Visualizing non-speech sounds for the deaf

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Visualizing Non-Speech Sounds for the Deaf

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ABSTRACT
Sounds constantly occur around us, keeping us aware of our surroundings. People who are deaf have difficulty maintaining an awareness of these ambient sounds. We present an investigation of peripheral, visual displays to help people who are deaf maintain an awareness of sounds in the environment. Our contribution is twofold. First, we present a set of visual design preferences and functional requirements for peripheral visualizations of non-speech audio that will help improve future applications. Visual design preferences include ease of interpretation, glance-ability, and appropriate distractions. Functional requirements include the ability to identify what sound occurred, view a history of displayed sounds, customize the information that is shown, and determine the accuracy of displayed information. Second, we designed, implemented, and evaluated two fully functioning prototypes that embody these preferences and requirements, serving as examples for future designers and furthering progress toward understanding how to best provide peripheral audio awareness for the deaf.

Categories and Subject Descriptors: H.5.2 User Interfaces: *Auditory (non-speech) feedback and strategies; user-centered design*. K.4.2 Social Issues: *assistive technologies for persons with disabilities*

General Terms: Human Factors, Design

Keywords: Sound visualization, peripheral display, deaf

INTRODUCTION
Sounds constantly occur around us, keeping us aware of our surroundings. Ambient sounds give people an understanding of serendipitous events (coworkers socializing in the hall, neighbors arriving home upstairs, children playing in the next room), problematic things (faucet dripping, fire alarm low-battery indicator, cell phone ringing at inappropriate times), and critical information (fire alarm, knocking on the door) relevant to their current situation or location. However, maintaining this awareness is difficult for people who are deaf.

Though there are some tools to notify people who are deaf of particular events, such as the phone, doorbell, or fire alarm, there is no tool that provides a continuous awareness of all the sounds in an environment. People who are deaf use techniques to maintain awareness, such as relying on vision or sensing vibrations in the ground, but not every sound creates a vibration or leaves a visual trace. Sounds like knocking on a door or coworkers socializing in the hall can go unnoticed. In the present study we extensively explored the design of peripheral, non-speech sound visualizations (see Fig. 1). We built upon past results [6], answering the following design questions with people who were deaf:

- In what places do people who are deaf want to know about the sounds around them (*e.g.,* at home, work, or while mobile)?
- What display size is preferred (*e.g.,* a PDA, PC monitor, or large wall screen)?
- What information about sounds is important to people who are deaf (*e.g.,* sound recognition, location, or characteristics like volume and pitch)?
- What visual design characteristics do users prefer?
- What functional issues are important to people who are deaf in a visualization of non-speech sounds?

We developed a rich set of design preferences and requirements based on interview results, implemented two prototypes, and conducted a summative evaluation.

Our contribution is twofold. First, we present a set of visual design preferences and functional requirements for peripheral visualizations of non-speech audio that will help improve future applications. Visual design preferences include ease of interpretation, glance-ability, and appropriate distractions given information importance instead of more detailed information or one type of notification (*e.g.,* only minimal distractions). Functional requirements include the ability to identify what sound occurred, view a history of displayed sounds, customize the information that is shown, and determine the accuracy of displayed information.

Second, we designed, implemented, and evaluated two fully functioning prototypes that embody these preferences and requirements, serving as examples for future designers and furthering progress toward understanding how to best provide peripheral audio awareness for the deaf.

Although Ho-Ching *et al.* [6] also conducted interviews with deaf participants, they did almost no exploration of visual design with people who were deaf before building prototypes. We conducted design interviews with people who are deaf and gathered a rich set of design preferences and requirements that are representative of our users. Also, in their evaluation of two displays, Ho-Ching *et al.* focused *quantitative* metrics (awareness and distraction) while our work complements theirs by focusing on *qualitative* feedback about a wider variety of designs and metrics.

In the next section, we discuss related work in assistive technology for the deaf, which tends to focus on sign language translation and recognition. Then we describe our design interview method and results, which led us to develop two displays making use of non-speech sound recognition. We next present details of our implementation, and describe the evaluation of our system, which

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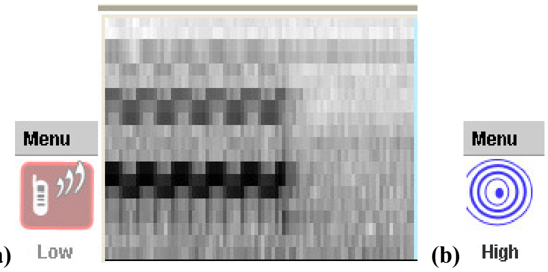
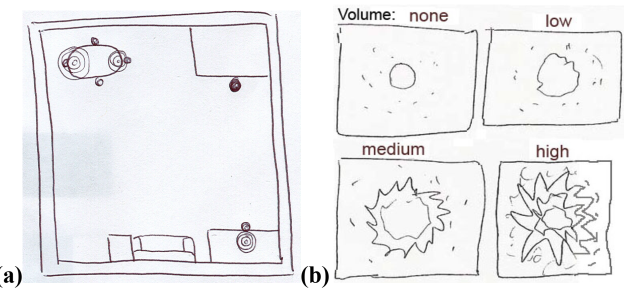


(a) (b)

Figure 1: **(a)** Implemented version of Spectrograph with Icon showing a phone ringing. This initial prototype places the spectrograph and icon windows side-by-side. **(b)** Single Icon showing a loud unrecognized sound with low frequency.



(a) (b)

Figure 2 (a) Map showing locations of sounds with rings. (b) Ambient Visualization showing a range of volumes, from none (top left) to high/loud (bottom right).

highlighted the importance of history as a key feature of such displays. We conclude with a discussion of future work.

RELATED WORK

Ethnographic research studying the Deaf culture helps us better understand how to approach research to support people who are deaf [9]. The terms *Deaf* and *Hearing* are used to emphasize communities with socialization, acculturation, and identity differences. Ethnographies have highlighted a cultural identity among the Deaf that is distinct from physiological deafness. Given this cultural distinction, we recruited both participants who were deaf and Deaf. Throughout the paper, we will refer to d/Deaf as “deaf” and h/Hearing as “hearing.”

Assistive technology research for the deaf has focused on support for verbal communication. Examples include automatic sign language recognition [3] and speech therapy, including technology enabling people who are deaf to practice articulation [1, 5] and intonation [10], and technology for showing waveform and spectrograph visualization to speech therapists trained to interpret them [4]. Thus, past research looks at *spoken communication*, and past visualizations, intended for use in *focal* contexts, require *expert* users to interpret them. In contrast, our work focuses on *peripheral* awareness of *non-speech* sounds, by *non-expert* users, who have no special training in interpreting visual representations of sound.

Commercial products exist for notifying the deaf of specific events for which sound is typically used [6], such as phone rings, doorbells, wake-up alarms, and emergency alarms. These products use flashing light as a notification. The drawback is that a separate, costly system is needed for each event of interest. In contrast, our research visualizes all sounds with the same system.

Work in peripherally visualizing all non-speech sounds in one display for the deaf began with Ho-Ching *et al.* [6]. This previous study involved formative interviews and an in-depth, quantitative comparison of two prototyped displays that primarily answered the following questions:

- What sound awareness issues are not well supported by current techniques for people who are deaf?
- How well do the two prototyped designs make people who are deaf *aware* of sounds?
- How *distracting* are the two different designs?

In the present study we were interested in learning much more about designing a visualization of ambient sound. We build upon the findings in [6] and seek to answer questions about many design issues ranging from place of use to type of information displayed. For example, what display size is most useful? To gather this, we conducted a more extensive design interview process, described in the next section, which resulted in new visual design knowledge and functional requirements, important to the deaf participants, that were not discovered in [6].

DESIGN INTERVIEWS

We conducted interviews to inform the design of our application. We wanted to explore the answers to our design questions by gathering preferences for

- place of use (home, work, mobile),
- size (PDA, PC monitor, large wall screen),
- type of sound information conveyed (sound recognition, location, and characteristics),
- visual design characteristics, and
- functional desires or issues.

Participants

We interviewed 8 participants who considered themselves deaf: 2 profoundly deaf, 2 mostly deaf, and 4 people who were hard-of-hearing with the help of hearing aids and mostly deaf without. Four participants wore a hearing aid(s), 1 had a cochlear implant, and 3 had neither. Three of our participants considered themselves culturally Deaf. Six of our participants were female, 2 were male. Participant ages were between 28 and 57. We had 4 participants who were employed full-time in an office, 1 student, 1 homemaker, 1 retired, and 1 unemployed.

Table 1: Design sketch descriptions. Thumbs indicate overall user opinions: up = like; down = dislike; sideways = mixed.

Sound Info	Size		Name	Description
Recognized sound, volume, pitch	Small	👍	Spectrograph with Icon	An icon or text of recognized sounds is displayed on a spectrograph (*e.g.,* a phone icon appears over spectrograph when phone rings) (see Figure 1a for the implemented version).
Recognized sound, location, volume, pitch	Small	👍	Directional Icons	Icons appear at edges of computer screen, indicating both what sound occurred and its relative location to the screen (see Figure 3b).
	Large	👍	Map	Overview map of a room, icons (recognized sounds) or colored rings (unrecognized sounds) appear on map where sound occurred (see Figure 2a).
Location, volume, pitch	Large	☞	Ambient Visualization	An attractive, abstract representation of sound volume and pitch, that moves around screen to indicate sound location (see Figure 2b).
		👎	You Map	"You" are always at the center of the screen and sounds are displayed as colored rings relative to you, indicating their location.
	Small	☞	Rings	Colored rings appear at edges of a PC monitor, indicating volume (ring size), pitch (color), and relative location (*e.g.,* rings on the left side of screen occurred to the left of the screen, *etc.*). (See Figure 3a).
		☞	LED Panels	A row of physical LEDs on either side of a PC or TV screen, indicate volume (number of lit LEDs), pitch (color), and relative location (same as Rings).
		☞	Color Border	A border around PC screen filled with color indicating relative locations of sounds (same as Rings), volume (color intensity), and pitch (color chosen).
Proximity, volume, pitch	Small	👎	Location Bubbles Sidebar	Sidebar on PC screen with a row of bubbles that indicate proximity of sounds to screen with bubble size (*e.g.,* if sound is close to screen, bubbles higher on sidebar are larger, if sound is far from screen, lower bubbles are larger).
Any	Small	👍	PDA Display	Any of the other displays adapted to a PDA. Vibrates for alerts.

Method

The interviews were split into two parts that occurred back-to-back. The first part was a formal interview. In the second part, we presented the participant with design sketches of potential applications and asked for feedback.

During the formal interview, we asked participants about their hearing: what sounds they heard if any, how well they comprehended sounds, frequency ranges or hearing, and if they had implants or hearing aids. Then we asked about places: home, work and other locations where they spend time. Next we asked about sounds of interest and tools and techniques used to maintain awareness of these sounds at home, work, and while mobile.

During the design sketch interview, we presented participants with ten design sketches and a description of each. Table 1 describes each sketch and the type of sound information it showed. We developed these sketches based on results from [6] and design characteristics relevant to our questions (place of use, size, type of information conveyed, visual design elements). In particular, the design varied in their visual design and information conveyed: recognized sounds, location of sounds, and sound volume and pitch. For each design, we asked participants to tell us their preferred place of use (*e.g.,* home, office, or while mobile) and size (*e.g.,* displayed on a PDA or PC screen). Then for each design sketch, we asked them whether or not they would like to use the application, what is good and bad/confusing about it, and ways to improve it. We instructed participants to imagine that the technical logistics (such as having an extra screen, battery life, and memory) are not a concern.

For in-person and video relay phone interviews, each design sketch and its description were on a single paper. For IM interviews, each design was shown on a webpage (http://www.eecs.berkeley.edu/~tmatthew/ic2hear/).

Results

In this section we present the results of the interviews. The results help us derive visual design preferences and functional requirements for displays of this type.

Formal Interview

In this portion, we asked about peoples' daily lives and sound awareness needs. Participants spent the majority of time at home or work/school, though they emphasized a desire to be more aware of sounds in *all* places. In particular, they listed sounds at home, work, in the car, and while walking that would be useful to monitor.

In an office, people were most interested in knowing about the presence and activities of coworkers, emergency alarms, phone ringing, coworkers trying to get their attention, and faxes.

At home people wanted to know about emergency alarms, wake-up alarms, doorbell and knocking, phone ringing, people shouting, intruders, children knocking things over, gas hissing, and appliances (faucets dripping, water boiling, the garbage disposal, *etc.*). One participant told a story about a time when his wife burned food, which caused the fire alarm to beep. Since both were deaf, they did not know the fire alarm was beeping until a hearing friend visited. Another participant expressed a desire to hear her children playing (or fighting) when she could not see them. A third participant told us, "Once I left the vacuum cleaner on all night." The same participant also told us that when she needs a wake-up alarm because, "Before an early flight, I will stay up all night."

While walking or running outside, people wanted to know about dogs barking, honking, vehicles, bikes or people coming up behind them, and whether they were blocking another person (*e.g.,* "excuse me," "watch out"). One participant told about problems while running, "When I first moved to L.A. I was surprised at how some drivers are aggressive on the roads and at intersections. I had some close calls."

While driving, people were interested in knowing about other cars honking, sirens, and sounds indicating problems with the car. One participant said, "When there is something wrong with the car… it tends to go unnoticed until it is very expensive to fix." Another participant said she used to own a sports car and would drive with the top down to be more visually aware.

In addition to general awareness, one participant was particularly interested in learning about sounds. When asked what sounds she would like to know about, she exclaimed, "The ocean!" She also expressed a love for music: she loved watching live musicians and feeling the vibrations through the floor or speakers.

When asked about current tools and techniques used for maintaining sound awareness, all participants emphasized visual awareness: "I tend to look forward ahead of me much further than typical people… My eye sight is so important I've come to depend on it." One participant with a deaf husband said she got his attention by sending IMs to his Sidekick® and vice versa. Another participant stayed aware of her surroundings with vibrations, "I use vibration to feel grounded." This participant also said, "I read other people, though this doesn't always work well."

For phone ringing, doorbells, and emergency alarms, participants mentioned commercial products with strobe lights. However, each sound required its own specialized system. Most (5) participants did not have these tools because of the expense and difficulty of installing them. Three participants had one or two but not all. One participant said, "I think that the signal alert systems can be cumbersome and expensive, and I don't think it's worth the hassle." Cost was a major concern for all participants.

Overall, participants indicated they would value increased awareness of a number of sounds at work, home, *and* when mobile. In the next section, we discuss the designs participants preferred and how these varied in each place.

Design Sketch Interview

Immediately following the formal interview, we began the design sketch interview. We explored all ten designs with participants. Their preferences are presented in this section and summarized in Table 1: thumbs-up for favored displays (all of which recognized sounds), thumbs-sideways for mixed responses (all displayed location), and thumbs-down for disliked displays (one displayed proximity, one location). The results enabled us to identify important visual design preferences: ease of interpretation, glance-ability, and appropriate distractions, rather than detailed information. Their verbal feedback indicated important functions for any design, including the ability to identify what sound occurred, view a history of displayed sounds, customize the

(a) **(b)**

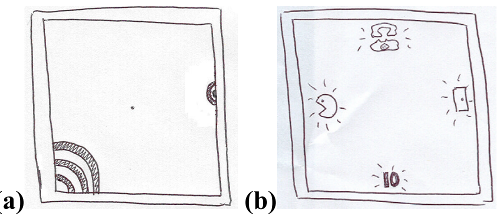


Figure 3: Rings, showing relative locations of sounds: a loud sound to the left and behind the screen, and a soft sound to the right. (b) Directional Icons, showing a voice to the left, a phone ring in front, a door knock to the right, and a very loud, unrecognized sound behind the screen.

information shown, and determine the accuracy of displayed information.

Overall, participants liked the three displays that showed recognized sounds: Map (originally, Map showed rings for all sounds, but participants requested that it identify certain sounds with icons, as described in Table 1), Spectrograph with Icon, and Directional Icons. They liked these displays largely because of the icons, which enabled them to *identify sounds of importance* quickly and easily. The Map also conveyed location information, which participants liked because it further enabled them to identify sounds. The other two used less screen space while still being highly informative. One participant said, "I think using the Spectrograph will be useful, so I can glance at it and figure out the sound." Another participant said she liked icons because they show "what kind of sound is being made. I think this is simpler – it is one look to instantly know what… is making the sound"

Participants had mixed feelings about Ambient Visualization, Rings, LED Panels, and Color Border, all of which show location, volume, and pitch. Two participants loved Ambient Visualization, saying it would "look like a piece of art on the walls… I wouldn't mind having it hanging in the living room." Others thought it was not easy enough to interpret: "I'd have to practice and learn this to understand it." The other three displays were favored by 2 or 3 participants, but others thought they would be too visually distracting or not informative enough. One participant said of Rings, "Do you think someone is going to want to see those rings ALL the time on the monitor – that'd be annoying." Another participant thought the Color Border did not provide enough information: "[it's] just a pretty light show, but it'll take some time to decipher what the noise is."

By and large, participants liked the You Map and Location Bubbles Sidebar, displays that show location or proximity, volume, and pitch. Participants thought they were more difficult to interpret than other displays and took too much screen space. Of You Map, a participant said, "the Map is better... more clear." Another person said, "If you can make it smaller that would be better… Cost would be a huge factor. [You Map] I think is just a waste of screen space." Of Location Bubbles Sidebar, a participant said, "It doesn't identify WHAT noise is being made and if it's an important noise… I would prefer some sort of identification of the noise that is being made."

Several participants described their ideal applications. A favorite was to have a single icon (for recognized sounds) and rings (for unrecognized sounds) appear in the corner of a PC screen.

Participants thought this would be a less distracting and smaller alternative to the other displays.

Participants discussed size preferences. In all locations, they preferred smaller displays, either on a PDA or using part of a PC screen. However, at home participants also valued large, wall screens for better visibility throughout a room. One participant said her ideal was Map and it would go at home on a "flat panel LCD display that I can just stick to the wall in a visible location."

Other important issues relevant to all the design sketches surfaced. First, participants wanted a way to look at a *history* of detected sounds: "I wouldn't want to be looking at the monitor all the time, [but it would work] if it has a history component." Participants thought it would be great "if it could keep a log that [I] could go back and look over. [I] could see that [I] missed the phone ring."

Second, participants wanted the ability to *customize* the displays. Customization requests focused on recognizing sounds and managing distractions. Four participants wanted to chose the recognized sounds that would be displayed. One said it was "important to have it programmed to identify the sounds I want to know about." Two participants wanted to filter out background noises: "I don't really care about hearing the other environmental noises." Though they wanted the ability to "turn off" all but the important sounds, most of these people still wanted the ability to show all sounds. One person wished to vary the amount of information shown, saying she "would need a way to customize it: turn down the sensitivity of the… display when there is a lot of noise and/or you need to get work done."

Third, two participants were concerned about the display showing false information. One participant said "I am worried about it showing 'voices' when I'm at home. If no one was there I would wonder 'what is going on?'" Another participant said, "I wouldn't want to have it show a phone and then I look at my phone and it didn't ring… I trust my own ability to interpret sounds more than the computer's." Clearly, the designs needed a way to show the system's confidence in information it displays.

Discussion

The interview results provided us with an understanding of participants' visual design preferences and functional requirements. Visually, participants preferred designs that were easy to interpret, glance-able, and appropriately distracting. Displays with icons were preferred because participants could easily understand what sound occurred in a glance. Participants criticized displays they thought would be overly distracting, like Rings. More complex displays like Ambient Visualization and Location Bubbles Sidebar were criticized for being difficult to understand.

We also derive several functional requirements from the interviews. In particular, users wanted mechanisms to

- *identify* what sound occurred,
- view a *history* of displayed sounds,
- *customize* the information that is shown, and
- determine the *accuracy* of displayed information.

With these results, we decided to implement two interfaces, employing a sound recognition system [7], and adding support for our functional requirements: Spectrograph with Icon and Single Icon (a single icon for recognized sounds and a ring for unrecognized sounds that appears in the corner of a PC screen). The Single Icon display was described by several participants, though it was not one of our design sketches.

We chose these two interfaces because of their ability to identify and display sounds of interest to the user, a feature that all participants emphasized as important. The two displays also differ in interesting ways, which enabled us to explore other features like screen space used and distraction that participants mentioned as important. In particular, the Single Icon is very small and minimally distracting. The Spectrograph with Icon is slightly larger and possibly more distracting, yet more informative since it shows more raw sound information.

SYSTEM IMPLEMENTATION

In this section, we describe the two interfaces resulting from our design requirements: Single Icon (Figure 1b) and Spectrograph with Icon (Figure 1a). Both displays were designed to take up a small amount of desktop screen space. Despite their small size, the icons are simple so as to enable users to quickly identify recognized sounds. We present the display designs, and ,discuss implementation issues such as the training and performance of the sound recognition system we used [7].

Single Icon

The Single Icon prototype (Figure 1b) displays recognized sounds as icons, located on the upper right corner of the user's computer monitor. These icons were designed to be small (55 x 93 pixels) so as to conserve screen space, and to be minimally distracting. Participants also wanted the ability to interpret sounds not recognized by the system. Unrecognized sounds are displayed as rings. A higher number of rings indicate a louder sound, and conversely, a lower number of rings indicate a softer sound. The pitch of the sound is conveyed through the color of the rings – blue for low, and red for high.

The ability to view a history of displayed sounds was an important requirement for participants. The "show History" option in the Single Icon menu enables this. It creates a new window, the History Display, showing each sound as a colored bar along a time axis (Figure 4).

Customization of displayed sounds was also important to participants. The Single Icon menu enables users to specify which sounds to display and to turn on or off the display of unrecognized sounds.

Finally, participants wanted the ability to determine the accuracy of displayed information. The Single Icon interface indicates the system's confidence in its identification of a sound by displaying either "High," "Medium," or "Low." The opacity of the icon also varies with the level of confidence. For example, if the system is highly confident that it has correctly identified a sound, the icon is very opaque, and the text displayed is "High."

Spectrograph with Icon

The Spectrograph with Icon display is Single Icon augmented with a black and white spectrograph that visualizes raw sound information. This prototype is slightly larger at 263 x 155 pixels.

The driving motivation behind the implementation of Spectrograph with Icon was that some of our interviewees expressed a desire to learn about and discover sounds, like the woman who wanted to hear the ocean. The icon shown allows the user to associate a particular sound with its shape on the spectrograph.

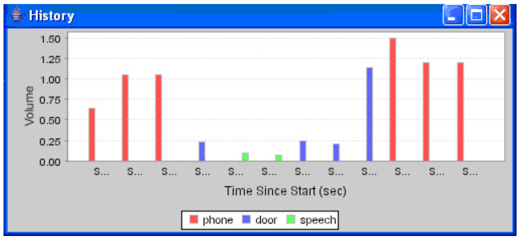


Figure 4: History Display shows each sound recognized as a different colored bar along a time axis. The height of the bar indicates the relative volume of the sound.

History, customization, and system accuracy are handled by the icon portion of the display, as described in the Single Icon section. In addition, we enable users to turn off the spectrograph portion of the display, which reverts the display to Single Icon.

Together, these displays cover both minimally distracting (Single Icon) and more informative (Spectrograph with Icon). Both have the capability to identify sounds of interest to the user. In addition, our designs enable users to view a history of sounds, customize the application, and determine the accuracy of information. These four capabilities were not implemented in previous work [6].

Implementation

The displays were implemented using Java Swing. Non-speech sound recognition was handled by Malkin's state-of-the-art system [7], which uses audio only to detect and classify events. We an audio-only system, because of the cost, complexity, and intrusiveness of the many sensors involved in multimodal event detection (as in [8]).

Because of the extensive training required by [7], we had to pick a deployment space early. While the recognition system can be trained for use in any place, we chose an office environment because we wanted to user test the application in a controlled, yet realistic setting that could be simulated in our lab. Our system was trained on office sounds of interest to our interviewees: speech, phone ringing, door opening/closing and knocking. We also trained the system on common office sounds to be filtered out: typing, mouse clicks, chair creaks, and continuous background noises (*e.g.,* heaters and fans).

The sound recognition system returns a best guess as to the classification of a sound, with a normalized confidence level based on thresholds we set. We chose thresholds for the normalized likelihoods based on test data. The confusion matrix yielded by testing the system showed that phone ringing and speech were correctly identified 100% of the time. Door opening and closing were often confused for each other and therefore treated as a single event (this still meets the design requirement of indicating the source of an event to the user).

USER EVALUATION

To evaluate our implemented applications, we asked four people who are deaf to come to our lab, use each system for 25 minutes, and give us feedback. The participants in this evaluation were different from those in the design interviews, giving us fresh perspectives. The results of this evaluation, though tempered by small numbers, show that such an application is most helpful when it indicates an event of interest has occurred, and a history of identified sounds is effective at showing this.

Participants

Each participant had a varying degree of hearing ability. The first participant we interviewed was profoundly deaf. The second wore a hearing aid to hear sounds but could rarely identify them. An ASL interpreter served as a translator for these two participants. The third and fourth participants wore hearing aids and could hear and identify many sounds with them. During the study, both participants 3 and 4 could hear most sounds and identify some, such as a phone ring. The participants included a technical support worker, a journalist, a substitute teacher/graduate student, and a childcare worker.

Method

We began the lab session by introducing the user to the project. We then asked about his/her hearing ability, work and home environments, and the tools and techniques currently used to maintain an awareness of sounds. Then we introduced the Single Icon display, demonstrated it recognizing several sounds and showing several unrecognized sounds, and explained confidence levels, customization, and the History Display. We informed the participant of the limitations of our sound recognition system (the possibly of it mis-recognizing sounds and the time lag between the occurrence of a sound and its display). Then we allowed the user to "play" with the display for 5 minutes to get used to it. We observed the ways in which the user learned about the display.

For the second part of the lab session, the user was instructed to check his/her email or browse the Internet on the computer with his/her back to the door and researcher. Single Icon was running in the upper-left corner of the computer screen. We instructed the user to pretend this was his/her office and to react to the sounds displayed as s/he would at work. Then we caused the following sounds to occur at random intervals, in a random order: phone ringing, talking, door opening/closing, coughing, pen clicking, shuffling papers, knocking on the door, banging a plastic toy against the table, and hitting a metal bookcase. We then repeated the first and second parts of the lab session for Spectrograph with Icon.

For the third part of the lab session, we asked about the user's thoughts on each display and why s/he reacted in the ways s/he did during the lab session.

Results

All four participants favored the History Display as a stand-alone display. Variation in hearing ability among participants affected their preferences, though all said that sound recognition was important to them. Overall, participants were positive about the applications because "[people who are deaf] miss out on a lot of things."

Reactions to Single Icon

All participants liked the Single Icon Display because it identified each sound event. One participant said, "[I] need to know what the sound is."

Participants provided feedback on aspects of the display that could be improved or enhanced. Two participants thought the icon changed too frequently (once per second), causing it to be confusing and distracting at inappropriate times. They suggested that the icon flash when the sound was "really important," and be more "visual[ly] quiet" for less important sounds. For a sound that the system did not recognize, two participants emphasized the importance of knowing its location and one wanted to know the number of times it had occurred. One participant who could hear some sounds was frustrated when the system reported a sound inaccurately, or when a sound was correctly identified but the system reported a "Low" confidence.

Reactions to Spectrograph with Icon

Overall, participants liked Spectrograph with Icon less than Single Icon. Their reactions to the spectrograph were a mixture of interest and confusion. All participants expressed concern about the difficulty of interpreting the spectrograph. For example, one participant said, "[The spectrograph] is like a hearing aid. It's just a bunch of noise, and I can't focus on what's important." Another participant said, "It's just a blurry picture. I have no idea what the sound is." However, the spectrograph was effective in attracting this participant's attention when the door was slammed: "[The spectrograph] caught my attention because of the black." In addition, one participant thought the presence of both the icon and the spectrograph was distracting. The last participant suggested, "if the icon, or just text popped up in the same window as the spectrograph, it'd be better."

Three of the participants showed an interest in using the spectrograph and icon together to learn about sounds. One participant was fascinated by the Spectrograph with Icon prototype and played with it by clapping and knocking on the desktop and watching the resulting shapes. Another participant watched the spectrograph to see if she could learn to identify a sound by its shape, saying "I wanted to see what [the sound] was. I wanted to see the shape on the spectrograph to see if I could recognize it." However, all participants expressed skepticism about being able to learn how the patterns map to particular sounds.

History Display

All participants favored the History Display over the other designs as a stand-alone display. One participant said it allowed him to know what sounds occurred without having to watch the display all the time. Two participants liked that it showed relative volumes of sounds, because it attracted their attention for louder sounds which were more interesting to them. As one user explained, "small sounds I don't bother with, but loud sounds [get my attention]." They wanted to keep the history window display open all the time, but make it "small and thin and have it at the top of my screen."

DISCUSSION

Here we combine results from design interviews and prototype evaluations to answer our research questions about the design of peripheral, visualizations of non-speech sound for the deaf.

In what places is sound awareness important?

Participants wanted awareness of sounds in all places. They spent the most time at home and work, but were often mobile. Clearly, audio awareness was important, as people wanted it wherever they went.

What display size is preferred?

In all locations, participants preferred smaller-sized displays. However, in the home participants also valued large, wall screens for better visibility throughout a room.

What information about sounds is important?

The most useful information was anything that enabled participants to identify events of interest and prototype evaluation results indicate that identifying sounds is a good way to provide this information. Interview participants also emphasized the usefulness of sound recognition, favoring displays of this information. Secondly, a history of sounds was critical to evaluation participants since it allowed them to maintain awareness of sounds without constantly watching the display.

What visual design characteristics are preferred?

Participants preferred visual designs that were easy to interpret, glance-able, and appropriately distracting, over designs with more detailed information or one type of notification (*e.g.,* only minimal distractions).

It is clear after the prototype evaluation, that the History Display was preferred by all users over Single Icon and Spectrograph with Icon. The prototype evaluation showed that the History Display appropriately distracted users by showing relative volumes, unlike Single Icon which drew no distinction between more and less important sounds. Participants still liked Single Icon for its easy to interpret icons, which abstract sound identification and confidence levels into one picture. The least popular spectrograph was regarded as difficult to interpret and peripherally monitor because it displayed too much detail. This contradicts results from past work [6], which found that a spectrograph was useful to people who are deaf. Further investigation is necessary before drawing conclusions.

What functional issues are important?

Important functional requirements identified in design interviews include the ability to identify what sound occurred, view a history of displayed sounds, customize the information that is shown, and determine the accuracy of displayed information. Prototype evaluations validated that these issues were critical.

CONCLUSION AND FUTURE WORK

In this paper, we presented the iterative design and implementation of two peripheral, visual displays to help people who are deaf maintain an awareness of non-speech sounds in the environment. Leveraging past work [6], we gathered feedback on a wider variety of designs with representative users, implemented two fully-functional prototypes using a sound recognition system [7], and evaluated the prototypes with users who were deaf. Our contributions are (1) a set visual design preferences (ease of interpretation, glance-ability, and appropriate distractions) and functional requirements (the ability to identify sounds, view a history of displayed sounds, customize the information that is shown, and determine the accuracy of displayed information) for peripheral visualizations of non-speech audio, and (2) the design, implementation, and evaluation of two fully functioning prototypes that embody these preferences and requirements.

Our design interviews have left us with a wealth of knowledge with which to design future applications. While the applications presented in this paper were deployed in an office setting, participants also expressed a need for sound awareness at home and in mobile settings. We plan to implement applications designed for home and mobile use. In addition, participants thought the location of a sound could be valuable for identifying it. We also plan to incorporate support for locating sounds in a space. Finally, we plan to conduct a long-term deployment of our iterated application.

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