Audible Beacons and Wearables in Schools: Helping Young Visually Impaired Children Play and Move Independently

Euan Freeman[1], **Graham Wilson**[1], **Stephen Brewster**[1], **Gabriel Baud-Bovy**[2], **Charlotte Magnusson**[3] **and Hector Caltenco**[3]

[1]Glasgow Interactive Systems Section
University of Glasgow
Glasgow, Scotland
{first.last}@glasgow.ac.uk

[2]RBCS
Italian Institute of Technology
Genoa, Italy
{first.last}@iit.it

[3]Certec
Lund University
Lund, Sweden
{first.last}@certec.lth.se

ABSTRACT

Young children with visual impairments tend to engage less with their surroundings, limiting the benefits from activities at school. We investigated novel ways of using sound from a bracelet, such as speech or familiar noises, to tell children about nearby people, places and activities, to encourage them to engage more during play and help them move independently. We present a series of studies, the first two involving visual impairment educators, that give insight into challenges faced by visually impaired children at school and how sound might help them. We then present a focus group with visually impaired children that gives further insight into the effective use of sound. Our findings reveal novel ways of combining sounds from wearables with sounds from the environment, motivating *audible beacons*, devices for audio output and proximity estimation. We present scenarios, findings and a design space that show the novel ways such devices could be used alongside wearables to help visually impaired children at school.

Author Keywords

Visual Impairment; Children; Play; Beacons; Wearables.

ACM Classification Keywords

K.4.2. Computers and Society: Social Issues – Assistive technologies for persons with disabilities.

INTRODUCTION

The early school years play a vital role in a young child's development. As well as education, they provide opportunities to develop social skills, movement skills, and independence from adults. Unstructured play is one example. This has an important role in early development, helping children learn more about the world, the things and people within it, and the interactions between them. This contributes to motor, language and social skills, amongst others. School also helps children become more independent, developing the skills and confidence to look after themselves as they grow older.

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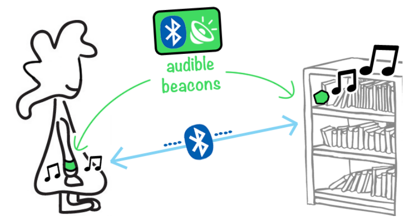

Figure 1. *Audible beacons* can be worn or placed in the environment. They communicate using Bluetooth and can also produce sound.

Young children with visual impairments face challenges that limit access to these development opportunities, reducing their benefits. They tend to engage in less complex, less social, and less varied types of play than their sighted peers [31]. Instead, they spend more time alone, withdrawing from others [6] and engaging in simpler play [31]. Many also resort to self-stimulatory behaviours (e.g., staring at lights, poking their eyes) that hinder development by disengaging them from more meaningful experiences [17, 13]. Visual impairment also hinders the ability to move independently, requiring orientation and mobility training from as early an age as possible [23, 24].

We have been investigating the use of 'audio bracelets', bracelets that make sounds from the wrist, to help visually impaired children while at school. Audio bracelets have been used successfully in rehabilitating spatial cognition in young visually impaired children [14, 15] and have been used for inclusive social games [8]. Our research investigates how this technology might be used during the school day to help children get more out of play and to support independent mobility. Our approach focuses on using sound to give children a greater awareness of what activities, people and places are nearby, as well as encouragement to 'explore' and be more active.

To understand more about the challenges faced by visually impaired children at school, and how technology like audio bracelets might help, we held discussions with visual impairment educators. These discussions led to the creation of three scenarios that demonstrate how sound from wearables might support play and movement. We then used a survey to explore these scenarios further, investigating effective sound design and presentation. Finally, we held a focus group with visually impaired children to validate our findings about sound design and presentation.

We found the importance of presenting sounds from the environment as well as from a bracelet and we found novel ways of combining such sounds. This led to ‘audible beacons’ (Figure 1), small devices that can be used to estimate proximity and produce sounds; they can be worn (as an audio bracelet) or placed in the room (as a distal sound source). In this paper, we contribute findings from three studies about how sound can be used to support visually impaired children with play and mobility. These findings are significant as they provide a basis for designing mobility aids for visually impaired children. We then describe audible beacons and discuss the diverse and previously unknown design possibilities such devices offer and how they may be used to assist visually impaired people.

RELATED WORK

Many researchers have investigated auditory systems that use sound to give users information about their surroundings or help them navigate. These are often designed for mobile devices like smartphones, with sound being delivered through the device loudspeaker or headphones. Loudspeakers are not ideal because the sounds lack important spatial properties that are helpful to visually impaired people. Others have addressed this by using spatially-encoded audio, delivered through headphones (e.g., [4, 5]); however, this disconnects users from their surroundings and companions, and it also risks occluding important sounds in the environment. Wearable devices have also been used for delivering non-visual assistive information, although these also often lack spatial information, as the sound comes from the user’s body (e.g., from a bracelet).

An alternative approach is to instrument the environment so that auditory cues come directly from the points of interest, rather than from a device held or worn by the user. An advantage of this approach is that users can localise sound cues, hearing where a point of interest is in relation to themselves. This approach is more suited to smaller scales, typically indoor spaces, like the nurseries and schools we consider in our research. This literature review begins by discussing systems where sound comes from a device held or worn by the user, then looks at those using sounds from the environment instead.

Sound from a mobile device

AudioGPS [16] was a mobile system that used audio cues from headphones to guide users to landmarks. Spatial sound allowed users to hear the direction of landmarks and repeating tones (like a Geiger counter) told users about their proximity to them. *Audio Bubbles* [20] used a similar audio design, although it did not use spatial sound to indicate direction. This was so that users did not need to wear headphones that might obscure ambient noise from their surroundings. These systems, and others like them, use sound to tell users where nearby points of interest are, although they did not present other information about them. We consider a different approach in this paper, as giving visually impaired children information about points of interest might help them orient themselves more effectively [27] or encourage them to seek a new activity.

Talking Points [29], *Audvert* [3], and work by Sareela [26] used speech to tell users about their surroundings: as they approached items or moved through a space, contextually-relevant information was spoken aloud by a mobile device. Using speech meant that detailed information could be given, allowing systems to present more guidance than simply making users aware of nearby landmarks (as in *AudioGPS* or *Audio Bubbles*, for example). Ankolekar *et al.* [1] suggested using *Musicons*, short snippets of music, as an alternative way of presenting meaningful audio information about things in the environment. They argued that Musicons would create more engaging experiences than alternative audio cues, like speech or Auditory Icons (familiar noises). While Musicons did not perform as well as speech, they did create a more enjoyable user experience. Such an approach may be inappropriate for our user group, as children would have to learn the abstract mappings between Musicons and areas of their school or classroom. As we discuss later, experts suggested that this may be too complex. Instead, we consider the combined use of speech and non-abstract audio (e.g. Auditory Icons).

Blum *et al.* [4, 5] argued that mobile assistive systems should not just use naive text-to-speech, which may be distracting and intrusive. They investigated an alternative that combined Auditory Icons and speech, to convey information less obtrusively. Spatial audio output was also used, so that users could hear where points of interest were situated. An evaluation of their system [22] found that users preferred to get basic information about a point of interest, rather than just a short snippet informing them of its presence. However, they also found that the amount of information could overwhelm. Sanchez and Elias [27] also discuss the risk of overload; a balance between quality and quantity of information is important.

Choosing information to present as audio can be challenging, as the previous paragraph suggests. Chen *et al.* [10] investigated how information should be structured when giving audio cues for navigation, taking inspiration from visual impaired peoples’ routines and from interviewing an orientation & mobility instructor. Their design recommendations include keeping cues concise, presenting required directions or actions before other information, and giving descriptions using a clock position metaphor (e.g. “at two o’clock”). Sanchez and Elias [27] also provide recommendations for relevant and useful information presentation. The *wayfindr* [34] standard gives guidance on presenting audio cues for wayfinding, focused on smartphone and beacon use.

Sound from wearables

Handheld devices are the most common mobile devices used for assistive feedback, although some have used wearable devices to tell users about their surroundings. This is the approach we consider in our research, because wearables are more appropriate for young children than handheld devices, which might obstruct play and other activities. Keeping the hands free is also important for other reasons, including safety and the use of other handheld mobility aids [33].

Ugulino and Fuks [33] investigated smart-glasses that used speech to tell visually impaired people about their indoor surroundings. They chose speech as it was less likely to cause cognitive overload, compared to other techniques like sonification. Wilson and Brewster [35] suggested using sound from a bracelet to encourage children to reach for nearby objects and explore their surroundings. Their initial exploration of this idea found that sound from the wrist was less useful than sound from the objects themselves. We build on these ideas by investigating in greater detail how sounds from wearables can be used to support active play and independent movement. Others have used wearables for vibration (e.g., [7, 9, 25, 36]) but we focus on sound for a first investigation of this area.

Sound from surroundings

An alternative to presenting sound from a mobile device is to present sound from the environment itself. Coroama and Röthenbacher [12] discussed their concept of a *chatty environment*: a space which presents a continuous stream of auditory information, telling visually impaired users about things they may be unable to see. Users hear information about objects in their surroundings and they are able to investigate a particular object in more detail using their smartphone, or by picking it up and exploring it. They give an example of a chatty supermarket, which allows shoppers to hear what goods are available and where they are on the shelves.

A similar type of interaction was supported by *audio-tactile location markers* [30]. These are physical tags—like Bluetooth beacons—that use a ticking sound to make visually impaired users aware of them and to let them hear where they are located. These markers are intended to support accessible use of location-based interactions by helping users locate and interact with tags in the environment. Like the *chatty environment*, users would interact with these tags using a mobile device; for example, holding it beside the tag for more information.

Chatty environments and *audio-tactile location markers* used sound from the environment to tell users about nearby objects. *BlueView* [11] told users about points of interest instead; for example, telling them about rooms and spaces rather than items *within* a room. *BlueView* paired Bluetooth beacons with loudspeakers, which users could then interact with using their smartphone. The smartphone scans for beacons in the nearby area and displays results in a list; when users select a beacon from the list, the speaker makes a noise to help the user find it.

Onyx Beacon [21] deployed a system with similar interaction to *BlueView* on a public transport network. They placed Bluetooth beacons on buses to help visually impaired users find the right bus at busy stations. Users searched for a bus on a smartphone app, then waited for it to arrive. When it arrived (detected by its beacon), a notification was sent to the phone. The beacon on the bus made a buzzing noise, to help the user find it if there were several buses at the stop. Our research considers a different prompting approach to *BlueView* and *Onyx Beacon*, because our users would not always explicitly interact to trigger audio prompts. Instead, our system would make the decisions about when to present sound; for example, playing sound when a child should be encouraged to move to a new activity or when a friend has moved somewhere else.

In this section, we discussed feedback that gives users navigation instructions or tells them about their surroundings. These systems used a number of approaches: presenting sound from a handheld device (often through headphones), delivering sound or vibration from wearables, and presenting sound directly from the environment. Our findings in this paper will show that sound from the environment is a compelling area for more research, leading to our audible beacons. However, we also consider the novel possibility of combining sounds from audible beacons with sounds from wearables.

Audio bracelets, devices that produce sound from the wrist, have been successfully used to develop motor and social skills in visually impaired children. For example, Finocchietti *et al.* [15, 14] used them to synthesise sound in response to arm movements, for use in spatial cognition rehabilitation. Caltenco *et al.* [8] used them for inclusive social games, to allow sighted and visually impaired children to play together. We are investigating how they may be used instead to help with the problems we identified in the introduction.

STUDY 1: EXPERT DISCUSSIONS

We started our investigation of audio bracelets in schools after discussions with experts in the education of visually impaired children. These initial discussions highlighted some of the challenges such young children with visual impairments face while at nursery and school. To learn more about these challenges and possible technology solutions, we held formative discussions with a large group of experts (approx. 30 people) at the annual meeting of the Scottish Association for Visual Impairment Education (SAVIE); this meeting was well attended by visual impairment education professionals, including teachers, rehabilitators, policy makers, and academics. An alternative approach would have been to start our discussions with children, although we chose to start with experts because they understand the developmental and educational needs of visually impaired children. To make sure our findings also aligned with the needs of the children, we held a focus group with visually impaired school pupils (Study 3, described later).

At this stage in our research, we were considering how audio bracelets could be used in conjunction with indoor localisation technologies, like beacons, to expand the range of possible interactions. Before the discussion, we demonstrated a prototype audio bracelet and beacons, showing their capabilities and what they might be used for. The purpose of this was to show the potential of current technologies, so that ideas were not limited by perceived technological constraints. We wanted to show that we could: (1) estimate proximity and position indoors (e.g., in classrooms or school corridors); (2) detect activity and movement from wearable devices, like our audio bracelet; and (3) deliver sound cues from a wearable device.

We then had a semi-structured discussion about the problems faced by visually impaired children in their early school years. This involved all attendees and lasted one hour. The experts drove the discussion as they were identifying the problems that needed addressing. As topics were raised, we probed for more information and encouraged discussion around the problems. Audio recordings and hand-written notes were made for later analysis. This study resulted in many suggestions of how audio bracelets and other technologies might provide assistance.

Challenges for Young Visually Impaired Children

Most of the discussion during these sessions focused on issues which arose during times of play, when children are free to engage in unstructured and independent play (‘independent’ meaning without adult involvement, rather than playing on their own). Play is important for children, as it contributes to the development of many key skills, including social and language skills. Our participants also discussed issues relating to safe, independent movement, e.g. in the school corridor or when visiting unfamiliar buildings. We now describe the most prevalent challenges in more detail, along with the suggestions of how technology could be used to meet the childrens' needs.

Moving Independently Between Play Activities

During play time, sighted children will generally move between lots of activities and will do so independently. Visually impaired children, however, tend to stay in one place doing the same activity for a longer time. Similar behaviours have also been reported in other research, with visually impaired children engaging in less complex and less social types of play than their sighted peers [31]. It is important to encourage them to take part in active and varied play, as this exposes them to more sensory experiences, helps them socialise, and helps to develop skills and confidence.

Our participants told us that teachers and classroom assistants—who may be unaware of the needs of visually impaired students—might think that a child's lack of movement means they are happy to stay at an activity, so leave them alone. The lack of movement may mean the child lacks confidence in their ability to find their own way to a new activity, however. Instead, they need adult assistance or encouragement to move, but that is often unavailable. Over longer periods of time (days, weeks, etc.), a child might return to the same activity, leading their teacher to think that it is their favourite; rather, the activity may just be familiar to the child and they are unaware of the other available options for play.

It was suggested that an audio bracelet could be used to make a child aware of what activities are nearby, using sound to encourage them to find new activities or to explore independently. This assistance could be given only when necessary, e.g., if a child remains in one place for too long. Teachers could also interact with the system and change the types of activities it promotes; for example, they may want to encourage a child to take part in an activity which benefits a developmental need or addresses part of the curriculum. An interesting debate was whether sound should come from the environment as well as (or instead of) a bracelet. Sounds from the environment could be localised, meaning the child can hear where another activity is located. We investigate this more in the following studies.

Awareness of Friends and Adults

A common barrier to social play was that visually impaired children were often unaware of friends going away; children move around spontaneously and without announcing that they are doing so, and visually impaired children might not immediately know that a friend has left. This means they are often left alone and may lack the confidence to find friends on their own. Some experts suggested that an audio bracelet could be used to help in these situations, by informing the wearer that his or her friends have left, then helping them find where they went. It was also suggested that bracelets could also be worn by close friends, with sounds from the friend's bracelet helping the child find them or know when they are nearby.

Children with visual impairments often need adult assistance or encouragement during play and other classroom activities, as discussed before. They often have to rely on an adult noticing them or checking up on them because they may be unable to ask for help on their own (e.g., they do not know where the teacher is or if there is someone nearby). However, teachers and assistants are not always available because they have to supervise and tend to the other children. Participants suggested we could use audio bracelets to help in these situations and to help a child find a teacher; for example, they could use sound to tell the child when a teacher is nearby, or the teacher could also wear a bracelet to help the child find him/her.

Discouraging Inactivity and Passive Behaviours

As already discussed, visually impaired children may not move much during play time because they lack confidence to do so; however, they may also be inactive because they are engaging in self-stimulatory behaviour (like rocking back and forth, or flapping their hands in front of their eyes) [32]. Children with sensory impairments often show such behaviours, which should be discouraged because they take the child away from more meaningful activities [17]; instead, they should be encouraged to seek stimulation from the world around them.

Participants suggested that we could try to discourage these behaviours; for example, if a bracelet could sense when a child had not moved for a prolonged period, or if it could sense these repetitive motions taking place, then the teacher could be informed and could intervene. Sound cues from the wearable could also be used to interrupt these behaviours and encourage the child to move. For example, others have been investigating how audio bracelets could encourage children to "reach out" and be more active with their surroundings [35].

Independent Movement Around School

Some children have difficulty finding their way around the school, especially in the early years of education. For example, one of the teachers told us about a young student who had difficulty finding his way around the school because he had difficulty seeing and remembering visual landmarks. It was suggested that other sensory information could be used to create non-visual landmarks, so that he could learn the school layout and find his way. For example, he could 'hear' when he passes the cloakroom and use it as a reference point.

There are many examples of this sort of solution. Saarela [26] placed beacons in a shopping mall in Helsinki so that smartphones could detect them and create auditory landmarks to assist in wayfinding. Her system provided many levels of information, supporting users with varying familiarity of the shopping mall. In our context, a child may need fewer cues as they become more familiar with a school layout. *Wayfindr* [34] deployed beacons in Pimlico Station on London's Underground, with sound delivered through a smartphone; they used a "less is more" approach for audio cues, giving only essential information about landmarks. The experts agreed: support development of skills, rather than replace them with extra information.

Summary of Expert Discussion Topics

In this section, we identified four topics which were commonly brought up by our participants when discussing the problems faced by visually impaired children at nursery and school. These issues relate to play and movement, both of which have an important role in early development. We received many suggestions of how technology—especially audio bracelets—could be used to help with these issues, which have not been addressed before. In the following section, we present three scenarios inspired by these ideas, showing how bracelets and beacons may be used to help visually impaired children play and move independently.

Scenarios: Wearables and Beacons in School

Scenario 1: Finding New Activities

Amy, a visually impaired child, has been given an audio bracelet by her teacher to encourage her to try new activities during playtime and to give her a greater awareness of what activities and toys are nearby as she moves through the playroom. Her teacher wants to encourage her to move more and experience more activities, so her bracelet is configured to vibrate gently if she stays in one place for more than fifteen minutes. After playing with the musical toys in the corner of the playroom, Amy's bracelet tells her to move. She gets up to move to another activity. As she walks through the room, a large open plan area, her bracelet uses sound to tell her what is near (as in Figure 2). She hears a sound telling her about the building blocks and wants to play with them; the sound from the bracelet gets louder as she moves towards them, letting her know that she is getting closer. Once she is next to the blocks, another sound from her bracelet tells her she has arrived.

In this scenario, the bracelet encouraged Amy to move and told her about nearby areas of interest. The aim was not to provide navigation instructions towards a certain activity but to give her a better awareness of what activities were nearby.

Scenario 2: Helping a Child Find His or Her Friends

Jack, a visually impaired child, is playing in the craft corner of the nursery playroom with his sighted friend Sally; both are wearing audio bracelets. Sally gets up and moves across the room to play with the animal toys. Jack's bracelet detects that Sally has moved further away and plays the sound of a sheep ("baa"). This tells him that Sally has moved to the animal toys. He gets up and moves across the room. As he gets closer to Sally, he hears the sheep again, letting him know he is moving towards her (as in Figure 3). When he reaches the animal toys, Sally's bracelet makes a noise as well.

In this scenario, Jack's bracelet informs him when one of his friends moves to a new activity. A challenge highlighted by this scenario is using sound to help the child once he is near an item or person of interest. Once Jack is close to Sally, he may need further guidance to identify her amongst a larger group.

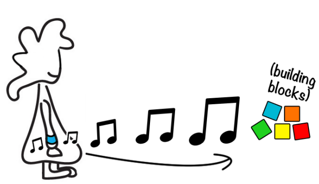

Figure 2. Amy's audio bracelet uses sound to tell her about the nearby building blocks activity, getting louder as she gets closer to them.

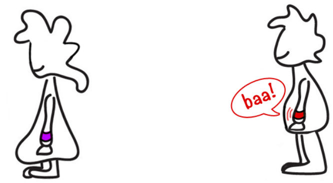

Figure 3. Jack's bracelet uses sound to help him find his friend Sally.

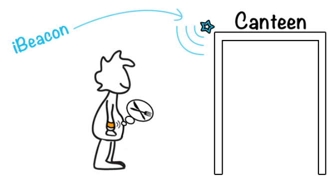

Figure 4. Michael's wearable presents sounds to tell him about nearby places in the school.

Scenario 3: Learning About New Places

Michael has just started primary school. His visual impairment means he has difficulty remembering landmarks and finding his way in unfamiliar places. His school has given him a bracelet that will use sound to help him find his way and learn the layout of the school. As Michael moves along the corridors, his bracelet delivers short sounds to inform him about nearby landmarks, like the school canteen. For example, as he passes the entrance to the canteen, his bracelet makes the sound of cutlery clattering together (as in Figure 4).

In this scenario, Michael's bracelet uses sound to tell him about nearby points of interest, to help him learn where important rooms in the school are. This type of interaction could also tell him about nearby obstacles—like stairs or doorways—so that he can safely move around the school. The aim of this type of interaction is to provide a greater awareness of surroundings, rather than to provide precise instructions to a destination.

Design Problems

These scenarios described three ways that audio bracelets could be used in schools to help visually impaired children: by promoting active and varied play, by supporting social play, and by creating non-visual landmarks for wayfinding. Although we gave examples of audio designs in the scenarios, more research is needed to investigate effective sound designs for these interactions. Most of the existing research has focused on finding effective ways of using sound and speech for navigation cues (e.g., [4, 5, 10, 34]). Work is needed to investigate sound designs for promoting awareness of nearby activities, people, etc. Research is also needed to see how audible assistive cues can be used in an acceptable way in schools. Because our work focuses on play and movement around the school, the auditory cues are less likely to disturb quieter classroom activities; however, they may still be noticeable to other people so must be acceptable to everyone, especially the children wearing the bracelets.

The sounds in our scenarios were presented by audio bracelets, as we were investigating these based on success in other work. However, the discussions suggested that sound could also come from within the room or from other people, as well as—or instead of—the sounds from the bracelet. Others have developed systems for presenting sounds from the environment (discussed earlier), although it is not known if this would be effective, especially for our scenarios. The novel possibility of combining the approaches—sound from a wearable and from the room—has also not yet been investigated.

STUDY 2: ONLINE SURVEY

We used an online survey to evaluate the ideas in our scenarios and to further investigate the design problems within them. We chose an online survey as that would allow us to reach a wider audience in the visual impairment education community. We recruited participants using mailing lists which focus on visual impairment education; some respondents also shared the survey on social media or through word of mouth, which helped it reach a wider audience. The survey website was available in English and Swedish, as we worked with visual impairment organisations in both the UK and Sweden. The survey was also accessible for screen readers, etc., so that visually impaired people could respond as well.

The survey presented our three scenarios in a random order to respondents. We asked a series of questions for each scenario, that evaluated the usefulness of the ideas and investigated sound design issues within each scenario. For example, we asked what sounds would be appropriate for different types of information, where sound should be presented from, and if there were any ways they would change the functionality within the scenarios. Three types of question were used: (1) five-point Likert scales; (2) checkboxes (e.g., Yes/No or selecting from multiple options); and (3) freeform text comments. There were 33 questions in total for the survey. Please see the supplementary material for all of the questions.

This section describes the survey participants, followed by a discussion of findings from each of the scenarios. These findings highlight design requirements and identify areas for future research. Most of the discussion focuses on when and how audio cues should be presented, which appeared to be more important to the participants than what it sounds like.

Participants

Thirty people completed the survey. Twenty-eight were female and two were male. Two were aged 26–35, 17 were aged 36–50 and 11 were aged 50–65. Respondents were from the UK (24) and Sweden (6); those from the UK were from all four countries (Scotland, England, Wales, Northern Ireland).

Three of the survey respondents indicated that they had a visual impairment. One of them had low vision, one was totally blind and the other did not give any information about his visual impairment. Six respondents indicated that they had a family member with a visual impairment. One had a child who had been blind since birth, another a child with cerebral visual impairment and one a child with low vision. The other three respondents did not give any more information.

Twenty-five of the respondents work with visually impaired children. This includes 15 teachers/nursery nurses/classroom assistants and six habilitation specialists, which includes general habilitation and orientation & mobility skills. Of the five other participants, four had a visually impaired child and one worked with older visually impaired people.

Survey Findings

Scenario 1: Finding New Activities

Overall, respondents thought it was important to encourage more varied play and that sound could be a good way of providing awareness of what activities are nearby. The idea of giving a child a reminder to move and be more active divided participants: fifteen were unsure if this was a good idea. Those who disliked the idea thought interventions may upset some children, especially if they were really engaged with an activity, or thought that such reminders may move children away from otherwise beneficial activities. This highlights the importance of fully understanding when sound should be presented, something that is likely to need customising for each child. Some participants suggested that the system could alert the teacher instead, who could then determine if the child should be encouraged to try a new activity.

Two responses suggested turning this scenario into a game that encourages children to be more active. One expert said the bracelet could make noise while the child moves and would be silent while they sit still; they suggested that this could encourage greater movement, as the sound rewards activity. As the child moves, they could hear sounds about nearby activities and could be encouraged to find a sound they like or to find more sounds by moving more. Another participant suggested using the bracelet to tell the child about a sound they must ‘find’ in the room, encouraging them to explore the space and find it. The ‘hidden’ sounds could come from sound sources placed around the room. In other research, Caltenco *et al.* [8] co-designed similar games with visually impaired children, using an audio bracelet to generate movement-based sound. They found that these games offered playful and social experiences. That work demonstrated some potential benefits of creating games from auditory cues. Turning assistive cues into games might also encourage the children to engage more with the technology, increasing its benefits [27].

A respondent suggested that children could query for sounds instead of having the system interrupt their current activity. Our scenarios inferred when to present sounds: e.g., after periods of inactivity or proximity to something. Direct interactions, like tapping or shaking an audio bracelet, could also be used to provoke output. Our research has so far focused on audio prompts but future work could investigate ways of directly interacting with the system to hear information.

The survey responses suggest that sound from the environment would be most useful, either instead of (14), or as well as (10), sound from a wearable. Sound from surroundings—e.g., from inside a room, from an activity area, or even from people wearing a sound source—inform the child about what is happening around them and who is nearby. Sounds from the environment would provide important localisation cues and would work alongside the existing orientation and mobility training which visually impaired children receive. They are taught to listen to what is happening around them, so a wearable could encourage them to listen to natural sounds, be aware of what is happening nearby, and seek out something that interests them.

Others suggested that sounds could also remind the children about their training and skills. For example, when encouraging them to move, there could also be speech prompts that remind them about safe movement and techniques like mental maps.

Responses for this scenario highlighted the potential for overload if children are given too much auditory information. Complex audio cues, as well as too many cues, risk confusing young children. Visually impaired children are already dependent on this modality for other information. When we consider the novel ways in which we might use auditory feedback, we need to be mindful of how much information—and how many types of information—we are presenting. The functionality described in our scenarios may be better suited to independent use (i.e., one type of functionality at a time), with parents or teachers telling the child what mode their bracelet is in. For example, the functionality in Scenario 1 might be used during some play sessions and the functionality from Scenario 2 (awareness of friends) may be used at different times, when social play is to be encouraged. These findings agree with recommendations by Sanchez and Elias [27] to minimise the risk over short-term memory overload.

Speech was favoured by many participants for this scenario, because it can be used to clearly communicate information and instructions. However, some people cautioned that the speech would have to be appropriately designed and presented to avoid confusion. If the voice used for feedback was familiar—e.g., if it sounded like a teacher or parent—then the child might think that person was in the room and might try to find them. It would also have to be clear that the voice was not a real person and that the child is the person being 'spoken to' by the feedback—very important if there are multiple visually impaired children in the same area. It was suggested that speech could be preceeded by a jingle, to draw attention to the voice and to signify that it is not a person in the room.

Scenario 2: Helping a Child Find His or Her Friends

Participants found the functionality described in this scenario a good use of technology. There was strong agreement that social play is an important part of education and most respondents (27) agreed that it would be helpful to tell children when their friends have moved away. Most (25) also agreed that sound was an appropriate way of communicating this and that sound could be a good way of guiding children to their friends.

Almost all participants (28) thought that sound should come from a device worn by the friend, as well as—or instead of—the child's own device. Many people said that children are taught to listen for voices and move towards them if they want to find someone. Because of this, they thought it would be more beneficial for the child to hear sound from their friends as they move away; this would let them know that their friends have left and where they are going and they could follow the sound if they wanted to go with them. Others proposed interactions where the other person was prompted to say something or make a noise, so that the child can hear where they are. Visually impaired children are taught to listen for voices and move towards them if they want to find someone, so this could be an effective way of helping them find people and it supports their other training. Scenario 1 discussed a similar use of 'real' sounds, rather than digital ones; more research is needed to investigate how sounds from other people or places can be made part of interactions with technology like ours.

Building on the idea of supporting other forms of training, sensors within wearables could also monitor a child's movement to give feedback that supports skill development. Feedback could be given in real time—for example, using sound to indicate when the child veers from a straight line—or could be given later—for example, telling the child if they need to be more mindful of their balance when walking.

Some responses to this scenario suggested ways that two bracelets—the child's and a friend's—could be used together. Playrooms and playgrounds are often noisy so sound from the bracelet may be difficult to hear or a child might think it is noise from another activity. One respondent suggested that the child's bracelet could make the same sound as the friend's bracelet, so they knew what sound to listen out for. Someone else proposed a similar idea, framing it as a game where the child had to find their friend by seeking out a sound that was also being made by their bracelet. Similar games were suggested in responses for Scenario 1. Others suggested that the child's bracelet could vibrate to tell them their friend had left and they should listen for them.

Scenario 3: Learning About New Places

Respondents unanimously agreed about the importance of independent movement at school. Almost all of them (27) thought it would be useful to tell children about nearby landmarks as they moved through a school and they (27) thought sound was an appropriate way of giving this information.

Most responses favoured the use of speech (22) and "reference sounds" (27), which are familiar noises from items or activities. These were preferred to other types of audio (music: 7, abstract sounds: 5) because of their explicit meaning. Abstract sounds and music were less appropriate because of the added complexity of learning and remembering what different sounds mean, which might be especially challenging for young children. Reference sounds were also liked because of their similarity to 'real' noises, which visually impaired children are encouraged to listen to identify nearby activities.

Most thought it would be better if sound came from the point of interest as well as (18)—or instead of (11)—an audio bracelet. This is because it would be easy for them to localise the sound and hear where the landmark is. However, it was suggested that artificial sounds would not always be necessary if there were ambient sounds to listen for instead; for example, sounds from the canteen or music room. This approach would help develop the important skill of listening to and understanding what is happening nearby. Similar responses were discussed for the other scenarios: sound from the environment is a good thing because it supports important skills and the sounds hint towards the location of things.

Respondents suggested that children might have difficulty hearing sounds from the environment in school corridors, which are often noisy when the children have breaks or are moving between classes. Many participants (25) thought that vibration from a wearable would be a good way to catch a child's attention instead of sound: this could be used to tell the child that something is happening nearby and they should listen for it (and would not be masked by background noise). One respondent suggested that a wearable could 'mimic' sounds that the child should listen for. This would help them know which sounds are important and might encourage them to seek out sounds they might otherwise miss. Research is needed to investigate ways of drawing attention to sound cues, e.g. using vibration or novel sounds from multiple sound sources.

Summary

This section presented findings from an online survey—completed by professionals who specialise in working with visually impaired children—that investigated some of the design issues relating to our scenarios. These findings give a better understanding of technology for visually impaired children. A key finding was that sounds should come from the environment as well as (or instead of) sounds from a wearable. There were many reasons for this, most notably because it supports existing skills and the sounds can be easily localised.

Our research initially focused on audio bracelets and our findings suggest that these could be helpful in our scenarios. Wearables could be used as well as sound sources in the room and our participants gave many suggestions of how sound from these different sources could be combined. Sounds from a wearable could give a child hints about what to listen for and they could encourage them to listen to natural sounds from their surroundings, for example. Sounds could also come from audio bracelets worn by other people, so that a visually impaired child can hear when and where they are in the room.

Study 1 and 2 involved professionals who specialise in visual impairment education, giving important insight into the needs of visually impaired children at school and how technology might be able to help them. We also wanted to involve the children themselves in the design process, so we held a focus group with visually impaired children to further investigate good sound design and delivery.

STUDY 3: IN-SCHOOL FOCUS GROUP

We held the focus group at a local high school with a dedicated visual impairment education unit. Ten children, aged 12–17, took part and were supervised by a teacher. All children had a visual impairment but none were fully blind. Although our research focuses on younger children, we recruited high school pupils for the focus group because it gave us access to a larger group of participants and because they would be better able to reflect on their experiences growing up and articulate them in a way that younger children might be unable to.

We started the focus group by discussing Scenarios 1 and 2 as both were about play. We asked if the functionality described in those scenarios would have been useful when participants were younger. All agreed and one of them said that it would be helpful to her now because she was often unaware of things happening at school, like clubs. If she passed a room with a club in it, she would like to hear about it and be told when it was happening. Others agreed that contextual information like this would be helpful to them now, as notices about school events are inaccessible to them and they are reliant on others mentioning that they are happening. The earlier studies also found the importance of context awareness, e.g., telling a child what their friends are doing or where they are.

We asked about what sounds would be suitable for giving this type of information. Participants thought that speech would be best because it is less ambiguous than other sounds. However, some thought that it would be good to have reference sounds as well as the speech, to draw attention to simpler things that did not need to be described. We asked what the speech should consist of; the names of activities were considered important but further description may also be required, especially for younger children who might not know what happens at a particular activity. With greater familiarity, users may require less information. If the speech came from their audio bracelet then the approximate direction to the activity would also be helpful, so they would know where it is. Being told who else was at an activity might help encourage the child to try it. These findings are similar to those from earlier work about what information is relevant to blind children [27].

Next we discussed the third scenario, which used sound to tell children about their surroundings at school. The group thought this was useful and many said it would be helpful to them even in high school. They explained their own techniques for finding their way about their school: they use 'landmarks' for orientation. For example, they would remember notable architectural features or distinct areas of the school. In their school, different departments were in colour-coded corridors so they could use the colours to orient themselves. However, these visual landmarks were less useful when they were close to something they wanted to find, due to poor visual acuity. They said it would be helpful to hear sounds about their surroundings, to help them with the final steps towards a room. We asked when cues should be presented; they wanted to hear about things when they were 5-10 steps away and moving towards it, as this supported spatial awareness without telling them about less relevant places that were further away (e.g., at the end of the corridor or behind them). Information about more distant things was considered less relevant and might be distracting, due to the increased quantity of sound cues.

Sounds from the rooms, rather than from an audio bracelet, would be helpful because users could hear where things were relative to themselves. This would also help them identify particular rooms if there were two doors next to each other, common in school corridors. There were some cases where they would prefer sound from a wearable, however. Warnings about obstacles ('wet floor' signs and bins, in particular) or stairways were more suited to a wearable device because they would know from further away when they were near, could anticipate approaching them, and were more likely to hear it when the corridor was noisy. This would require some information about the obstacle location as there would be no spatial aspect of the sound. Some also raised concerns about the amount of information given: they would prefer to only be told about nearby places (e.g., five steps away), rather than those that are further away. Speech was the preferred way of presenting information, as 'reference sounds' might be ambiguous or mistaken for ambient noise. Over time, reference sounds could replace speech as children learn the building and develop their mental maps. Others [27] also note the importance of only providing necessary information to help children improve their orientation and mobility skills.

Summary

Our findings from the three studies show the importance of sound from the environment as well as from wearables. This was our motivation for *audible beacons*, small devices that support wireless communication and audio output. Such devices would support the functionality described in our scenarios, as they could be used to estimate proximity to a person or place, and would also be able to deliver auditory information from the environment. A device offering both of these features—an audible beacon—is simpler than having separate beacons and sound sources and can be easily reconfigured. In the next section we discuss our development of prototype audible beacons. These have a compact form factor that means they can be discreetly placed in a room or can be worn as an audio bracelet instead, used like the devices in our scenarios.

The focus group investigated the best ways of combining sounds from wearables and the environment, as the importance of this was discovered from Study 2. We learned that sounds from a point of interest are ideal when a few steps away, but wearables are more appropriate for sounds about hazards or things that are further away. This was unexpected, as we thought they would want to hear where obstacles were located; however, sound from a wearable would mean they were not reliant on hearing distal sounds which they might miss, or might not hear until too late. Speech was the preferred sound type for all scenarios, although some participants thought reference sounds could be presented with speech as well. This was a surprising contrast to the results of Study 2, where reference sounds were the most popular sound type. We asked if they would be willing to have speech output even if it was audible to others, but that was not a concern if it was useful. Despite this, an important aspect of sound design is that it should not draw attention to the user as requiring an assistive technology [28], an interesting consideration for future work.

AUDIBLE BEACONS: PROTOTYPES AND DESIGN SPACE

Two requirements for audible beacons have been established: flexible audio (i.e., sounds, speech, etc) and Bluetooth (for beacons and remote control). Detecting proximity to other people and delivering sound from their location is important, so small audible beacons could also be worn; these would essentially be audio bracelets with beacon capabilities. Such devices would support the requirements identified by our findings.

We have prototyped a wearable audible beacon (Figure 5). A custom circuit and loudspeaker sit inside a 3D-printed enclosure, which has two slots so it can be attached to a wrist strap.

Figure 5. A render and photo of our audible beacon prototype.

They have an audio synthesiser that can generate sounds, as well as play recorded audio, e.g., speech. They act as standard Bluetooth beacons and can be used for proximity estimation. Other devices can connect to them to control output; for example, loading a sound design, adjusting volume, or stopping playback. At the moment, we play recordings of speech but our findings show a speech synthesiser is also necessary.

A Design Space for Audible Beacon Output

From our scenarios and study findings, we have identified a design space (Table 1) that describes use of audible beacons in terms of three dimensions: their *location*, the *trigger* for their audio output, and the *purpose* of the output. *Location* identifies if audible beacons are worn, in the environment, or if both approaches are used. Previous research typically used sounds from sources fixed in the environment [12, 30] but our findings show that more flexibility is needed. We distinguish between beacons worn by the user and by another person as our studies showed benefits of sounds from another's location. We also distinguish between fixed and mobile beacons, since they could be embedded in toys, for example, which could use sound to 'advertise' themselves or enhance play. Audible beacon systems may also combine sound sources, an idea which some people suggested during our studies; for example, sound from a child's audio bracelet telling them what to listen for nearby or different devices delivering different information.

Our design space identifies events or actions that may *trigger* audio output. Previous research used sounds triggered by movement or queries to the system through another device. However, our scenarios show that many other triggers are required, for example inference (Scenario 1), social (Scenario 2), and movement (Scenario 3) triggers, and the survey suggested that feedback could be given in response to user input or scheduled in advance. This suggests future systems should consider a broader range of inputs to meet the needs of visually impaired children. It is also important to identify the *purpose* of output. Other research has used sound to inform [12, 30], to guide [20, 16, 35], and for gameplay [8], and we found new reasons for output (e.g., to encourage, to vocalise). This aspect can provide pointers for future research or assistive technologies. Systems may want to focus on a particular set of purposes, to avoid information overload.

The design space in Table 1 can be used when designing audible beacon systems to assist visually impaired people. Designers should consider the *purpose* of the sounds and how these relate to the *location* and *trigger* of the beacons. For example, we found wearables ideal for informing children about obstacles and environmental beacons were appropriate for informing them about nearby places or activities. Some purposes may require other users in the system, e.g. for encouraging a user to speak aloud. The implications of the *trigger* for output also need to be considered; e.g., social triggers may necessitate wearable audible beacons and users may benefit if sound encourages people to vocalise. Finally, the design space can also be used to inspire novel solutions to problems by identifying new applications of audible beacons; e.g., previous research on navigation may benefit from new output *triggers* and sound *locations*.

• **Location**	Location of the audible beacon (AB).
◦ **Wearable**	An AB worn on the body.
→ **Users**	AB worn by the user.
→ **Others**	AB worn by another person.
◦ **Environment**	An AB in the environment.
→ **Fixed**	AB fixed in place; e.g., beside a door.
→ **Mobile**	AB may move; e.g., placed on a toy.
• **Trigger**	Event/action that causes audio output.
◦ **Social**	Sound triggered by another person's actions; e.g., a friend approaching.
◦ **Movement**	Sound triggered by user's movement or lack of movement.
◦ **Proximity**	Sound triggered by user's proximity to a beacon.
◦ **Query**	Sound triggered by an interaction; e.g., tapping on an audio bracelet.
◦ **Inference**	System infers when to trigger sound; e.g., if it detects low activity levels.
◦ **Schedule**	Sounds are scheduled; e.g., a reminder about an upcoming activity.
• **Purpose**	The reason output was triggered.
◦ **Encourage**	To encourage a user to do something; e.g., to move, to try something new.
◦ **Discourage**	To discourage user from something; e.g., stop stereotypical behaviours.
◦ **Inform**	To tell a user something; e.g., tell them about nearby places or people.
◦ **Guide**	To guide a user's actions or movement; e.g., guide child to a teacher.
◦ **Highlight**	To draw attention to something; e.g., 'mimic' a nearby sound to listen for.
◦ **Vocalise**	To encourage someone to speak; e.g., so a child can hear them.
◦ **Remind**	To remind the user about something; e.g., about safe movement or skills.
◦ **Gameplay**	To support gameplay; e.g., playing the sound 'hidden' in the room to find.
◦ **Habilitate**	To support (re)habilitation activities; e.g., for spatial cognition [15].

Table 1. Design space describing audio beacon configurations.

OVERALL DISCUSSION AND CONCLUSIONS

We investigated ways of using audio bracelets—bracelets that produce sound—in schools and nurseries to assist visually impaired children. Audio bracelets have been successfully used in rehabilitation [15, 14] and social play [8, 19], so our research explored new ways they might be used to give assistance. Formative discussions with visual impairment education professionals revealed a number of issues faced by young children with visual impairments. These issues affected play—which has an important role in the development of social, language and movement skills—and independent movement, which is an important ability because it develops skills for independent living. From these discussions we identified ways that audio bracelets could be used to help through sound cues and we developed three scenarios that illustrate those ideas. These scenarios were important because they identified key problems we needed to address in Studies 2 and 3. The scenarios, and our evaluations of them, are useful to others developing technology for visually impaired children because they give insight into how sound may be used effectively.

An online survey for visual impairment educators and a focus group with visually impaired children evaluated the usefulness of the ideas in our scenarios. They also investigated some of the design questions that arose from them, for example, where audio cues should come from and what they should sound like. We found that speech and "reference sounds" were considered the best use of the audio modality, as they have a clear and explicit meaning. While speech is able to clearly communicate information, care needs to be taken to avoid confusing or startling the child: voices should not sound familiar and it should be clear that that voice is not from a person in the room, otherwise the child might try to find the person. Our findings also hinted at the importance of encouraging listening to ambient sounds from the people or places nearby. Research is needed to investigate the best way of drawing attention to these sounds and seeing if they are effective as assistive cues. This approach has been successful in navigation instructions (e.g., *auditory perceptible landmarks* [2] and *soundmarks* [18]) but it is unknown if it could improve spatial cognition or encourage more activity in young children.

Our studies also showed the benefits of our ideas for audio bracelets and provided useful insight into how this technology could be used effectively. Our findings revealed novel ways of combining sound from audio bracelets with sounds in the environment and gave insight into sound design for these situations. The main reasons sound should also be delivered from the environment are that this supports the development of existing skills and provides useful localisation cues. This inspired audible beacons. These satisfy the technical requirements of our scenarios, through their ability to estimate proximity and remotely produce sound.

In this paper, we described the implementation of an audible beacon that has a wearable form factor, meaning it can also be used as an audio bracelet. This reference hardware meets the requirements we identified through our design studies, showing the technical feasibility of our scenarios. We also presented a design space showing the broad range of novel interactions possible with audible beacons. This design space should be used when developing auditory systems for visually impaired children because it highlights key considerations about the design and delivery of feedback. Our findings also contribute a better understanding of the factors within this space, for example showing the importance of pairing types of sound with appropriate sound locations and triggers. To conclude, this paper presents a formative investigation of how sound can be used in schools to help visually impaired children. Our key finding was that sounds from different sources are necessary, so we contribute a design space and findings that provide a foundation for design and research in this area.

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