

# Perceptual Assistant for Sound Source Orientation via Visual and Vibratory-coded Devices

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## ABSTRACT

People with functional hearing use environmental sound as one of the sources to obtain information and learn what is happening in the surroundings. However, this type of media becomes less beneficial for people who are deaf or with hearing loss. In this paper we propose several wearable visual and tactile interfaces enable deaf and hearing-impaired people identify in which of the eight cardinal direction is the sound coming from. The study compares various types of encoding scheme being displayed on different accessories including a smartwatch, a glasses, and a baseball cap for visual display devices. As well on the other hand, four vibro-tactile devices designed for three body locations are investigated: a hat, a belt, a wristband, and an armband. Prototype systems and applications are developed to evaluate performance and usability for each device and scheme through experimentations. 10 hearing-impaired subjects with different severity level participated in the experiment. The results showed an over all improvement in sound direction identification at over 60% in accuracy and half the time less in response period when using wearable devices. Moreover, we report on the users' preferences of accessories and display methods, and derive further suggestions for the design of wearable assistive devices.

## Author Keywords

Visual display; vibro-tactile display; sound direction; deaf; hearing-impaired; wearable assistive device

## INTRODUCTION

Environmental sound is one of the sources that contain crucial information which allow human beings to learn what is happening in the surroundings. We are less likely to get hurt by something easily avoided if we heard it coming. However, this type of information becomes less beneficial for people who are deaf or hard-of-hearing. A simple interview were conducted with six hearing-impaired participants who use hearing aids communicate and one of which uses cochlear

implants. We found a common agreement from all participants that the existing devices do not fully meet the needs of aiding them identify certain information of sound, namely the direction of the sound source.

Congenitally, regular human beings use the five traditional senses to perceive knowledge and information from the living environment; they are sight, hearing, touch, smell, and taste. It is clear that most of the time humans rely on hearing to comprehend the location of the sound based on its time and intensity difference [18]. Despite that the remaining sensors cannot obtain acoustic information, it is however possible for human to perceive and recognize directions by using visual and touch sensing stimuli. This can be proven from several other studies, e.g. [2, 7, 17], that implement visual and tactile interface for various purposes including navigation.

In our study, we propose using wearable device with visual and tactile cue display as a sensory aid to provide directional information of an environmental sound. The device aims to help people with hearing loss quickly identify the orientation of sound to create a better perception of the upcoming events. It is noteworthy that the main focus of this study is the evaluation of human factor and performance of such assistive devices. However, the actual sound source detection feature is not included as a part of the design.

Two experiments are conducted to compare performances and user feedback on different devices applied with various encoding scheme. The goal of the previous experiment is to eliminate, based on result, the types of encoding scheme that are inefficient, inaccurate, and least preferred by normal hearing user. Moreover, the first experiment is split into two parts (1A and 1B) in order to study the usability and performances of visual and tactile displays individually. In the second experiment, same procedure are carried out as the first but only the remaining display scheme are put to test. We ask hearing impaired participants to accomplish the test based on a controlled scenario. Audio equipments are added in second experiment to simulate the environmental sound in a real life setting.

## RELATED WORK

Research related to this study falls into two categories: tools for navigation, and tools for sound visualization. Many studies on human navigation systems and location-aware information services proposed various forms of wearable interfaces

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such as glasses, gloves, shoes, vests, and so on. Researches in regards with wearable tactile interfaces has been carried out, such as Cyber Touch [9], GentleGuide [3], a tactile display vest by Tan et al. [14], and ActiveBelt [17]. Cyber Touch can generate tactile feedbacks of objects in virtual world, using six vibrators attached on gloves. GentleGuide proposed a tactile navigation system via two bracelets. It outputs three commands, left, right, and stop. A pair of glasses enhanced with 4 vibrators and 3 microphones with the purpose to locate sound sources for visually and hearing impaired people was presented in [2]. In the meanwhile, we conduct an investigation with our approach using eight vibrators and various display patterns, which we believed users can obtain directional information more intuitively.

Two popular forms of wearable tactile interface are designed on vests and belts. Several applications of simulating directional lines and geometric patterns on tactile display are proposed in [14]. They attached a matrix of vibrators to the back of a vest, and tried transmitting directions and other information to user. Another research on tactile displays implemented a similar technique in aircraft cockpits [12]. The project used a vest-type tactile displays to provide pilots with navigational information. In our study, we tried scaling down the vest model to a size of an armband so fits on the forearm. ActiveBelt is an example of a belt-type tactile display. It is a waist belt with GPS sensor and eight vibration motors installed that enables users to obtain multiple directional information for navigation purposes.

Regarding to the enhancement of acoustic awareness for deaf people, many researches had proposed using visual feedback as wearable assistive interface. A glasses-type assistive device was designed to detect ambient sound from four directions by using various Microelectromechanical-systems (MEMS) microphones attached to the surface. Four LEDs are installed on the glasses to display directional estimation for deaf users [8]. The prototype device in the study successfully displayed the estimated direction to user via visual display. However, instead of investigating usability and preferences via visual interface, the research was mainly focused on the algorithm used for estimating direction. Hence, there were no experimentation conducted with real participants nor discussion related to its design. A British artist and designer elaborated a project to design a pair of shoes that is capable to navigate its owner to any destination using build-in GPS and light indicator on the shoes [19]. Although the interface design sufficiently displayed directional information to user, but due to the fact that the shoes are normally not within sight, it is unable to provide immediate notification when necessary.

Another approach using augmented reality system to assist hearing impaired visualize sound source location in indoor settings were proposed in [13]. The system recognized the sound source and its location using acoustic processing. Then it notifies the user through different visual markers by augmented visioning. In addition, several other researches investigate types of forms of visual display and display devices for providing awareness of environmental audio to deaf individuals. The studies include evaluations of various figure

representation such as iconic imagery, spectrograph, and ripples, that will be exhibited on large displays, for instance, personal computers, televisions, and even ceiling [7, 10, 11, 16]. All the previous works mentioned seems to be promising to deliver useful information. They are, however, lacking the characteristic of mobility and feasibility in outdoor settings.

In conclusion, many related works had been done previously to report the usability and performances of visual and tactile devices. However, most of them are aimed to provide directional information solely for navigation purposes. Others proposed application for helping the deaf improve their acoustic awareness with certain types of device, but they are only applicable on certain parts of the body location. There are no comprehensive comparison and evaluation between all the possible interfaces and display methods of sound source localization for people with hearing loss.

## PROTOTYPE AND PATTERN DESIGN

Each prototype devices is designed to convey signals in eight directions corresponding to user's position. This was proposed in [15] to minimize the perceptual error. A set of visual and vibro-tactile encoding schemes suitable for directional pointing of target angles in the complete 360°-range are mapped out and shown in figure 1 to 4.

### Visual Devices

Three types of accessories are used to implement in visual display: glasses, baseball cap, and smartwatch. Due to the shape and size of each device are distinctively different, it would be difficult to design just one or same types of display pattern to fit on all devices. As a result, three different types of encoded cues are designed for each accessory at the beginning. However, except for smartwatch which uses its native display panel and runs a micro App to display directional imagery, the glasses and baseball cap are both equipped with multiple yellow-greenish LEDs to indicate the direction of a sound source. Device detail and design patterns are described.

#### Glasses

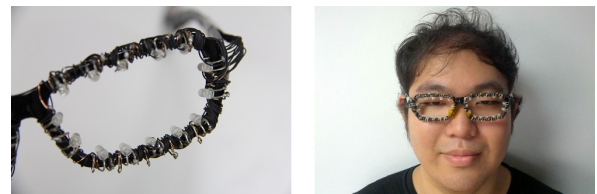


Figure 5. LED glasses.

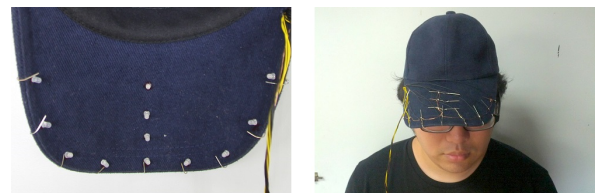


Figure 6. LED cap.

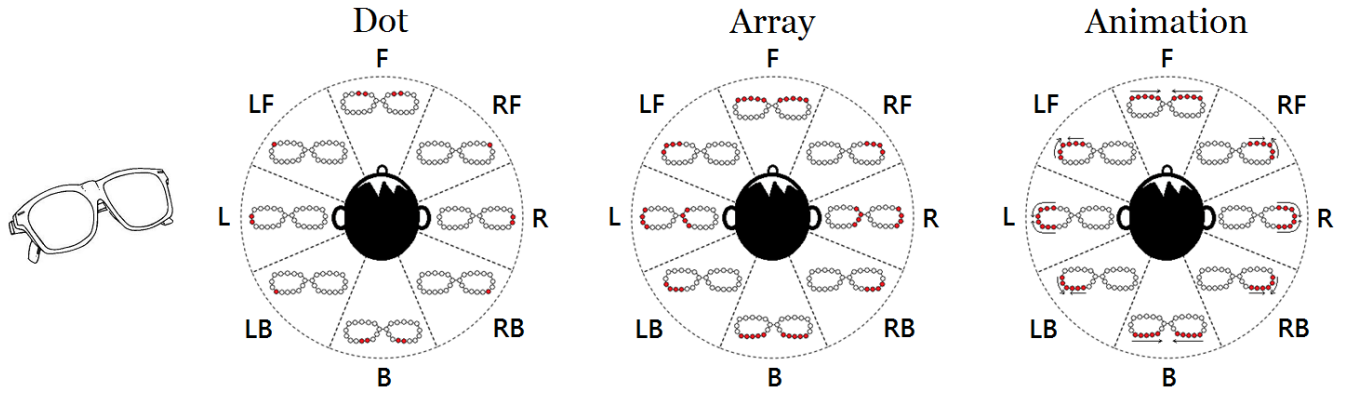


Figure 1. LED glasses pattern schemes.

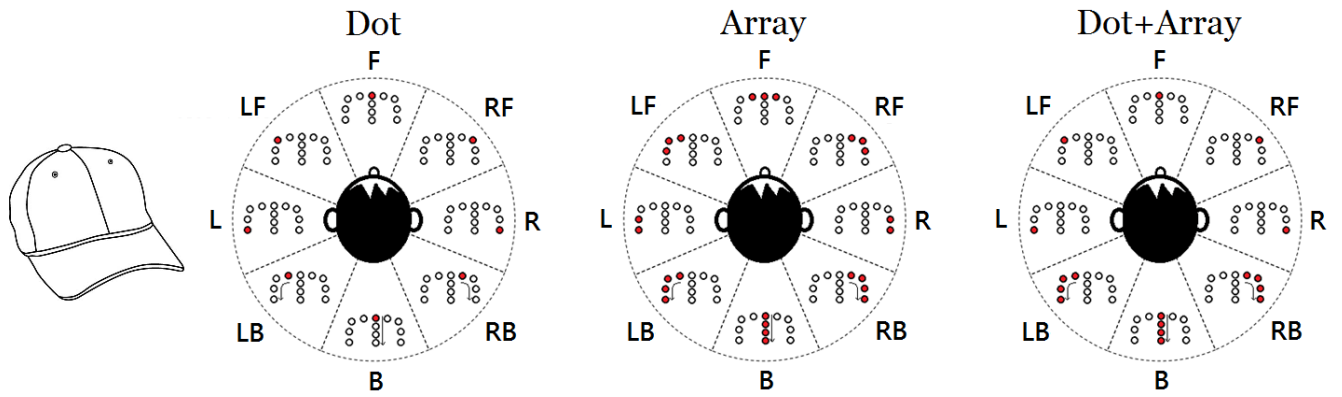


Figure 2. LED cap pattern schemes.

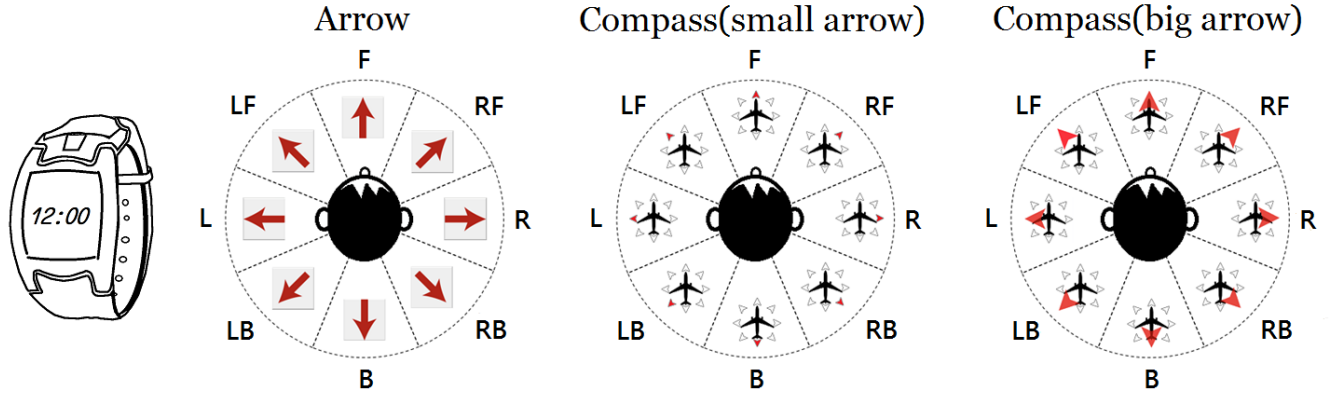


Figure 3. Smartwatch pattern schemes.



Figure 7. Smartwatch.

To perform complex display patterns, a high density LEDs setup is installed around the glasses frame. We use a regular lensless glasses as the base of the prototype (see Figure 5). Small holes were drilled around its frame in order to install LEDs. Electrical wires are connected to the LEDs and strapped around the frame rims and bundled alongside the temples (see Figure 5). There are 28 LEDs in total (14 on each side of the glasses), and they are evenly distributed across the frame rims in a circular formation. The tip of LEDs

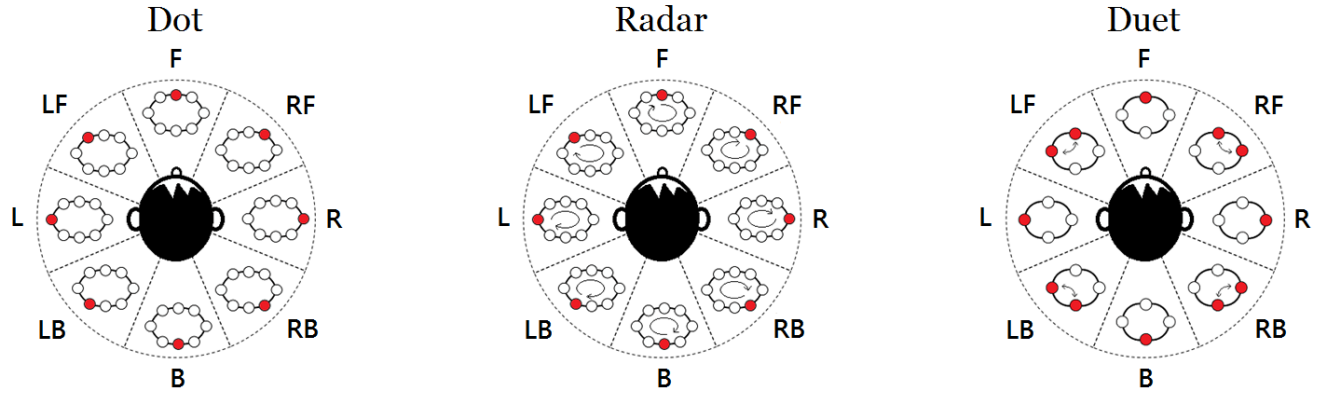


Figure 4. Vibration devices pattern schemes.

are bent inward to point at the user's eyes so the light can be seen easily while emitting.

Three patterns are designed to be used on glasses, which are: "single-double", "light array", and "tail tracing". In the first two patterns, all configured LEDs blink together continuously, whereas in the third configuration the LEDs are turned on in a gradual motion and turned off the same way recursively, similar to an electronic marquee.

In the "single-double" setting, the glasses indicate four relative directions (front, back, left, and right) using two or a pair of two LEDs which blink simultaneously; and only one will blink at the corner when indicating diagonal directions. In the second pattern, "light array", a whole set of LEDs are lit up together on each side of the rim representing the respective direction. Diagonal directions are performed by lighting up multiple LEDs on each corner. The last pattern is more complex; front and back are displayed in sliding motion, which will appear to user as two beams of lights running through the rim entering from each side of the glasses and disappearing in the middle. Whilst left and right are presented with lights running from mid-top and mid-bottom rims toward the according side, then disappear at the point where both light beams meet on the side of the glasses. For diagonal direction, both side of the adjacent rims of the corresponding corner lights up in gradual motion toward the corner itself then disappear in same order as appearance.

Since the surface of the glasses is flat and vertical, our designed pattern are then displayed in a vertical format. Therefore, it is necessary for user to remap the given directional information from vertical to horizontal space. For instance, if LEDs are blinking on the top rim of the glasses, it means that the sound is coming from the front relative to user. On the other hand, if LEDs blink on the bottom side of the glasses, it indicates the sound is coming from behind. It is considered that some user may think reversely (i.e., top as back, and bottom as front) due to intuition or by custom. We put this aspect in observation with the experiment by asking users whether they felt the need to reverse the setting.

#### LED Cap

A normal-sized baseball cap is used for the study. It has bill of approximately 17.78 cm (7 in.) x 9.5 cm (3.74 in.) in dimension. LEDs are installed on the bill of the cap in the shape of a trident tip (see Figure 6). The LEDs are pinned through the bill and facing down toward the user. Wires are connected to the LEDs on top of the bill and bundled on the right corner of the bill.

Different than the glasses, we are able to design a set of horizontal display patterns since the bill is close to a flat surface. Nonetheless, when it is worn, the area of which human eyes can see using peripheral vision is limited. We propose three display patterns which are "loading dots", "progress bar", and "combo loader".

Three types of display patterns are designed based on the arrangement of the trident-shaped LEDs setup. "Loading dots" pattern performs orientational information using only one LED for all directions in the field of view (FOV), (i.e., front, left, right, front-left, and front-right). The remaining three directions on the back are displayed by using single LED which jumps backward toward the user's head. The second method, "progress bar", turns on two or more lights to present directions in the FOV. For the three backward directions, it is displayed with a bar of LEDs lit backward progressively. The last pattern is a combination of previous two; it is composed of single blinking LED for FOV angles and the display patterns of "progress bar" for backward directions.

#### Smartwatch

We use *WIMM One* smartwatch manufactured by *WIMM Labs* for wrist-worn prototype (see Figure 7). The smartwatch runs on a modified Android platform of version 2.1, and it is equipped with a 160 x 160 pixel, 2.5 cm (1.0 in.) square display. For this study, we created a micro App to display images to represent directional information. The difference between smartwatch and other devices is that it uses native display panel to show directions rather than using LEDs. Plus, it uses the build-in vibration feature as part of the notification alert.

Using different designs of imagery, we proposed three types of representation of directions. They are "single arrow", "basic compass", and "big pointers". The first type displays



large arrows to indicate directions, and each arrow occupies the whole display which allow user to see clearly. The second design implements similar concept as a compass; with eight arrows pointing at eight cardinal directions on the panel, one of which is colored in red at a time to indicate direction. An image of an airplane is put in the middle to show the relative orientation to the colored arrow. The third type is fairly identical to the second except the size of the colored arrow is significantly larger than the rest when directions are displayed.

### Tactile Devices

Four accessories are designed to perform experiment: hat, belt, wristband, and armband. We evaluated a wide range of vibrators and selected coin-shaped vibrators with a diameter of 10 mm (310-103 Vibration Motor 2.7 mm Button Type from Precision Microdrives) that have been developed for vibro-tactile feedback in hand-held applications. In order to clearly distinguish each individual vibrator and prevent misinterpretation, isolating shock waves between each vibrators is fairly important. Since the shape and vibrator arrangement of all tactile devices are similar, all of the designed patterns for tactual sense are suitable for every device. Therefore, the patterns will be lastly introduced after device description.

#### Vibration Hat

The hat is composed of soft material which aimed to avoid unwanted propagation of vibration sense through conduction. Eight vibrators are distributed evenly around the hat (see Figure 8).

#### Belt



Figure 8. Vibration hat.



Figure 9. Belt.

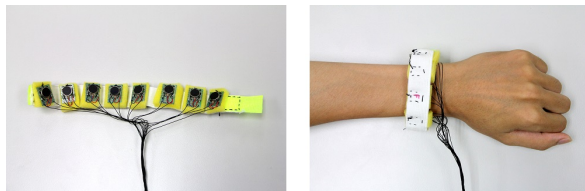


Figure 10. Wristband.

Since every user's waistline is predictively different. We designed a universal-size belt that consists of adjustable clips in which the vibrators are attached and elastic strip fit to majority of the users (see Figure 9). Moreover, to ensure the output is strong enough to be sensed through clothings, we use cylindrical-shaped vibrators with diameter of 5 mm, length of 20 mm to perform stronger vibration.

#### Wristband

The watch function is unconcerned in the study of tactile design. Therefore, we emulate the integration of vibro-tactile interface into a watch band by enhancing a wristband with vibrators which are arranged circularly around user's wrist (see Figure 10). We have wired each vibrators loosely on an elastic band and every vibrator is fixed on a foam-rubber cushion to isolate the shock wave from each other.

#### Armband

Different from the previous accessories, this device is made up of a square-shaped vibration array that will be strapped onto the back of user's forearm using a semi-elastic sport bandage (see Figure 11). As the design of the wristband, each vibrator is positioned on an isolated foam-rubber to prevent unnecessary conduction. The size of vibration array is 10 cm x 10 cm.

#### Patterns for Tactile Device

Thinking of possible patterns that can provide directional information by vibrators, we design four distinguish patterns in the beginning: "single pointer", "radar search", "singular radar", and "alternate-cornering". All of the patterns are running in a continuous on-off fashion.

The first pattern is performed by single vibrator activated at a time to represent individual direction. In the second display pattern, all vibrators are turned on one after another in clockwise order starting from the pointing direction with a longer pulse of vibration.

The third display pattern is a combination of the first and the second; two vibrators are activated at a time but only one is circulating in clockwise order, and the other one vibrates on a fixed location of certain direction. The last pattern is operated using four vibrators; four absolute directions: front, back, left, and right are performed by single vibrator allocated on relative location like the first pattern, and the corner directions is represented by nearby two vibrators activating alternately. For example, front-right is indicated by vibrating front and right unit alternately.

Each of the designed patterns are proposed to withhold certain advantage. Discard the first basic pattern for instance, we

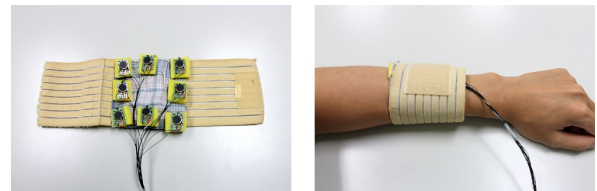


Figure 11. Armband.

hypothesis the alternate-cornering can reduce the difficulty of distinguishing the vibrator in high density array settings; radar search can help user easily recognize relative position of each vibrator in the array; and the singular radar will present the one direction in fixed position continuously therefore easier to grasp.

Before the experimentation, a five-person pilot study is conducted to test all proposed patterns. We discovered that the third pattern is relatively hard to identify directions. User often misinterpret the position of vibrator when there are two or more vibration presented at a time. As a result, only single pointing, radar search, and alternate-cornering are chosen to perform in experiment.

## EXPERIMENT 1

### Experiment Description

Our primary interest in experiment 1 is to understand which devices and which patterns are intuitively chosen by the users. The experiment requires participants to wear each of our devices alternatively and perform the experimental tasks. In each task, participants are asked to interpret directional information that our device delivered. At the end of the experiment, we filtered out the inefficient patterns and devices by analyzing the error rate and response time of each participant which are recorded during experiment. The first experiment is separated into two parts (experiment 1A and 1B) for the purpose of alleviating task loads per experiment. Therefore we will conduct the study and evaluation of visual and tactile devices separately.

### Apparatus

The experiment was conducted using a mobile device (*Galaxy Nexus*, running Android platform ver. 4.2.2), an Arduino Mega 2560 R3 (a bluetooth module, *Bluetooth Bee* is added to the board), and the proposed wearable devices. The wearable devices are connected to Arduino. They can be remotely controlled via bluetooth using a mobile application we created for the exchange of task commands between hardware and recording user's answer during experiment.

### Participants

Since the purpose of the experiment at this stage is to pick out the most efficient and intuitive devices and patterns, users hearing ability is not directly relevant to the outcome. Therefore, we found 20 hearing individuals (8 males, average 22.6) volunteered to participate in the first study. The participants are in a variety of academic backgrounds, such as advertising, management, ocean engineering, computer engineering and etc. Regardless of age, we distribute the number of participants evenly in terms of gender to take part in each of the experiment (1A and 1B).

### Procedure

The experiment for tactile devices consist of 12 tests (3 cue types x 4 devices), and 9 tests (3 cue types x 3 devices) for visual devices. The tests are sub-divided into sets of 3 (3 patters per device). Each test include 16 trials of tasks (2 repeated tasks for each of the eight cardinal directions given



Figure 12. Mobile application for answer selection.

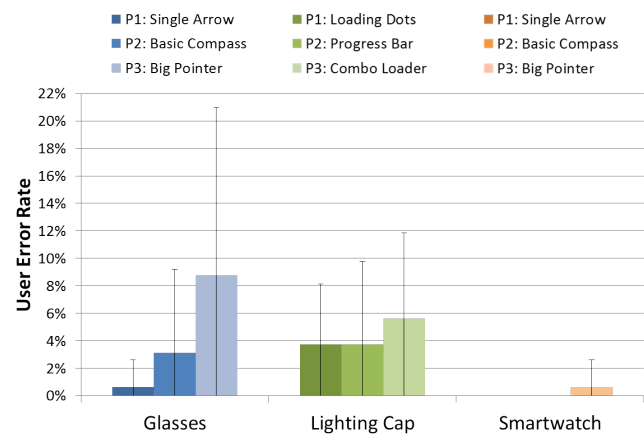


Figure 13. Mean error rate: Visual devices.

in random order). At the beginning of each test, we briefly explained and demonstrated the device and its pattern. Participants are given 90 seconds to learn each pattern on their own in practice mode. During the test when each pattern are presented, participants were instructed to choose an answer from the mobile screen as fast and accurate as possible (see Figure 12. 10 seconds were given for each trial to make selection otherwise the system automatically skips to next question. The order of the devices and patterns in each part of the experiment was counterbalanced. The system records the response time and selected answer of each device and pattern. At the end of each test set, participants were asked to fill in a short questionnaire providing comments and ratings for each of the pattern using a Likert scale. Lastly, after all tests were finished, participants were asked to give ratings for each device. Any further comments or feedbacks are also recorded in the questionnaire.

### Experiment 1A Result: Visual Display

Unlike tactile devices, the patterns designed between each wearable visual device are irrelevant to each other. Hence the result for each device is discussed separately. Figures 13 and 14 summarize the detection results of Experiment 1A. Both first and second pattern of smartwatch has gotten 0%

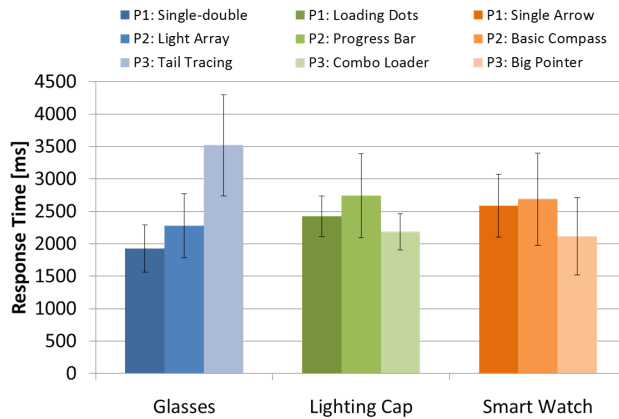


Figure 14. Mean response time: Visual devices.

error rate. Although the third pattern has an error rate of 0.63% higher than others, it is still considerably low. Surprisingly, the response time for third pattern of smartwatch is the shortest (2114 ms); about half a second faster than the others. This difference is confirmed by repeated-measured ANOVA (RMANOVA),  $F(2,8)=11.563$ ,  $P<0.05$ . Few participants stated that the distinctive size of the indication arrow makes it easier to identify. And overall, smartwatch has the lowest error rate among all devices whereas in contrast, LED cap obtained the highest.

The error rate of pattern three for glasses is noticeably higher than the others (9.09%), but the first pattern is only 0.63%. However, RMANOVA shows no significant difference in between the three. In terms of detection time, there was a statistically significant difference,  $F(2,8)=24.470$ ,  $p<0.05$ . The response time for pattern three exceeded the first by almost 1500 ms. This result match with the statement from two of the participants: “First pattern of the glasses is sufficient and clear, and the animation used in the third pattern is time consuming and sometimes confusing.”

Error rates of the first and second pattern for cap are the same, both at a rate of 3.75%. Even though the third is a bit higher (5.63%) than the rest, the response time for third pattern is however the shortest among the three at 2187 ms. RMANOVA shows a significant difference of response time ( $F(2,8)=7.006$ ,  $P<0.05$ ) among the three but not error rate. Most participants said the first single blinking pattern is enough and better than the second, and few of them mentioned that the difference between the two methods showing backward directions are unnoticeable. Overall, by the scale of preferences, cap is voted the most preferred whereas glasses are the least. Although error rate of the glasses is a bit lower than cap, half of the participants reported that the blinking LEDs in front of their eyes makes them uncomfortable.

### Experiment 1A Conclusion

The performance of the smartwatch is relatively high in terms of high accuracy. Since the smartwatch use simple imagery to display directional information, it is fairly easy for users to understand at a glance. We also discovered that when using relative positioning and referential sizing of icons to present

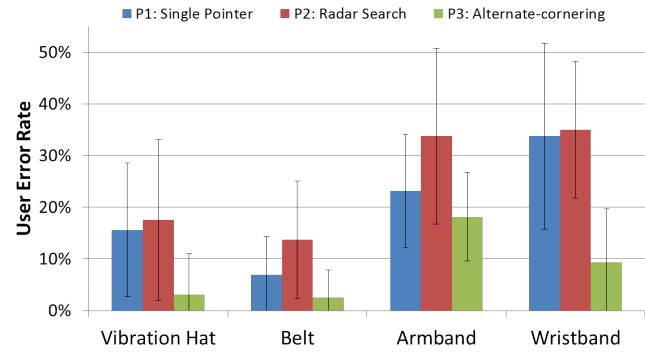


Figure 15. Mean error rate: Vibro-tactile devices.

directional information will raise the efficiency and intuitiveness for users to determine.

The glasses have the lowest error rate in one of the patterns which use two or less LEDs and simple blinking to represent directions. As the amount of LED lights increase, the performance and comfort level decreases dramatically. It is caused by two reasons: 1) one is that the brightness level is too high therefore brings burden to the eyes, and another is that 2) the surface of the glasses is too small to display complex patterns, it causes confusion when information are crammed together or overlaps each other. However, if appropriate lighting and position is considered when displaying information near the eyes, the outcome can be efficient. Due to the fact that when information is displayed, the interface can directly and immediately interact with the user’s eyes on sight. Users are then unlikely to miss important notification. Also, this process would not require too much physical activity to access the intended information, such as moving the head or raising the arm.

Lastly, the preference of the patterns on the cap shows a common principal as the glasses, “the simpler the better”. Users tend to prefer single blinking LED than complex and overlapping. In conclusion, for this experiment we have selected three patterns, big-arrow compass, single-double, and light jumper, one from each device to continue with the second experimentation.

### Experiment 1B Result: Tactile Display

The results from experiment 1A are summarized in Figure 15 and 16 showing detection error rates and response times respectively. The result of which is statistically significant ( $F(11,108)=9.137$ ,  $p=0$ ). The first pattern has shortest response time on every device (from 2290 ms to 3090 ms). Almost all users said that it is difficult to distinguish patterns when the density of the vibrators is too high, such as wristband or armband. The second pattern has high marks on both error rate (13.7% to 35%) and response time (3540 ms to 4480 ms). On contrary, the third pattern has the lowest error rate with a significant difference ( $p<0.05$ ) on every device but however the response time is nearly equal to first pattern, and



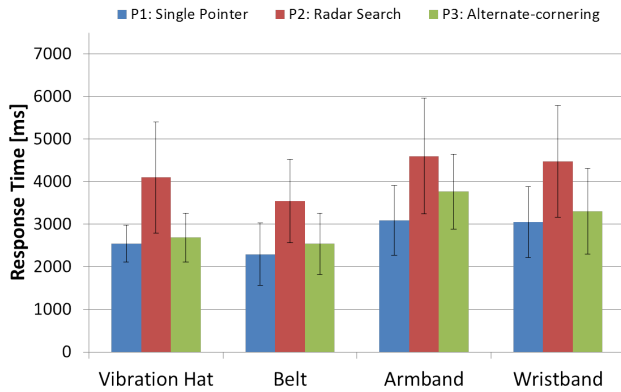


Figure 16. Mean response time: Vibro-tactile devices.

the users reports the direction can be clearly distinguished. Among all tactile accessories, armband has the highest error rate of 18.8% to 33.8% and response time of 3090 to 4600 ms on all patterns. It is evident in the questionnaire that armband is the least preferred overall.

### Experiment 1B Conclusion

During the pilot study, we know that it is confusing for user to distinguish the pattern of vibration if there are more than one vibrator activate at the same time. Since the tactile sense will be disturbed when the vibrators' position are near. Our result show the armband and wristband have high error rate due to the high density of vibrators. The reason for this issue is caused by the design limitation of small surface contact area on the wrists and arms. And we also suspect that it was caused by the long time lapse between each cycle. Overall, the third pattern performed better than the second pattern in terms of the error rate and response time. This difference is statically significant ( $p < 0.05$ ). In addition, we found that complex patterns will result in skin numb.

Although the error rate of third pattern for wristband is relatively higher than those in belt and hat, its performance, is however higher than the other two patterns. Since the third display method reduced vibrator density into half by cutting down units of vibrators to four. This is evident that the error rate of the first pattern on both belt and armband is lower than pattern two ( $p < 0.05$ ). In addition, its performance is similar to the third pattern on the same devices. However, from the questionnaire, we observed a higher preferences by users on the third pattern due to its clear and easy to comprehend display pattern. In conclusion, we've selected pattern three of all devices to continue the study for the next experiment.

## EXPERIMENT 2

### Experiment Description

This part of the study was designed to evaluate the usability of our devices and feedbacks selected from the previous experiment for the hearing impaired in particular. We conducted analysis on user's workload for each test by using NASA Task Load Index (TLX), a subjective, multidimensional assessment tool that rates perceived workload based on six aspects: mental demand, physical demand, temporal demand,

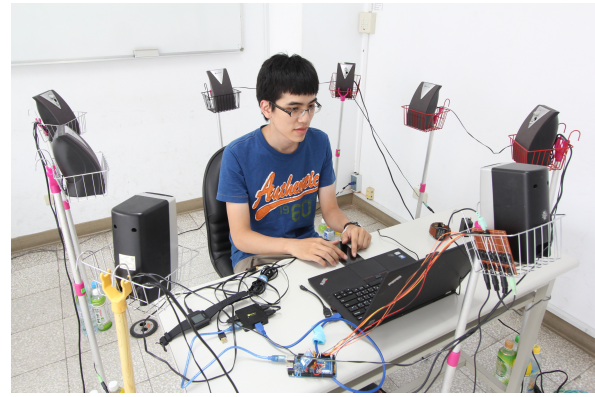


Figure 17. Test environment setup for experiment 2: Participants is surrounded by 8 speakers, and a laptop is set in front of the subject.

performance, effort, and frustration. In addition, users preferences on each accessories are accessed during a short interview. In the second experiment, all of the proposed devices and remaining display patterns chosen from the previous experiment will be used. In short, there are three goals to reach and discuss in this experiment: 1) investigation of perceptual assistance of sound source direction for people with hearing loss, 2) the comparison of efforts among completing tasks between each devices, and 3) explore user preferences from ratings and feedbacks.

### Apparatus

Six devices are compared in the experiment: glasses, LED cap, smartwatch, vibration hat, belt, and wristband. The armband was taken out of the list due to its low performance and cause of frustration to the users.

The tests were conducted in a sound environment in order to simulate real life scenario. The subject was seated in the center of a circle (diameter 2 m). Eight loudspeakers were placed on the periphery of the circle with a  $45^\circ$  separation to represent the sound source of eight directions (see Figure 17). During the test, an Arduino was used to choose which speaker to play the sound. A sequence of car horn in traffic were played by one of the eight speaker to simulate an incoming sound from the according direction. All loudspeakers are measured to play at the volume of approximately 65~70 dB. At the meanwhile, tactile or visual device will perform the cue pattern corresponded to the direction of the playing speaker. A laptop was set in front of the participant to display the simulation video.

### Participants

10 hearing impaired participants (4 females, average 29) took part in the second experiment, Subjects were students and school staffs recruited from campus. There are 2 moderately deaf, 5 severely deaf, and 3 extremely deaf. Nine participants wear hearing aids in daily bases, and two of them have cochlear implants. During the experiment, all participants were asked to configure their hearing instruments to normal settings used in daily life in order to prevent biases.

### Procedure



The procedure in experiment 2 is similar to experiment 1, except that participants were asked to look at the video played on the laptop. The test was to simulate a driving scenario which the subjects was told to be either a car driver, a motorcyclist, or a bicyclist as they wish. Subjects determine the direction till received an indication of a directional signal either from the playing speaker or from the wearable device. The experiment was structured into 7 tests. The first test investigates subject's ability of identifying sound direction without the help from our device. Participants in the first test wear only hearing aid and/or cochlear implant. Later on, 6 wearable devices were put on to complete the rest of the tests. The order of devices in each experiment was counter balanced.

As the previous experiment, 16 trials of randomly generated tasks are presented in each test. Participants are given 90 seconds to memorize the cue patterns. When the test begin, participants have 15 seconds to select the accounted direction. We recorded the response time and answers of each trial throughout the experiment. At the end of each test, a TLX questionnaire were filled by participant. And for each device, the comfort level, efficiency and willingness of use were rated respectively. Lastly, after all the tests were finished, a cross-device comparison of the same questions was accessed and put into order from the most favorable to the least.

## Experiment 2 Result

After the experiment, we recorded the response time and calculated the mean error rate of each participant with each device. The results are summarized in Figure 18 and Figure 19. The chart shows the calculated results of experiments conducted with subject's own hearing instruments and the rest of the devices we designed. As shown in the chart, when participants are not wearing any of our devices, an average error rate of 64.38% were presented in the first tests. An analysis of variance showed this difference to be highly significant ( $F(6,63)=69.632, p=0$ ). The lack of accuracy is significantly higher than when the devices are worn ( $p<.00001$ ). Among all proposed devices, the wristband has the highest mean error rate at 10.63%. On the other hand, smartwatch and vibration belt have the lowest average in error rate with 0.63%. Nonetheless, except for wristband, vibro-tactile devices has relatively lower or equal error rates to visual display devices.

In term of time consumption, vibration hat has the shortest response time in average (2538 ms) among all the vibro-tactile devices. Whereas the wristband had the longest response time at 3740 ms. Smartwatch on the other hand, has the shortest mean response time at 2149 ms, with a close match to the glasses at 2253 ms. The LED cap in this case consumed a bit longer time with 2716 ms. From the result of the NASA-TLX ratings, vibration wristband had the highest mark on all sub-scale in NASA-TLX, and smartwatch was the second highest in physical demand (see Figure 20).

To fit the condition in daily life, when smartwatch is worn, we instructed the participants to rest their arms before each notification is presented to prevent them from looking at the screen constantly. For this reason, more physical activity is required to obtain information. This argument is confirmed

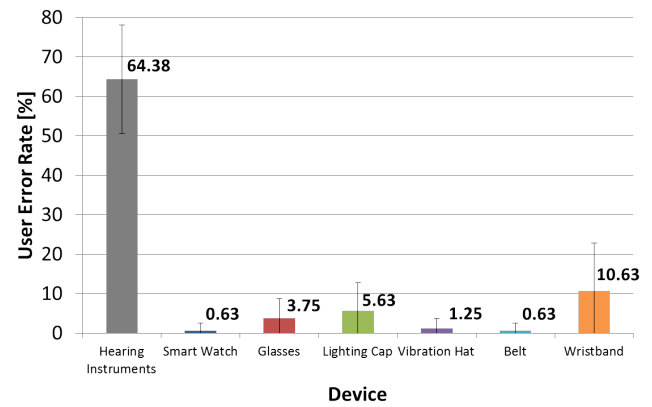


Figure 18. Mean error rate: All devices.

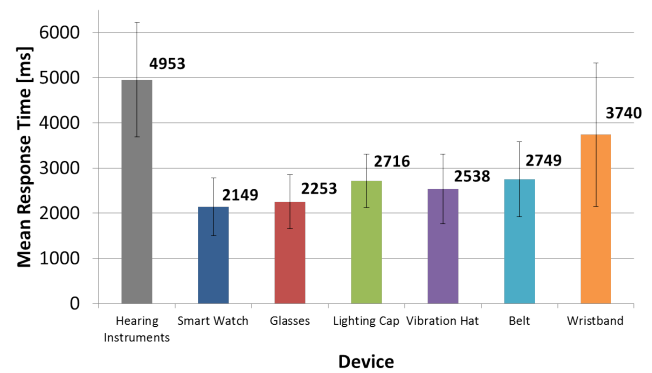


Figure 19. Mean response time: All devices.

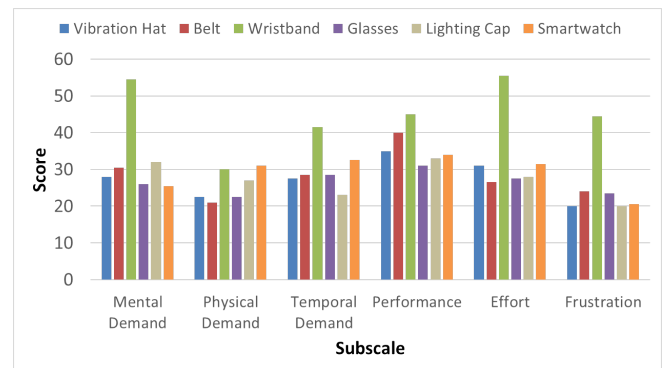


Figure 20. Mean score of NASA Task Load Index for each device.

by the NASA-TLX scale, which shows the smartwatch received higher score on physical demand than any other devices. However, this result does not correspond to the mean response time recorded from the tests (2149 ms, the lowest among all). Furthermore, the result stated that the average response time of vibration devices (3009 ms) are longer than those of visual devices (2373 ms) except for the LED cap.

## Questionnaire

In addition to the workload index estimated by NASA-TLX. The participants assessed 3 statements at the end of each 6 de-

vices about the intuitiveness of recognizing sound direction, the comfort level of the display method, and the willingness to use our devices. A continuous rating scale from 1 ('strongly disagree') to 5 ('strongly agree') has been used and the participants had to give a score depending on the agreement level of the statement. At the end of the questionnaire, the participants had the opportunity to answer several open questions in regards to improvements and general comments.

The visual devices (smartwatch, glasses, and LED cap) were evaluated more efficient than the vibration devices (vibration hat, vibration belt, and vibration wristband). However, three participants mentioned that they spent more times to memorize the patterns of LED cap than others. Smartwatch was rated as the most intuitive device. In contrast, vibration wristband was rated the least. Almost all of the participants reported that it is difficult to identify the vibration signal from the wristband since vibration units are too close to each other. *"It feels like the whole wrist is shaking,"* stated by two of the participants. Few participants mentioned that recognizing diagonal directions in vibration belt and hat are time-consuming. Since two vibrators are activated alternatively, it requires user to make sure two vibrators are presented in order to determine directions. Two of the participants said that it is hard to distinguish the lights on the lower corners of glasses from the bottom; one due to the reason of *"too close to each other"*, and other might be caused by nearsightedness.

In comparison of comfort level, smartwatch was rated the most comfortable whereas vibration hat was rated as the least. Besides, three participants mentioned that noise and disturbance was caused by vibration to the hearing aids while using vibration hat. Some said that they felt uncomfortable by the sudden shock of vibration. In addition, few of participants stated that the lights on the LED glasses are too bright.

Most participants showed a high willingness of using smartwatch. On the contrary, vibration hat received the lowest score in willingness. Furthermore, we noticed that younger participants find LED cap more helpful than the elder ones. They assume the reason might be that younger users have better performance in remembering the patterns than the elders.

### Experiment 2 Conclusion

After experiment 2 was conducted, it is clear that our devices has significantly improved users perception on sound source direction detection. Even though most tactile devices have relatively low error rates than visual devices, user feedbacks from the questionnaire shows a higher intuitive level of visual devices than that of tactile devices. This explained why visual devices had shorter response time than most tactile devices. Moreover, from the questionnaire, it seems that the factor of which the willingness of using a device is firstly based on the level of comfort instead of its efficiency. It also showed that the vibration hat, LED glasses, and smartwatch can cause distraction to user's attention. Although more than half of the participants complained about vibration hat, its error rate is surprisingly low. Therefore, without effecting the performance, we believe the discomfort of the vibration can be improved through adjustment of intensity and a better hardware design.

### CONCLUSION AND DISCUSSION

We have proposed several design of wearable devices with different display methods. The study focused on supporting auditory perception for people with hearing loss to recognize directions of environmental sound. Experiments were conducted with both hearing and deaf individuals to evaluate various type of visual and vibratory-coded devices. Our results showed a significant improvement in deaf users' acoustic awareness to sound source direction when our devices are implemented. Furthermore, we discussed the usability and performances on each of the device and proposed encoding schemes based on several aspects, which are level of comfort in regards of the display methods, intuitiveness on recognizing cue patterns, and willingness to use such devices.

Our findings have a number of implications for the use of wearable visual and vibro-tactile interfaces. We discovered human's vision and tactile sensory capability is limited in processing complex information, especially when it is encoded. Using imagery information or simple coded pattern to represent direction is more efficient. Using of appropriate lighting intensity to avoid blinding or exhaustion to human eyes is critical. On the other hand, human's sensibility to vibro-tactile stimuli is also varied on different parts of the body location. For instance, head and waist are highly sensitive to tactual stimulation. But due to the reason that these body parts have larger surface contact area than wrist or arms. Therefore, even though users felt uncomfortable or ticklish when tactual sensation are applied on these body parts, they however performed a better result in directional interpretation. Furthermore, it is important to avoid a design with high density vibrator display.

As part of the result, smartwatch seems to have a good performance and high preferences overall. Since users tend to prefer using direct imagery to present directional information. Whether or not it would be useful if they are presented directly in sight is an interesting topic to discover. A possible implementation is using heads-up display to perform imagery information directly to users eyes. Without the need of extra physical activity such as moving the head or raising the arm, it may introduce less interference to user's visual attention to the environment, and may as well improve reaction time.

Another question we are interested to find out is how to express different types of characteristics of sound simultaneously through visual or tactile expression. For example, an interface that can display not only directional information of sound but intensity, distance, level of emergencies and other factors that can help people with hearing loss improve perception and awareness of the environmental sound.

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