear difference between the *One_Area* condition and both conditions with vibrotactile cueing (*Six_Areas* and *Two_Areas*) in median values of trial completion times, and also in the variability between the participants. The medians of the trial completion times for all the conditions are listed in Table 2.

We used a Monte Carlo permutation test to evaluate if the differences in trial completion times are statistically significant. The p value results of the test are shown in Table 3 and indicate that the differences between the *One_Area* condition and both conditions with vibrotactile cueing (*Six_Areas* and *Two_Areas*) in median values of trial completion times are statistically significant. We used a Bonferroni-corrected p value limit of $0.025 = 0.05/2$ as we had two pairwise comparisons.

Impact of the Number of Actuators on the Search Completion Time (RQ7)

Our expectation before the experiment was that there would be a clear difference between the two conditions with vibrotactile cueing, *Six_Areas* and *Two_Areas*. Observing the visualization of the trial completion times on the two conditions in Fig. 8 suggests that there is a difference between them, but that it is not that clear. The result of the Monte Carlo permutation test on the trial completion times is shown in Table 2 and indicates that the difference between the vibrotactile conditions was not statistically significant.

Completion Time Differences Between the Search Areas in Six_Areas Condition (RQ8)

Our expectation before the experiment was that as the participant in *Six_Areas* condition would be given the vibrotactile cue separately for each search area, he/she would be able (in principle) to go to the correct segment for detailed visual search, and the trial completion times on all the segments would be roughly the same. The time difference because of gaze moves from cue waiting gaze location to search segments would be relatively small compared to the total search times. The trial completion times related to different search segments look approximately the same, see Fig. 9, which confirms our expectations. We did run a

Table 2 Trial completion times, median of medians for all vibrotactile conditions

Condition	Medians of median values of trial completion times, in milliseconds
Six_Areas	2134
Two_Areas	2230
One_Area	3703

Table 3 p values between the trial completion time sets of different conditions using Monte Carlo permutation test as explained in "Data Analysis" section

p values	Six_Areas	Two_Areas	One_Area
Six_Areas	–	0.598	0.001
Two_Areas	0.598	–	0.000
One_Area	0.001	0.000	–

Monte Carlo permutation test on the trial completion time sets for different search areas and found that the there is one case of statistically significant difference, between the segments 4 and 6. We used the Bonferroni-corrected p value limit of $0.0033 = 0.05/15$ as we had 15 different pairs to compare.

Completion Time Differences Between the Search Areas in One_Area Condition

For comparison purposes, we studied also the trial completion time differences between the search segments for the *One_Area* condition. As the participants on that condition were not given any indication of the location of the target and they were free to select their own search strategies, we didn't have any specific expectations of the completion time distribution between the segments. As shown in Fig. 10, there are clear differences between the segments in trial completion times. The middle segments (3 and 4 as shown in Fig. 6) have the shortest trial completion times, and in the other segments the completion times increase the higher, the farther away the segments are from the middle ones. A straightforward interpretation would be that (at least some of) the participants would wait for the start of the next trial looking at the middle segments, would start their search also from there, and proceed farther later. We did run a Monte Carlo permutation test on the trial completion test sets for different segments and found that there were no statistically significant differences between the trial completion times for any pairs. We used the Bonferroni-corrected p value limit of $0.0033 = 0.05/15$ as we had 15 different pairs to compare.

Learning Effect in Trial Completion Times

We noticed a strong learning effect in the experiment. As the search task itself was new to participants, it took some time for them to find suitable search strategies, which is evident in observing how the average trial completion times changed during the experiment from session to session. For visualization, we collected all the trial completion time medians for the first test condition, for the second test condition, and for the third test condition and computed their median values, see Fig. 11 and Table 4. There is a very strong trend of decreasing trial completion times from session to session. We ran a statistical significance test between the sessions using the trial completion times and a Monte Carlo permutation test. The test results show that there is statistically significant difference between the first and third sessions, but not between the other pairs. The p

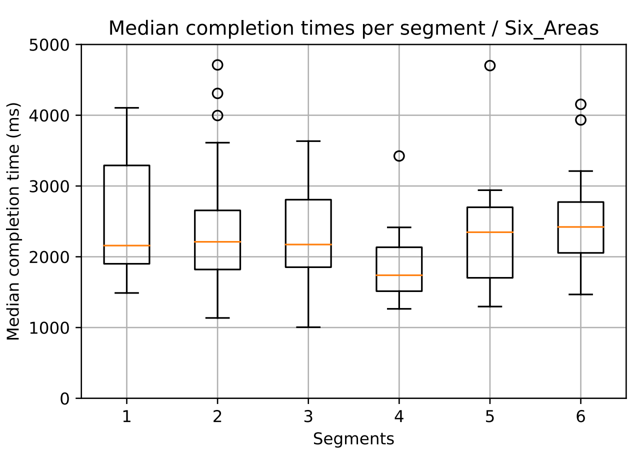

Fig. 9 Trial completion times for different search segments in *Six_Areas* condition, where all search segments are separately informed

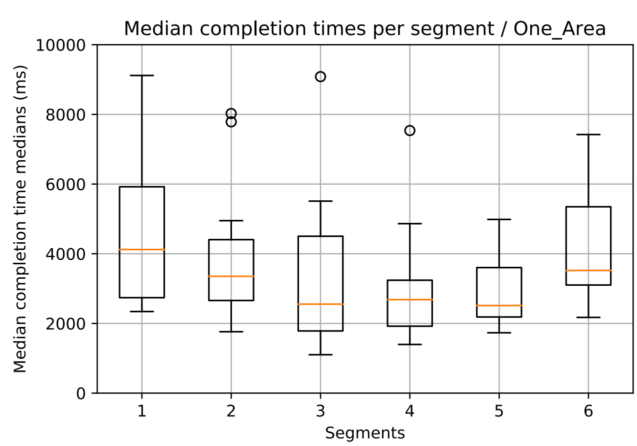

Fig. 10 Trial completion times for different search areas in *One_Area* condition

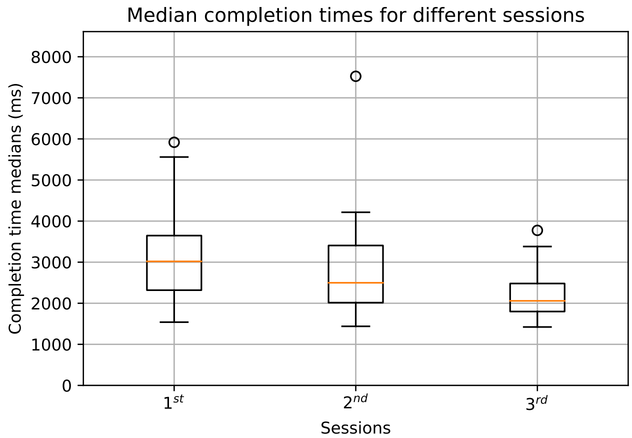

Fig. 11 Medians of trial completion times for different sessions in the experiment order. Different participants had different vibrotactile conditions in the first session, etc. The learning effect is clearly visible

Table 4 Trial completion times, median of medians for different sessions in the experiment order

Condition order	Median of median values of trial completion times, in milliseconds
First	3018
Second	2498
Third	2058

For example, the first value is the median of trial completion time medians of all experiment sessions that were done as the first condition for each participant

value limit was Bonferroni-corrected $0.0167 = 0.050/3$ as there were three different comparisons in the test.

Discussion

While the results in the search task experiment demonstrated that giving a vibrotactile cue of the search area leads to significantly faster completion times compared to not giving a vibrotactile cue (RQ6), adding even more actuators did not lead to clear improvements in the search performance (RQ7). We assume that the problem in scaling from two actuators to six actuators is not because of the basic idea that would not work for more than two actuators, but we must rethink the locations and spacing of the vibrotactile actuators. It is possible that the participants were not able to utilize the extra information given by six actuators because they couldn't consistently identify some of the actuators. We did notice already in Experiment 1 that there was a clear difference in the actuator identification accuracy depending on the actuator location (see "Actuator Localization (RQ5)" section). The middle actuators, numbers 3 and 4, were well identified while there were many mistakes for the other actuators.

General Discussion

In these two experiments, we were using vibrotactile stimulation of the forehead to cue gaze without showing predefined areas (cf. [23]). Our target was to see how users naturally move their gaze when perceiving vibrotactile stimuli on the forehead. For practical implementations, we assume that the headband system could be calibrated to each individual user. When a change in gaze direction is needed, the system would use the actuator that would lead to the most accurate response for the particular user.

In the search task experiment (Experiment 2), we decided not to use the view area calibration, however, as we noticed in Experiment 1 how narrow search areas we would have for some of the participants. The prototype system, consisting of only six actuators, would not allow flexible enough adaptation of stimulus location for all participants. Also, there would be big differences in area widths between the participants, and comparing trial completion times would be somewhat meaningless. Instead, we decided to use a fixed width search area structure and explain the search areas to participants in the introduction of the experiment.

There were several limitations in the current study. Firstly, in the first experiment instructing participants to move their gaze within the display area in front of them might have affected the resulting gaze angles. This rather controlled setup was chosen because we needed a remote eye tracker attached to the display to measure gaze movements. It would be also interesting to study how the gaze angles measured in more visually rich environments. Secondly, we chose to use six actuators which covered only part of the participant's forehead. Given that the measured gaze movements typically fell inside a visual angle of 31°, it could be possible to extend the actuator array by adding one actuator to both sides. With an array of eight actuators, we might be able to widen the angle of gaze movements up to 45° that can still be covered without accompanying head movements [19, 25]. On the other hand, it is not clear whether extending the array would result in a wider total angle of gaze movements. It is also possible that users would still prefer to use the same total angle, but divide it in narrower sectors per actuator. As we noticed quite many erroneous identifications for some of the actuators, we should also consider headband systems where the actuators are separated more on the sides than closer to the middle. For example, the distance from actuator 1 to actuator 2 might be significantly longer than the distance from actuator 2 to actuator 3 already on our existing device.

The research can be continued in several directions in the future. We could combine the directional cueing of gaze with head-mounted displays and virtual reality headsets, as in [6]. Also, we could combine our system to actuator setups like de Jesus Oliveira et al. [4, 6] who used actuators to point directions outside of the user's field of view. Then, we could use one system to first initiate a head turn and then the other system to make finer gaze pointing to objects.

In the second experiment, we didn't use the gaze tracker to follow the gaze direction. In future research, we could use gaze tracker to observe if the user is searching the right area, and give another vibrotactile cue after a while in case he/she is obviously searching a wrong area.

In conclusion, we found that the vibrotactile cueing of visual attention can augment the visual sense that is often overburdened in graphically heavy environments. In the search task experiment, we found that while the vibrotactile headband is beneficial and decreases the time needed for trial completion, achieving an efficient implementation with a more complicated actuator setup is not easy.

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Compliance with Ethical Standards

Conflicts of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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