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SONIFICATIONS FOR DIGITAL AUDIO WORKSTATIONS: REFLECTIONS ON A PARTICIPATORY DESIGN APPROACH

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ABSTRACT

Methods to engage users in the design process rely predominantly on visual techniques, such as paper prototypes, to facilitate the expression and communication of design ideas. The visual nature of these tools makes them inaccessible to people living with visual impairments. Additionally, while using visual means to express ideas for designing graphical interfaces is appropriate, it is harder to use them to articulate the design of non-visual displays. We applied a user-centred approach that incorporates various participatory design techniques to help make the design process accessible to visually impaired musicians and audio production specialists to examine how auditory displays, sonification and haptic interaction can support some of their activities. We describe this approach together with the resulting designs, and reflect on the benefits and challenges that we encountered when applying these techniques in the context of designing sonifications to support audio editing.

1. INTRODUCTION

Advances in technology are changing the way we interact with information, increasingly replacing traditional forms of representation by digital alternatives. Paradoxically, these advancements can have a hindering effect on users who rely on screen-readers as a primary means to access and interact with digital information. While screen-readers can be somewhat reliable for accessing sequentially presented information, such as written text, they can be inadequate for providing flexible access to dynamic and graphic information and can fall short of providing a good interaction model to support collaborative activities between sighted and visually-impaired people [1]. It is therefore important to investigate alternative ways to interact with digital information that go beyond the bounds of visual displays for the benefit of all potential users.

We have been exploring how to design for non-visual interaction with graph-base diagrams in a range of domains including engineering diagrams, subway maps, and visual programming, and more recently sound editing and audio production, which provides the context of this paper. In the audio production industry, visually-impaired audio engineers and production specialists rely on screen-readers to access digital audio workstations (DAWs), which are the primary tools for modern sound editing. However, unlike traditional audio production tools, modern DAWs interfaces

are highly visual and incorporate a number of graphical representations of audio parameters to support editing and mastering, such as waveforms and automation graphs¹, which are entirely inaccessible to users of screen-readers. In this context, we were interested in engaging end users to examine how non-visual interaction techniques can be used to design effective access to modern DAWs. Naturally, solutions to addressing accessibility issues faced by users living with visual impairments should be designed using non-visual modalities, such as audio, tactile and haptic displays. However, expressing design ideas that exploit these modalities is challenging. Unlike graphical designs, which can be drawn, edited and manipulated using low cost means, such as paper prototypes, it is harder to articulate, for example, how a particular shape or colour could be represented auditorially or haptically, or how to interact with an auditory or a tactile object. Additionally, involving users living with visual impairments in the design process means that visual tools that are typically used in participatory design should be adapted or replaced to accommodate the particular needs of this population of users. We developed and applied a user-centred approach that incorporates various techniques to help make a participatory design process more accessible to people living with visual impairments. This paper details our participatory design approach and reflects on the benefits and challenges that resulted from employing it. We also describe some of the designs that resulted from this approach, which combine auditory display, sonification and haptic interaction.

2. BACKGROUND

2.1. Non-visual participatory design

One of the challenges that designers face when co-designing with users living with visual impairments is that typical participatory design tools and techniques, such as sorting cards and low-fi paper prototypes, are visual tools and so cannot be readily employed to accommodate the needs of this population of users. A number of researchers have attempted to use alternative methods to overcome this issue. For example, using a scenario-based approach enabled rapid communication during workshop activities involving students and visually impaired stakeholders [2]. A detailed description of this approach is given in [3] where scenario-based textual narrative was tailored and used as a basis for design dialogue between a sighted designer and users living with visual impairments. Evaluations of this approach highlighted the importance



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¹An automation graph shows the portion of a sound to which an audio effect such as reverb or distortion is applied and the level at which the effect is applied, e.g. the amount of reverb or distortion.

of including users in the design process at two levels; first in the design of the scenarios themselves to ensure they include appropriate levels of description and use correct vocabulary that match experience with current accessibility technology; and second when employing those scenarios in design sessions. Other approaches that proposed alternatives to visual design tools include the use of a tactile paper prototype which was developed as part of the HyperBraille project [4]. In this project, a 120x60 two dimensional pin display is used to display multiple lines of text and graphics in combination with an audio display. But using Braille technology to display text as a design tool might exclude users who are not Braille literate. An alternative would be to use low-fi physical prototypes. An example of this is found in [5], which describes the use of raised paper together with rubber bands and pins to explore how line graphs can be constructed non-visually. A workshop that ran as part of the NordiCHI conference in 2008 focused on developing guidelines for haptic low-fi prototyping [6], many of the suggestions made during that workshop can be used as part of an accessible participatory design process. For example, using lego models and technology examples together with scenarios to help give users first hand experience of designed tools [7], or tangible models, such as cardboard mockups and plastic models, to support early prototyping activities of accessible haptic and tactile displays [8]. The main drawback of such tangible models are their static nature; once produced, it is hard to alter them in response to user feedback in real-time. Physical mockups are also naturally only suitable to prototype tactile interaction and do not adequately account for auditory interaction.

2.2. Design Problem Domain: Digital Audio Workstations

In the audio production industry, visually-impaired audio engineers and audio production specialists rely on screen-reader technology to access modern DAWs. But DAWs interfaces are highly visual and incorporate a number of graphical representations of sound to support editing and mastering, such as waveform representations, which are entirely inaccessible to screen-readers (e.g. Figure 1). In a competitive industry, the time it takes to overcome these accessibility barriers often hinders the ability to deliver projects in a timely manner and to effectively collaborate with sighted partners and hence can lead to the loss of business opportunities.

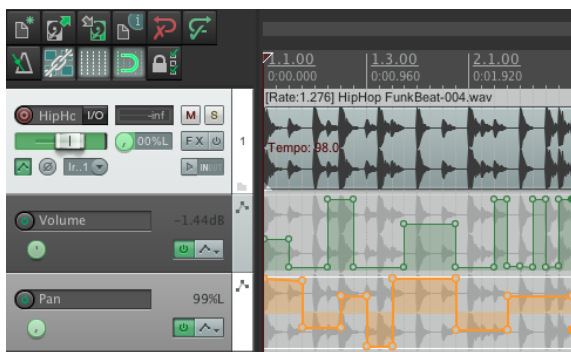


Figure 1: Example of a densely visual DAW interface.

3. APPROACH

Figure 2 shows an overview of our user-centred approach to conducting participatory design with people living with visual impairments. At the core of this approach was an attempt to incorporate accessible means for designing non-visual interaction by combining audio-tactile physical mock-ups with participatory prototyping and audio diaries. Our approach was organised around three main stages, an initial exploratory workshop, followed by a series of iterative participatory prototyping workshop sessions, and a final evaluation workshop. We describe each stage in the following sections together with the accessible techniques we employed and the designs that resulted from this process.

3.1. Participants & Setup

We advertised a call for participation in a number of specialised mailing lists for professionals living with visual impairments. We called for participants who specifically come across difficulties when engaging with sighted colleagues in their workplace due to the inaccessibility of tools they have available to them in the audio production industry. We recruited the first 18 respondents (14 male and 4 female, mean age 47) who worked across a number of domains as professional musicians, audio production specialists, sound engineers, and radio producers. All participants had no or very little sight, and all without exception used a speech or braille-based screen-reader to access information, and used a mobility aid such as a cane or a guide dog. Workshop sessions were held at the authors' institution in an informal workspace and lasted between 3 to 5 hours each.

3.2. Stage 1: Initial Workshop

The first stage of our participatory design approach involved setting up an initial workshop with participants organised around three main activities; focus group discussions, technology demonstrations, and audio-haptic mockups design activities.

Focus group discussions: The initial workshop was kick started with a group discussion involving both designers and participants. The discussions were structured around a number of topics to achieve the following aims:

- Establishing an understanding of current best practice in participants' various working domains and how current accessibility technology supports it.
- Establishing an understanding of the limitations of current accessibility technology.
- Building consensus around a priority list of tasks that are either difficult or impossible to accomplish using current accessibility solutions and that participants would like to be accessible. The aim was to use the list of tasks to drive the participatory design parts of this initial workshops as well as to set the direction for follow up activities.

Together with participants we explored work practices and current accessible solutions available to audio production specialists and musicians. As an example of best practice, participants explained that extending screen-reader functionality with specialised scripts is the most popular approach used to improve the accessibility of "hard-to-use" applications such as DAWs, yet they remain inadequate when accessing waveform representations, applying sound effects, or navigating a large parameter space.

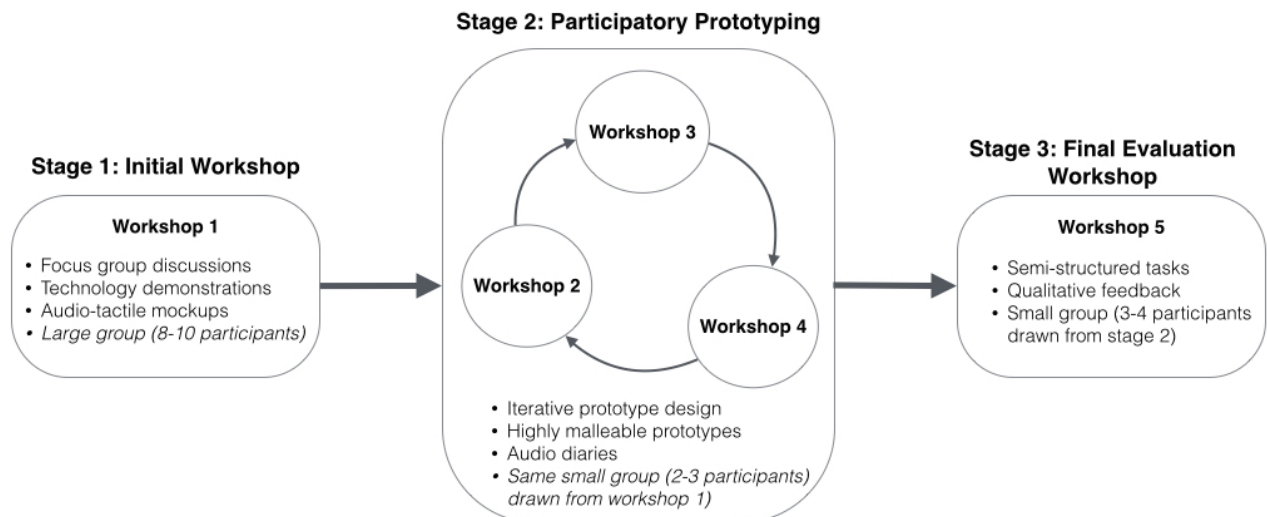


Figure 2: Overview of our approach to conducting accessible participatory design with people living with visual impairments. We employed this approach in two domains; diagram editing and audio production



Figure 3: Some of the technology demonstrated in the initial workshop stage.

Technology demonstrations: The second part of the initial workshop involved hands-on demonstrations of a range of accessible technology that could be used as a basis for designing better solutions to the accessibility limitations of DAWs identified in the focus discussions. Technology demonstrations were performed on either a one to one basis or with pairs of participants. We demonstrated the capabilities of two haptic devices (a Phantom Omni² and a Falcon³), a multi-touch tablet, motorised faders (see Figure 3), as well examples of sonification mappings and speech-based displays of information. We deliberately demonstrated the capabilities of a given technology without any reference to an actual application in order that the possibilities offered by the technology are not constrained by a specific domain or context. For example, in order to ensure an application-independent demonstration of the Phantom Omni and Falcon haptic devices, we used a custom program that allowed us to switch between different effects that could be simulated with these devices, such as vibration, spring effects and viscosity. The custom program allowed us to manipulate various parameters to demonstrate the range of representations and resolutions that could be achieved with each device in real-time. Similarly, we demonstrated sonifications of random data sets using a custom program that showed how manipulating different audio parameters alters the resulting audio output.

²<http://www.dentsable.com/haptic-phantom-omni.htm>

³<http://www.novint.com/index.php/novintfalcon>

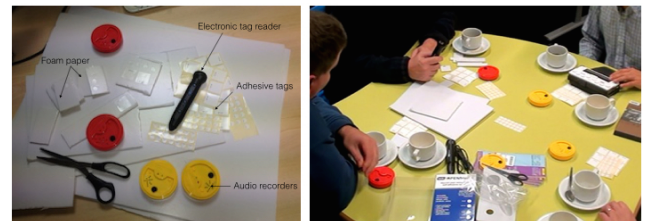


Figure 4: Foam paper, audio recorders, adhesive label tags and electronic tag readers used to create low-fi audio-tactile mock-ups.

Audio-tactile physical mock-up design: We then invited participants to actively think through new designs in the last part of the initial workshop. Having had a hands-on experience with the capabilities of new technology, participants worked in small groups, with one to two design team members forming part of each group, and explored the design of a new interface that could be used to address some of the problematic tasks identified in the initial discussions. Participants were encouraged to think about how such tasks could be supported using some or all of the technology that they experienced through the hands-on demonstrations or how these could augment existing solutions to achieved better outcomes. To help with this process, we attempted to use an accessible version of physical mock-up design [9]. The material used to construct the physical mock-ups included foam paper, basic audio recorders, label tags and electronic tag readers (see Figure 4). Foam paper could be cut into various forms and shapes with the assistance of the sighted group member and used to build tangible tactile structures. Self adhesive tags could be attached to pieces of foam paper, which could then be associated with an audio description that can be both recorded and read using electronic tag readers. Additionally, basic audio recorders (the circular devices shown on Figure 4), which could record up to 20 seconds of audio, were provided to allow

participants to record additional audio descriptions of their physical mock-ups. Thus, different pieces of auditorially labeled foam paper forms could be organised spatially and, if combined with the audio recording devices, could constitute physical low-fi semi-interactive audio-tactile mock-ups of an interface display or a flow of interaction. To close the session, participants were invited to present their physical mock-ups to the rest of the participants for further discussion. These design ideas were then used as a basis for driving the next stage in the design process.

3.3. Stage 2: Participatory Prototyping

The second stage in our participatory design approach involved conducting a series of participatory prototyping workshops to engage users in an iterative design process that gradually develops fully functional designs. We invited smaller groups of participants (2 to 3 participants who also took part in the initial workshop) to actively contribute to the design of basic prototype implementations that embodied the design ideas generated in the initial stage. We wanted to elicit the help of the same participants who were involved in the initial stage to ensure continuity in terms of where the ideas were generated from and how these are to be further developed and refined into concrete implementations.

Participatory prototyping activities in this stage (see Figure 5) had a number of important characteristics. First, rather than being exploratory in nature - as was the case in Stage 1 - activities at this stage were structured around the tasks that were identified as being problematic in the initial workshop. The aim was to expose the participants to prototype designs that embody the ideas generated in the initial workshop of how such tasks could be supported, and to work closely with them to improve on the implementations of these ideas through iterative prototype development. For example, participants used a sonification mapping that represented the peaks of a waveform to locate areas of interest within an audio track. The sonification mappings were based on ideas generated in the initial workshop, but could be manipulated programmatically in real time in response to participants' feedback. Secondly, as opposed to the low-fi physical mock-ups used in the previous stage, the prototype implementations were developed into a highly malleable digital form. Thirdly, each set of participatory prototyping sessions were held with the same group of participants through a collection of three to four workshops that were one to two weeks apart. While the design team worked on implementing participants' feedback in the interim periods, participants were asked to keep detailed audio diaries of domain activities.

Highly malleable prototypes: The prototypes we developed to embody the design ideas generated in the initial stage of this approach were highly malleable because they supported a number of alternatives for presenting a given information or supporting a given task or functionality. The key to employing a highly malleable prototype in our approach is that it was easily customisable and alternatives were quickly and easily generated in real-time. We achieved this flexibility by developing custom control panels, which we had available to us throughout the participatory prototyping sessions. For example, we developed a prototype DAW controller that supports the scanning of a waveform representation by moving a proxy in a given direction and displaying an audio-haptic effect whose main parameters are mapped to the data values represented by the waveform (e.g. amplitude mapped to friction and frequency mapped to texture; a haptification and sonification of data). This design was malleable in a number of ways; the di-



Figure 5: Participatory prototyping

rection of scanning could be altered to be horizontal or vertical and could be initiated at different starting points; the mapping used to drive the haptification and sonification of the waveform could also be adjusted in terms of scale and polarity; and finally, the haptic effects themselves could be altered to display, for instance, friction, vibration or viscosity. The malleability of prototypes allowed participants to explore different implementations of the same functionality in real-time, which in turn facilitated the contrasting of ideas and the expression of more informed preferences and feedback. Additionally, the prototypes could also be reprogrammed in real-time. That is, if participants wished to explore an alternative implementation of a given functionality or feature that could not be readily customised using the control panels, we reprogram these features on the fly as and when this was needed.

Audio diaries: Another technique that we employed in this stage was to ask participants to record audio diaries in the interim periods that preceded each participatory prototyping session. Specifically, we asked participants to attempt to complete similar tasks to the ones explored during the sessions at their homes or workplaces. We asked them to do this while using their current accessibility technology setup and encouraged them to reflect on the process of completing these tasks in light of the particular iteration of prototype development that they were exposed to in the preceding participatory prototyping session. Whenever participants produced an audio diary they would share it with the design team prior to the next prototyping session. This provided the designers with further feedback, thoughts and reflections that they could then incorporate in the next iteration of the prototypes and present to the participants in the next round of development.

3.4. Produced Designs

Here we present examples of the audio-haptic prototypes that resulted from the first and second stages of this design process. One of the tasks that was identified as difficult to achieve with current accessibility tools is applying sound effects to audio tracks. On a visual display, applying a sound effect can be achieved by drawing an automation graph overlaying the waveform representation of an audio track, which in turn involves editing the points that constitute the graph (e.g. Figure 6). Editing the graph is accomplished by: i) locating an existing point or creating a new one, ii) estimating the point's position on the X and Y axes, and iii) altering these coordinates to reflect the desired level of effect (Y axis) at a given time on the track timeline (X axis). The representations that support these tasks are inaccessible to screen-readers.

3.4.1. Point Estimation in Automation Graphs

The participatory design activities that we undertook explored how a range of alternative audio and haptic representations of automation graphs could be used to improve the accessibility of these

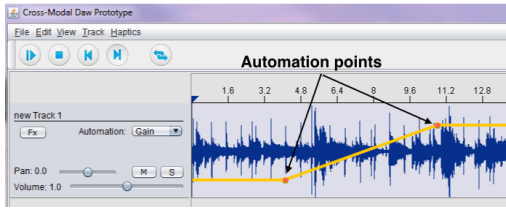


Figure 6: Applying an effect to a track using an automation graph.

artefacts in DAW interfaces. Participants highlighted the importance of providing adequate feedback to indicate the positions of automation points. However, representing the position of an automation point on the Y axis as a single tone was deemed by participants to be insufficient as they needed to know the position of a given point in relation to other points. We thus explored a number of alternative sonifications for conveying the position of automation points. We first designed a simple auditory interface to support the task of editing the position of a point when creating a graph, focussing on the part where users need to estimate the position of a point when placing it at a desired location on an axis. The interface allows users to manipulate the position of a point using the keyboard up and down arrow keys on an axis containing a total of 30 positions (ranging from -15 to 15, the value 0 being the middle position in accordance with typical scales used in DAWs). We then design different interactive sonifications to convey feedback about the position of a point and references that mark how far it is from an origin. Examples of these sonification have been submitted as MP3 file together this paper).

Pitch-Only Sonification Mapping: In the first design, we sonified the position of a point on an axis by mapping the pitch of a sine tone to the point's Y coordinate following a positive polarity. That is, the tone's pitch changes in accordance with the point's movements on the axis; moving the point up increases the pitch, moving it down decreases it. We used an exponential function to map the position of the point to frequencies in the range of 120Hz (for position -15) to 5000Hz (for position 15). The range and mapping were chosen to fit within the human hearing range, with the exponential distribution, subsequent frequencies differ by a constant factor instead of a constant term and this has been found to be superior to linear mappings [10]. Interaction with this sonification was designed such that the point moves when users press and hold a cursor key. Pressing and holding a cursor key would therefore trigger a continuous sonification of the point as it moves on the axis (SonExample1.mp3).

One-Reference Sonification Mapping: In the second design, we used the same pitch mapping described above and added one tone to convey a reference to an origin point. In this case, the reference tone represented the middle point on the scale (position 0 at a pitch frequency of 774Hz lasting 100 milliseconds). We designed this such that the user hears pitch changes that correspond to the movement of the point when they press and hold a cursor key, and hears the reference tone with a static pitch on key release. Comparing the two pitches (on key pressed and on key released) is meant to provide a sense of distance between the current position on the axis and the origin point based on pitch difference; the larger the difference in pitch between the two points the further away from the origin the point is located (SonExample2.mp3).

Multiple-References Sonification Mapping: In the third design, we again used the same pitch mapping as described above.

But, instead of hearing only one reference point on key release, the user hears multiple successive reference tones with varying pitches that correspond to all the points between the current position and the origin reference. Previous research has shown that the threshold for determining the order of temporally presented tones is from 20 to 100 milliseconds [11]. To create a succession of tones, our reference tones lasted 50 milliseconds and were interleaved by a delay also of 50 milliseconds. In this case, the position of a point in relation to an origin can be estimated by judging both the pitch difference at that point compared to the subsequent points, and the length of the sum of successive tones that separate it from the origin. A longer distance yields a longer succession of tones. Points located below the origin trigger an ascending set of tones, while those above the origin trigger a descending set of tones. For example, on reaching position 7, users hear a descending succession of tones made up of all the pitches of points 6, 5, 4, 3, 2, 1 and 0, the origin (SonExample3.mp3).



Figure 7: Phantom Omni device and the virtual vertical axis used in the audio-haptic design.

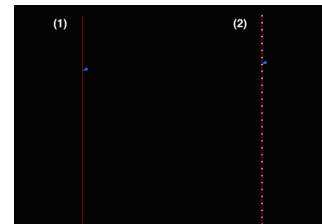


Figure 8: A free-form (1) and grid-based (2) haptic designs of a virtual axis.

Audio-Haptic Interaction: We also designed a simple user interface that allows users to manipulate the position of a point using a Phantom Omni haptic device instead of a keyboard by using its proxy to traverse a virtual axis with a vertical motion. The virtual axis was designed to be 16cm tall, sitting 5cm above the base of the device and 16cm away from it (Figure 7). We used two basic haptic design to render the vertical axis; in a *free-form* haptic design, we rendered the axis as a smooth line (Figure 8 (1)). In a *grid-based* haptic design, we introduced a grid like structure by highlighting each position on the line with a magnetic effect such that moving the proxy along the line feels like snapping from one point to another. Points were positioned about 0.5cm apart (Figure 8 (2)). A quick upwards or downwards movement in this design gives a textured as opposed to a smooth haptic sensation. In addition to these haptic designs, the user movements were constrained to the virtual axis, allowing users to feel both the top and the bottom of the axis. Movements on the axis and reference to the origin were also sonified using the sonification designs

described above, with the exception that a grid-based haptification rendered the sonification to be discrete rather than continuous (SonExample4.mp3).

3.4.2. Sonification of Peak Level Meters

Another task that was identified as difficult to achieve using screen-readers is gaining an overview of the overall shape of a waveform and identifying areas of interest within an audio track, for example whether the amplitude of an audio track goes past a threshold that causes the signal to distort – also known as clipping. The former is typically represented with a waveform representation (Figures 6 and 10), the latter with a visual indicator called the peak level meter, which conveys audio levels in real-time by flashing amber and red coloured signals (Figure 9).

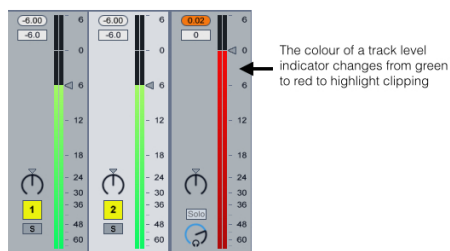


Figure 9: Visual peak level meters.

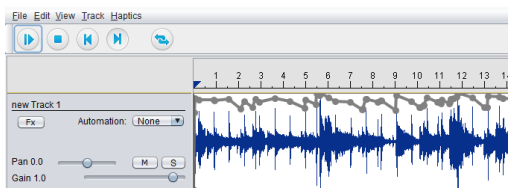


Figure 10: Extracting peak level information to be sonified.

Participants highlighted that the sonifications we designed for point estimation could be used to access peak level meter information. We thus explored how these sonifications could be modified and used to monitor variations in the shape of a waveform and to highlight clipping areas. The result was a sonification that can be used in two modes: a continuous mode in which the peaks of a signal from an audio track are used to modulated the frequency of a sine wave (Figure 10, SonExample5.mp3); and a clipping mode in which the sine wave modulation is only displayed when parts of an audio track exceed a user specified threshold. The clipping mode produces a short alarm beep (200 ms) each time the audio level goes past the threshold set by the user. We also used stereo panning to indicate whether the clipping occurs on the left or right audio output channel (SonExample6.mp3).

3.5. Stage 3: Final Workshop & Qualitative Evaluation

In the third and final stage of our design process we invited groups of participants (2-3 participants who also took part in stage 2) to evaluate the final designs and provide further feedback. We asked participants to complete semi-structured tasks based on those identified as difficult to accomplish using current accessibility solu-

tions in the initial workshop. The choice of tasks was chosen together with the participants prior to the workshop. The aim was to test the developed solutions using realistic scenarios that matched participants' actual working processes. To evaluate the sonifications of point estimation, we presented participants with audio tracks that were unknown to them and asked them to create automation graphs to apply various audio effects at different points on the tracks, such as panning and mixing track by inserting fade-in and outs at different points. This task involved scanning through the tracks, identifying where an audio effect should be applied, and then creating an automation graph by inserting automation points and estimating their positions. For the peak level meter sonification, we asked participants to examine a set of audio tracks and to use the sonification to monitor audio signal levels and to describe the information they could extract from the sonification and how they would use this as part of their working process.

Feedback: We collected participants feedback through observations, think aloud protocols and informal interviews. Participants were able to use the sonifications to create automation graphs, accurately inserting and editing audio effects to realise an outcome that they felt satisfied with. In particular, participants found that it was useful to combine the haptic and sonification displays as this gave their interactions an increased sense of immediacy and control. They also pointed out that, with little training (20 mins), they were able to edit audio effects as fast as they would have when using their typical setup with screen-reader scripts, but that they felt more expressive with the non-speech audio-haptic designs. One participant commented that a speech output during a creative process such as mixing audio effects can be unpleasant and distracting, and that replacing the speech element with non-spoken output such as the designed sonifications made the process more immersive and enjoyable. However, participants also pointed out that it was sometimes difficult to know how much pressure to apply when manipulating the haptic proxy at a given automation point. One participant concluded that this could be because of the vertical motion that tool enforced, highlighting that horizontal movements, e.g. placing the device proxy on a physical flat surface, might be more intuitive. The free-form haptification seems to have eased this difficulty since it was also received much better than the grid-based haptification. Participants highlighted that a grid-based display allowed them to count their way through the display when estimating point positions and distances on the vertical axis, however they found this to be too restrictive, forcing them to work in a manner similar to using a speech display due to the discrete nature of movement. Participants found the sonification of peak levels to be useful in exploring waveforms. Interestingly, the sonification designs were appropriated differently by each participants. For instance, one participant preferred the continuous sonification of peak levels to assess whether two audio tracks' levels are consistent after mixing them together. They highlighted that a sonification of this kind gives them more insight than using a speech display, which can only provide access to a single track at a time. Another participants preferred to use the sonification in the clipping mode, but appropriated its use by looping a portion of an audio track while gradually reducing the clipping threshold until this displayed a consistently continuous tone, and monitored this consistency to judge the overall signal level of the track. Interestingly, at the end of this process, this participant described the audio waveform using terms such as "thick" and "chunky", i.e. meaning that it had a low dynamic range, and thus was referring to its visual features rather than to how it was sounding.

3.6. Further Design Validations:

We sought to validate the produced designs in two ways. First we ran controlled user studies to compare the different sonifications and combinations of audio-haptic displays on point estimation tasks. Second, we developed and released the peak levels sonification as a VST plugin that can be freely downloaded and installed on modern DAWs as a way to collect more feedback from the community of users. The plugin has so far been downloaded by over 80 visually impaired users in the first 6 weeks of its release, which demonstrates that the approach we used can generate research findings, and develop concrete design concepts, prototypes, and products.

4. REFLECTIONS ON THE PROCESS

The user-centred approach presented in this paper attempts to address issues associated with the accessibility of a participatory design process to people living with visual impairments. In particular, the approach emphasised the use of audio-haptic technology throughout the design process in order to facilitate discussions about audio and haptic percepts and help the envisioning and capturing of non-visual design ideas. In our experience, close interaction with participants through detailed and thorough workshops such as the ones reported in this paper, allows designers to gain an appreciation of the issues faced by users living with visual impairments and a deeper understanding of how these could be addressed. In general, participants and designers brought different sets of expertise to the sessions. Participants had knowledge about the domain of their expertise but also in-depth knowledge about the practical limitations of current accessibility solutions, while designers brought design and technical knowledge. We consider the three stages that constitute this approach to be complimentary in terms of the nature and aims of the activities they encompass. The initial stage was exploratory in nature and aimed to establish basic understandings of practice and technology before attempting to engage participants in generating and capturing broad design ideas. The second stage was more focused and addressed finer details of tasks and functionality in an iterative design process. The final stage focused on evaluation of the produced designs based on realistic scenarios. Here, we reflect on the benefits and challenges of the various techniques we used our approach.

Understanding context & building a common vocabulary:

The initial workshop was valuable in helping all participants (users and designers) establish a deeper understanding of context and possibilities. From the designers' perspective, this included learning about the issues faced by users living with visual impairments, as well as when and where current technology failed to address those issues. From the users' perspective, this included encountering and understanding the capabilities of new technology, and hence new possibilities, as well as exchanging experiences with fellow users. In essence, only after each party learned more about these independent aspects (context and technological capabilities) were they then ready to move into a shared design space where they could effectively explore and generate design ideas together.

The technology demonstrations were thus a valuable part of the initial stage. The benefits of demoing technology were twofolds. First, the demonstrations helped familiarise every participant with the technology that will be used to design potential solutions, which they may or may not have already come across. All participants could then engage in the design process with the

same baseline of understanding and appreciation of possibilities. Second, the demonstrations helped in establishing a common vocabulary between designers and users that could then be used to express and communicate non-visual design ideas that later informed parts of the workshops. This exercise was particularly important for non-visual experiences particularly between sighted and visually impaired interlocutors, and this lack of vocabulary has previously been found to hinder design activities [12].

Communication barriers & asymmetry of participation:

Not all the techniques used in the first stage of the design process achieved their expected outcomes and benefits. In the final part of the initial workshop, we observed that participants attempted to use the material provided to create audio-tactile mock-ups but, as discussions unfolded, they drifted away from these materials and focused on verbal exchange only. In our experience, the less material participants used the more ideas they expressed. Thus, the process of constructing these mock-ups seems to have hindered rather than encouraged communication. Our audio-tactile mock-ups have therefore had the opposite effect of their visual counterpart methods, where the use of mock-ups is often associated with engendering imagination and conversation [13]. While it is possible that training might change the situation, in general, one of the benefits of low-fi mock-up design activities lies in the fact that they require minimal training while yielding significant design insights. More training is therefore not necessarily desirable in this case. Another explanation for this is that users living with visual impairments were not able to access the construction of a physical prototype in the same moment as it is being constructed and so the process lacks the emergent properties and illuminating qualities that it can have when shared by sighted co-designers. That is, the audio-tactile mock-ups no longer functioned as an immediate shared artefact, which may have contributed to decreasing the spontaneity that the visual counterpart process has. Indeed, the use of the physical mock-ups might also have contributed to creating an asymmetry between the contributions of the sighted designers – who could not only see the physical artefacts but also assist with their construction – and those of the other participants. In this sense, the shift away from the physical artefacts to the verbal descriptions would have contributed to balancing this asymmetry between designers and participants since all parties were then using a modality that could be equally shared amongst everyone.

Another possible explanation for this observation is indeed the type of users we worked with. Users living with visual impairments are perhaps used to talking about their experiences descriptively and so do not have the same need as other end user groups to realise their design ideas in a physical form in order to be able to listen and talk about them. Another possibility is that the tasks that users were trying to design for were too complex to be captured using the low-fi material provided. Our observations are nonetheless in line with previous work that found narrative scenario-based design to be a particularly effective tool of co-designing with participants living with visual impairments [2, 3]. Still, thorough comparisons of these different methods for non-visual participatory design is lacking and more studies are needed to further investigate these issues.

The collection of workshops that we held in the second and third stages of our process were valuable in helping us delve deeper into the design of the developed solutions and how these fit in with actual working scenarios. These sessions were an opportunity to collectively scrutinise finer aspects of design and thus provided a further joint learning space where participants learn more about

the technology and the techniques, e.g. sonification mappings, and designers learn about actual workflows and processes. The small number of participants in these sessions helped achieved higher degrees of engagement and detailed scrutiny (with sessions often lasting up to 5 hours). The medium for facilitating participatory prototyping in this space were the highly malleable prototypes.

Prototype malleability & Expanding reflection space: The malleability of these digital prototypes was critical in ensuring the success of the participatory prototyping sessions. Being able to present participants with different alternatives and reprogram features on the fly captured an essential characteristic that is found in, for example, paper prototyping techniques that make them an extremely effective design tools [9]. The prototypes capacity to be adaptable in response to changes and feedback generated from the joint prototyping process is crucial in prototyping activities [14], and non-visual design tools should therefore incorporate flexible levels of adaptability for them to attain the same level of efficiency as their visual counterparts. Thus, while this was not true in our experience with using the physical audio-tactile mock-ups, which hindered rather than nurtured communication and exchange of design ideas, digital implementations of highly malleable prototypes afforded a more supportive medium of communication between visually impaired participants and designers.

The use of audio diaries was also valuable in a number of ways; first, they expanded the space of reflection on designs to reach beyond the bounds of the workshop sessions themselves. Participants were able to go back to their familiar home or workplace settings, re-experience the tasks with their own technology, compare this to what they have experienced with the new prototypes and record these reflections on an audio diary. Secondly, audio diaries provided the designers with an extra resource of feedback, it gave the designers access to actual in-situ experiences with current accessibility solutions – often these were screen-reader based technologies, and so the audio diaries captured both participants commentary and the interface interactions in speech. Users provided running commentary, explaining rational for certain interactions, issues and potential solutions to them in light of their experience in the initial workshop session and the participatory prototyping sessions. Audio diaries thus gave direct access to actual experiences with accessibility technology that would have been harder to tap into otherwise.

5. CONCLUSION

We presented a user-centred approach for conducting participatory design with users living with visual impairments. This approach incorporates accessible means for expressing non-visual design ideas for editing audio using digital audio workstations. It emphasises the need to use non-visual technology throughout the design process in order to build shared vocabularies and support effective expression, communication and capture of auditory and haptic design ideas. Our approach combined an initial stage involving focused discussions, application-independent technology demonstrations and non-visual mock-up design activities; a second stage of iterative participatory prototyping sessions that rely on highly malleable non-visual prototypes and audio diaries; and third stage of qualitative evaluations. We presented the design of sonifications and audio-haptic interfaces that resulted from this process and reflected on the benefits and challenges that we experienced when applying this approach. In particular, non-visual audio-haptic technology demonstrations allowed us to establish a

baseline of shared understanding and to build a shared vocabulary for expressing non-visual design ideas, while low-fi physical audio-tactile mock-ups did not encourage co-design as anticipated and instead hindered communication. Participants switched to verbal descriptions to generate and capture design ideas instead. The use of highly malleable non-visual digital prototypes in the second and third stages provided an effective medium for shared design and implementation activities, while audio diaries expanded the users' reflection space to reach beyond design sessions and provided designers with a further resource of feedback.

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