THE AUDIBLE UNIVERSE WORKSHOP: AN INTERDISCIPLINARY APPROACH TO THE DESIGN AND EVALUATION OF TOOLS FOR ASTRONOMICAL DATA SONIFICATION

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ABSTRACT

Even if images of astrophysical objects are used by professional astronomers for research and by the public for outreach, we are all basically blind to the Universe. Challenging the idea that we should always use visualisations, there has been a growing interest in converting astronomical phenomena into sound, motivated by: making astronomy more accessible to people who are blind or visually impaired (BVI); creating more engaging educational resources, and enabling a deeper understanding of complex astronomical data.
The Audible Universe (AU) workshop focuses on consolidating what has been done in the field so far and identifying the areas where most effort is required to make progress over the coming years. The second edition of the AU workshop (AU2) took place in 2022, and brought together 50 experts, among whom astronomers interested in sonification, sound designers, experts in sound perception and educators. This community started a multi-disciplinary discussion about how to properly design and evaluate sonification tools. In this methodological and position paper, we present and discuss the main activities of the AU2 workshop, with a particular focus on activities concerned with the development of collaborative design processes, and the implementation of methods for evaluation. While this workshop was dedicated to fostering exchanges between the sonification community and astronomers, the structure and the methods used within the workshop are transferable to other application areas, and a contribution to the effort to develop interdisciplinary strategies for the development of the field of sonification.

1. INTRODUCTION

Every astronomical image starts as a set of numbers. Highly specialized instruments capture energy from specific ranges of the electromagnetic spectrum, which are mostly invisible to the human eye. To help us explore the data, we map it to colors that we can see. What we perceive as astronomical images are, in many cases, visual representations of invisible phenomena. While these images may be inspiring, it is important to remember that the data behind them is what holds the most scientific value. The choice to create a visual representation is a subjective one. Over the past decade, astronomers have been investigating an alternative display – mapping data to sound, or sonification, as reviewed recently by Zanella et al. [1].
The Audible Universe project was born from the meeting between astronomers interested in sonification ('Star' people), and experts in sound perception and design ('Sound' people), together with psychologists, and educators. The main drivers of the 'Star' people, interested in sonification, are: (1) making astronomy more accessible to people who are blind or vision impaired (BVI); (2) creating more engaging and inclusive educational resources; (3) developing innovative methods for scientific analysis and investigation of big and complex datasets. A handful of BVI professional astronomers have been participating in the project (Enrique Pérez Montero, Nicolas Bonne, Garry Foran and Argiris Koumtzis), who have experience in inventing and developing their own methods to perform their academic research [2].
The Audible Universe workshop #2 (AU2) followed a shorter online-only workshop (AU1) held in September 2021. The aim of the initial workshop was to review the progress made in the field and identify areas requiring further effort over the coming years. During the workshop, the attendees focused on several key areas, including accessibility in astronomy and outreach, improving the design process for sonification applications, and learning from sound experts to enhance future designs. Additionally, there was discussion on improving the evaluation process for both current and future sonification projects in astronomy. The results of these discussions were published in a series of four articles in Nature Astronomy ([1], [3], [4], [5]).
The AU2 workshop was designed to address the development needs that were identified in the previous workshop. It focused on a selected set of existing sonification tools developed for astronomical data, as shown in Table 1, and included introductory plenary talks followed by a series of collaborative splinter sessions on sonification, design, and evaluation. The

splinter sessions had the added benefit of providing sufficient interaction between professionals in disparate fields related to sonification [12] to acquire mutually understood vocabulary and modes of communication.
The main purpose of this paper is to present the methodological framework deployed during the AU2 workshop – together with some outcomes and results. We will focus on the sessions dedicated to knowledge exchange on how to design and evaluate current and new sonification tools in a collaborative and participatory manner. This was one of the major requirements identified during AU1 for sonification applied to astronomy to be successful and widely adopted by the astronomical community [1], [5]. We especially focus on how to integrate the often-missing step of evaluation in the development process.

2. A SELECTION OF SONIFICATION TOOLS FOR ASTRONOMY

A huge number of sonification projects, designed within and/or for the astronomy community exist. A large fraction of these use sonification *tools*, in the form of graphical user interfaces or scripted packages, where users can read in astronomical data and create their own sonification [1]. These data usually come in the form of time series (sometimes with multiple dimensions) or images. Many of the developers of such tools attended the AU2 workshop and their tools were showcased during the various sessions (see Sect. 3.2.1).
For sake of feasibility and working efficiency, a set of six tools were selected to be used and discussed within the design and evaluation activities. The selection criteria were, first, diversity (we included GUI-based tools, script-based tools, those focused on time-series data and those focused on images) and, second, pragmatism (the researchers and developers were attending the workshop, preferably in person). Table 1 details the main objectives and functionalities of the 6 tools considered in AU2.

Astronify https://astronify.readthedocs.io/en/latest/	Open-source python package to sonify one-dimensional data, such as light curves and spectra. Developed by Mikulski Archive for Space Telescopes (MAST). *Primarily for scientific analyses.*
Herakoi https://github.com/lucadimascolo/herakoi	Herakoi uses machine learning techniques to perform hand tracking and allow for a motion-sensing sound exploration of RGB images. *Primarily for public outreach.*
Afterglow Access https://idataproject.org/resources/	A complete browser-based astronomy image and data analysis software tool. The software is designed to work with screen readers and incorporates unique features that allow the user to experience images through sound, making astronomy more accessible to the blind and visually impaired (BVI). *Primarily for analysis in an education context (additional accessibility focus).*
STRAUSS https://github.com/james-trayford/strauss	A sonification tool built in python. It can be used with a variety of data sets with multiple dimensions. Flexible sound mapping, including using samples or in-built synthesiser. Spatialisation means broad applicability (e.g. for surround sound and VR) *Primarily designed for scientific analyses, but also for scientists to create sonification for public outreach.*
StarSound https://www.jeffreyhannam.com/starsound	A standalone software developed in Max for the sonification of multi-dimensional datasets. It can be accessed through a user interface, with accessibility features, or a config. file. *Primarily for scientific analyses (additional accessibility focus).*
SonoUNO https://www.sonouno.org.ar/	An online tool, or standalone user interface. Suitable for one-dimensional data, such as light curves and spectra. *Primarily for scientific analyses and education (add. accessibility focus).*

Table 1: selection and brief description of sonification tools for astronomy considered in the Audible Universe 2 workshop.

3. THE AUDIBLE UNIVERSE WORKSHOP AS A WHOLE

The second Audible Universe workshop (AU2) was held at the Lorentz Center in Leiden, The Netherlands, in December 2022. Similar to the SonEnvir Workshop by De Campo and colleagues [10], it brought together for a number of days (5 days in the AU2 case), 50 experts from various fields. This included astronomers, sound designers, sound perception experts, and educators. The week-long event provided a dedicated space for experts to exchange ideas and insights. While the SonEnvir workshop focused on several tools tackling the sonification of data from many different disciplines, AU2 concentrated only on astronomy data. Additionally, and quite uniquely, AU2 focused on exchanging knowledge on design and evaluation processes for sonification tools.

3.1. Global aims of the workshop

While there is an increasing interest in sonification research in astronomy, this field has largely been driven by motivated astronomers who lack expertise in sound perception and design techniques. Additionally, scientific sonification software often fails to meet basic accessibility criteria set out by the International Organization for Standardization, as pointed out by Garcia et al. [11]. There is also a lack of methodological testing with the target beneficiaries, further highlighting the need for improvement in this area.
Consequently, the AU2 workshop had the following goals:
• To consolidate the status of efforts in sonification of astronomical data and presenting updates since AU1;
• To foster multidisciplinary discussions on astronomical data sonification
• To work collaboratively on a scientifically-driven approach to designing sonification tools for both academic and education/outreach applications;
• To develop evaluation methods suitable for the existing and future sonification tools in astronomy.

3.2. Structure of the workshop

The AU2 workshop focused on (1) reviewing existing work and initiatives, (2) improving the design process, and (3) enhancing methods for evaluation, through plenary and splinter sessions.

3.2.1. Review and Dissemination activities

On the first day of the workshop, participants dedicated their time to networking and reviewing the status of sonification in astronomy. To kick off the collaborations, a "speed introduction" session was held, where each participant had 1-2 minutes to introduce themselves. This session included slides prepared in advance, which were designed to be BVI accessible, by the workshop organisers. Participants with sonification projects were then gave 3-minute "Flash Talks" to introduce their project. This plenary session was followed by an informal, "Show and Tell" session, where the projects could be presented informally. The format for this involved free-form discussions between participants, which took place in multiple office spaces. This turned out to be very popular among participants.
Following these informal interactions, a more structured "Hands-on" experience was scheduled in break-out sessions. Each session specifically concentrated on a selected set of sonification tools (see Table 1). In the hands-on sessions, participants were given astronomical data to explore and determine the best way to turn it into sound for different hypothetical applications, using the tools they had been assigned. This experience proved to be an effective way for participants to become more familiar with the technical components of different sonification tools, begin the conversation of best practice, and to explore future possibilities for improved design and evaluation.

3.2.2. Development of the design process

After plenary introductions to design practices, the participants were split into break-out groups with a mixture of expertise to facilitate knowledge exchange. Experts in sonification and sound design took the lead in the design activities to support other participants in tackling the design process. During these sessions, the groups were tasked to consider how they would develop an existing sonification tool and were provided with a sonification design "canvas" to structure their design process [6, 7]. More details about these sessions are presented in Sect. 4.1.

3.2.3. Improving evaluation methods

The goal here was to ensure that the sonifications and tools developed undergo proper evaluation (a key target for improvement from AU1 [3]). Experts in this area provided an overview of evaluation techniques and how they could be applied in the context of sonification for astronomy. Break-out groups were formed to undertake specific tasks aimed at developing an evaluation approach for the sonification designs and tools discussed during the previous days. More details about these sessions are presented in Sect. 4.2.

4. THE AUDIBLE UNIVERSE WORKSHOP: DESIGN AND EVALUATION SESSIONS METHODS

This section describes the methods used in the design and evaluation sessions. For both the design and evaluation sessions, participants were divided in 6 groups: 3 "in person" and 3 hybrid groups (which contained participants in situ and online). Each group included tool developers, astronomers and sound experts. Two people in each group, with expertise in design and/or sound, were identified by the workshop organisers as group moderators. Their role was to facilitate the execution of the brief in an efficient manner. The 6 groups remained almost unchanged between the design and evaluation sessions with only a few changes of persons or/and moderators.

4.1. Sound Design Ideation Sessions

The following section details the *rationale* and the general *structure* of the AU2 sound design sessions.

4.1.1. Rationale

The general goal of the design sessions was to ideate and possibly sketch, in interdisciplinary groups, how an astronomy sonification tool might be developed with the aim of improving some aspect of its current design. We emphasized the divergent and explorative nature of the ideation process, encouraging participants not to be limited by practical considerations, using instead a "*there are no bad ideas*" mindset and considering actively challenging commonly held beliefs or assumptions.
The starting point for these design sessions were the outcomes of the first Audible Universe workshop. One conclusion of AU1 was that there are several design areas in which sound can contribute to expand and improve astronomy applications for research and education. Examples include universality, multimodality and accessibility [5]. We also identified two main possible design goals: 1) developing an aspect of an existing astronomy tool using sound (e.g. the accessibility of an existing visualisation could be improved by augmenting it with sound); 2) developing an aspect of an existing astronomical sonification (e.g. an existing sonification that is found to be not easily comprehensible, i.e. not easy to use, could be improved by reconsidering and redesigning its data to sound mapping.
To progress further in these areas, we decided that during the design sessions AU2 participants should focus on ideating new designs for existing tools along one or two specific characteristics chosen among accessibility, standardization, multimodality, analogy, interactivity, training, efficiency and usability. This approach would allow us to identify differences and similarities in the way in which separate groups might consider the same design characteristic. To facilitate communication within the interdisciplinary groups, we provided participants with brief and simple descriptions of these terms accompanied by a relevant sound example (see Table 2).

Design characteristic	Sound example
Accessibility: The quality of a software tool of being able to be used by everyone, independently of people's different abilities.	Sound of electric/quiet vehicle
Standardization: The process of coming to agreement about the basic features among items of the same type	There are standards for fire alarms

Multimodality: Involving several sensory modalities for operating or interacting with something	Multimodal ringtones in smartphones (sound plus vibration)
Analogy: Comparing features or qualities of two different things to show their similarity	The Mac "empty-the-trash" auditory icon using the sound of crumpling paper
Interactivity: The involvement of users in the exchange of information with a system	The sound in video games helps the exchange of information between player and game
Training: The process of learning the skills needed for a particular activity	The "fasten-your-seatbelt" earcon in a car needs very quick initial learning before being understood at all times
Efficiency: A situation in which a person or system works well and quickly	The feedback provided by the sound of an engine failing allows the mechanic to be efficient in diagnosing the problem
Usability: The degree to which something is easy to use	The microwave beep sound makes it easy to use by telling the user when the food is ready

Table 2. Design characteristic description and sound example.

Furthermore, we provided participants with a digital and accessible version of the Data Sonification Canvas [6] made in PowerPoint and transferred to Google Slides. We ensured that the tools could fulfill accessibility requirements and BVI compatibility. The Canvas provides designers with a systematic way to think about different aspects of a sonification design. It is divided in four main areas encouraging the designer to reflect on: (1) the use case; (2) the sonification approach; (3) the mapping choices; and (4) the desired listening experience for their design. These areas are then further subdivided to facilitate focusing on specific aspects of a design; for example, what kind of sounds should be used, or whether the final design should be more analytical and abstract rather than narrative or story-based (see Figure 1 for an example of a filled in Canvas). Each section of the Sonification Canvas is accompanied by questions that clarify what aspect of the design participants are meant to consider. For example, the question related to "Behaviour" is "What are the rules that link changes in the dataset to changes in the sounds?", which helps clarify that here the designer is meant to consider the connection between sound and data, rather than how users are meant to interact with the sonification, for instance. The questions related to "Analytical", and "Narrative" are: "Are you representing hard values from a dataset?" and "Do you want to communicate a message or tell a story?" respectively, again helping clarify the focus of this section.

4.1.2. Structure

Groups were given a design brief with the following aims: (1) To develop novel sonification design ideas for one of the sonification tools explored in the workshop; (2) To focus on developing ideas for a maximum of two design characteristics. The suggested method included two tasks: firstly, to use the sonification canvas to describe the chosen tool in its current status. This would allow the group to analyse and reflect upon the design characteristics of the tool as well as become familiar with the Sonification Canvas. Secondly, to use the sonification canvas to describe the novel sonification design ideas. Finally, groups were instructed to record their thinking process – "how did you get to these ideas" – using a given "Record of Work" notebook. Groups were provided with links to free sound design libraries and sound design toolkits (eg. https://freesound.org/, or https://github.com/SkAT-VG/SDT) which they could use if they wished to sketch sound ideas. Each group worked together for two 1.5 hour design sessions. The next day, each group reported their main results to all participants in 10-minute slots.

4.2. Evaluation Sessions

The following section details the *rationale* and the general *structure* of the AU2 evaluation sessions.

4.2.1. Rationale

The general goal of the evaluation sessions was to find a way for assessing the new sonification ideas that have been produced during the design sessions (Sect. 4.1). For that, each interdisciplinary group (same as for the design sessions) were asked to focus on one or two experimental paradigms they thought to be appropriate for the evaluation of their proposed design solutions. To help and guide the working groups in their reflections, choices, and implementations – especially, people who were not familiar with experimental psychology – we suggested taking inspiration from the tutorial sessions we made during the 1st edition of the AudibleUnivese workshop (AU1), and more specifically the one focused on "Perceptual evaluation of sound-producing objects applied to data sonification" (compiled by R. Bresin and P. Susini). We gave access to this preliminary ressource together with two additional ones (described further below): (1) a perspective article published following AU1 [5]; and (2) an online toolbox providing access to a series of typical paradigms often used in auditory perception experiments.
The perspective article globally presents basic elements gathered and contextualized by sound experts in their respective fields (sound perception/cognition, sound design, psychoacoustics, experimental psychology), to anchor sonification for astronomy in a well-informed methodological and creative process. The last section of the article – titled "From psychoacoustics to sonification evaluation" – presents general methods related to experimental psychology and psychoacoustics, and raises questions related to astronomical data sonification that can be approached by these methods (see an edited and simplified version of this resource in Table 3).

Method	**Question that can be answered**
Threshold measurements	Can the user perceive differences between characteristics of different astronomical objects?
Scaling methods	How should one auditory dimension vary for fitting the characteristics of an astronomical object?

Dissimilarity ratings	What are the main differences between multidimensional sonified astronomical objects?
Semantic scales	What are the auditory profiles related to different words associated with different astronomical objects?
Sorting tasks	What is the most typical auditory configuration for a class of astronomical objects?
Identification tasks	What are the sonic configurations that make it possible to classify different types of astronomical objects?
Preference scales	Which is the preferred sound model for the sonification of a specific astronomical object?
Continuous evaluations	Do users detect real-time changes in the sonification of relative position of astronomical moving objects?

Table 3. Typical questions addressed for each basic method.

The second additional resource was an online toolbox (developed by Matthieu Fraticelli, within the Ircam STMS /SPD group) for perceptual experiments in audition – using jsPsych environment, based on javaScript language – that gives access to basic methods in experimental psychology (among which, the ones listed in Table 3) in the form of templates for experiments (https://matthieufra.github.io/jsPsychPDS/). These templates could help to understand a given paradigm and work as a model when starting to practically design and implement an auditory perception experiment. Moreover, and for sake of reactivity and interactivity, a communication channel (Zoom link) with M. Fraticelli was implemented during the evaluation session, to allow participants to ask technical questions about the code, or more broadly, the functioning of the jsPsych protocol.

4.2.2. Structure

The 6 groups were given the following initial instructions: (1) to select a paradigm they want to focus on, and (2) to define the hypothesis they want to test according to design characteristic(s) and tool(s) they considered during the design sessions.
Groups were asked to construct an evaluation with the following aims: (1) to reflect on and define a proper framework according to the dimensions that were chosen as the focus during the design sessions and that could be interesting to assess according to the chosen design characteristics; (2) To think about the experiment in a standard way addressing successively the following questions: which stimuli? which participants? which method? which expected results and analysis? (for that, an experiment description template was provided, for example and information purposes); (3) According to time and inclination, to try to implement an experiment prototype by using, when possible, the coded modules of the jsPsych Toolkit, or any other language or environment people might be more familiar with.
The proposed method incorporated an additional task of documenting thoughts and findings in an online notebook. It also suggested, but did not enforce, a workflow that involved collaborative work at the outset for idea sharing and formalization. Subsequently, participants were encouraged to work independently, dividing their efforts equally to address different aspects of the experimental approach. Finally, the method recommended reconvening for discussions and a concluding summary. Each group worked together for two 1.5 hour evaluation sessions. The next day – and last day of the workshop – each group reported their main results to all participants in 10-minute slots.

5. DESIGN AND EVALUATION SESSIONS OUTCOMES

The following section details the main *outcomes* of the AU2 design and evaluation sessions.

5.1. Design sessions outcomes

The emphasis of this session was on clearly defining design requirements based on the underlying goals and context, which is a fundamental step that non-design experts may overlook. Additionally, there was extensive discussion on how designers approach creating specific listening experiences for users, including the concept of "listening modes" (reduced, causal, or semantic – see below) which were unfamiliar to non-sound design/perception participants.
All 6 groups were able to complete the main tasks in the given time. All groups used the sonification canvas to describe the current tool, as well as the new ideated tool. Five out of 6 groups were able to also fill in the "Record of Work" notebook, which provides a concise report of their work as well as feedback to the organisers about the sessions. We can summarise the main results from the design sessions as follows:
• All groups indicated that data analysis and exploration were the primary function of the tool they analyzed. Undergraduate students were considered the potential primary users of the tools. Additional users were teachers, younger students, educators, and astronomy researchers. Outreach was explicitly considered as an important application for two tools. When ideating improvements for the tools, all groups indicated that they wanted to increase the flexibility of the tool as well as widen its intended audience, attempting to cater for both sighted and BVI audiences. For example, if the tool was already audio-visual, the group would consider adding a haptic device; or if the original tool had a Graphical User Interface (GUI), the group would add a command line option more easily accessible by BVI users. On the other hand, if the original tool required scripting, the group would add a GUI to cater for a sighted audience. This is reflected in the design characteristics chosen as the focus of the sessions. Four out of 6 groups chose to increase multimodality; 3 out of 6 focused on accessibility; while usability, interactivity, analogy were the focus for 2 out of 6 groups; and training was the focus for 1 group. Four out of 6 groups wanted to augment the tool with the possibility of using hand gestures, a tactile interface, or a haptic device.
• All 6 groups stated that the original tool provided analytical sonifications; 5 of them ideated with the intention to move the tool towards a more narrative, story-based sonification.
• All groups aimed to increase the palette of sonification mappings. If a tool's default was mapping data to pitch, several additional options were suggested, the most popular being loudness, and timbre (e.g. providing more complex synthetic sounds; a wider number of musical instruments; filtering; distortion and so on). Two groups suggested using speech to give information about labels of axis, and noise or percussive/rhythmic sounds to provide information about

markers in a data set. A couple of groups suggested that redundancy (providing the same information through two or more auditory characteristics) might help to ensure that the information is conveyed efficiently. One group was the most explicit in suggesting that correspondences between astronomy data “primitives” (for example, emission lines which are one of the building blocks of astronomical spectra) and sonic “primitives” (for example, frequencies present in a sound spectrum) could be found and made to connect to each other to make use of sonic analogies. One group did not specify a clear listening mode for the final listening experience. All remaining groups indicated that a reduced listening mode (when the user would need to focus on the evolution in time of acoustic parameters such as pitch or loudness) would be used to understand the sonification, and 4 out of 6 groups aimed, with their ideation, to facilitate a move towards semantic listening.
It must be noted that many participants (especially non-sound experts) found it very difficult to understand the different listening modes proposed by the canvas and therefore what they meant by moving towards “semantic listening” is not often clear. The canvas refers to Pierre Schaeffer, and later, Michel Chion’s definitions [8, 9] of these terms, which were explained during the introduction of the design session, however remained quite difficult to grasp during the workshop. This aspect will be further discussed in the General Discussion (Sect. 6) of this paper. Nonetheless, one group aimed to create a sonification that would use all three listening modes.
• At the end, two groups were able to delve into very specific use cases: group A on an outreach event for primary school children; group E on an outreach event for sighted and BVI users explaining how researchers detect exoplanets.

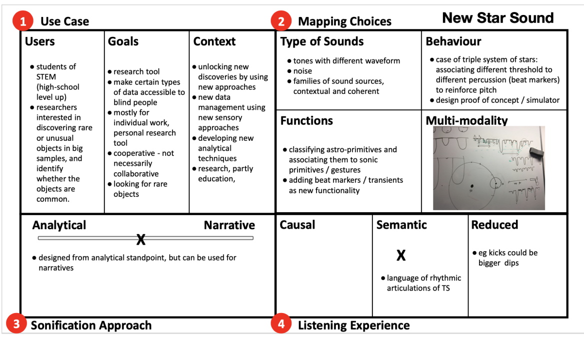

Figure 1. Sonification Canvas for StarSound (new) by Group-F

5.2. Evaluation sessions outcomes

Globally, groups conducted impromptu evaluations or devised well-structured evaluation plans with tangible implementation steps. The diverse range of expertise in each group proved to be highly beneficial, as the experts were able to share their insights on effective/ineffective methods in volunteer participatory evaluation studies. This facilitated a robust and thorough evaluation process, which was essential in ensuring the efficacy and utility of the sonification tools being developed.
The main outcomes of the evaluation session could be summarized, on form and content, as follows:
On form, all groups duly filled in the initially provided experiment description template in a rather complete and precise manner – so that each of these descriptions could nearly constitute the “Method” section of potential publications. More precisely, in that template, all groups clearly succeeded in defining hypothesis, variables (independent and dependent), participants, apparatus, and protocol for their respective experiment. This being, the description of sound stimuli and mapping functions often lacked a bit of precision as some groups relied on the default sonification setting of the tool they were considering (and therefore they did not explicitly describe this aspect), while a few other groups tried to evaluate a new sonification setting they had designed in the previous session (in that case, they took time to properly describe stimuli and mappings). Moreover, most of the groups (5 out of 6) wrote consistent notes in the online “record of work” notebook, including adding graphical sketches, block diagrams and even photos of their white-board sketches (Figure 2). With respect to the experimental implementation, the outcomes are more limited: even if some of the groups reported to have referred during their work to the online jsPsych Toolkit, only 1 group implemented a pilot experiment it, and with the help of a Google Form template. In this case, fruitful real-time exchanges with M. Fraticelli were made during the session, but for lack of time, a quicker solution was chosen (a Google Form). Three other groups formalized rather in detail the algorithmic aspects of a possible pilot experiment but stopped before the implementation due to time restrictions.
On content, it seems that a few types of experimental approaches were elicited for astronomical data sonification: detection (of peaks in curve or signals), recognition (of shapes), identification (of galaxies’ type), together with semantic scale ratings (of pleasantness, tiredness, engagement) are some of the protocols mainly mentioned and sketched within all groups. Within that, it is also striking that most groups chose to conduct the evaluation approach in a contextualized manner, i.e. by formalizing an interactive experiment directly considering a use case for the considered tool. Instead, one could have considered a first step of preliminary evaluation focused on basic sound properties (pitch, brightness, etc.) or matters (abstract, musical, natural, etc.) assessed in a static and decontextualized way with regards to astronomical objects (peaks, stars, galaxies, etc.), for instance by means of a categorization paradigm. In other words, we could assume that the groups here primarily dealt with the evaluation in the context of an interactive sonification scenario. Additionally, depending on the tool, it is worth noticing that the protocol formalized for their evaluation logically, but consistently, took into account potential multimodal interactions for sonification – especially audio-haptics, but also audio-visual where the vision modality defines a control group of the experiment.
In this methodological deployment, it is also worth noting that – depending on type of tool, context of use and objectives – the target users were taken thoroughly into consideration as each group seemed to have consciously chosen their participants’ profile. That is, either in terms of expertise (astronomers, undergraduate students), or disabilities (BVI or sighted).

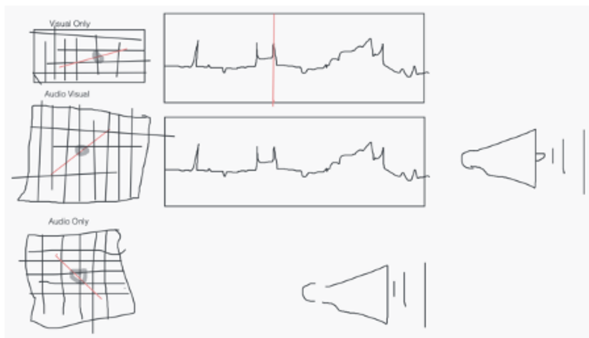

Figure 2. Sketch of a GUI for an identification experiment evaluating galaxies’ major rotation axes including a display modality factor (audio/visual) – ©Group-C

6. GENERAL DISCUSSION

A general discussion on the Audible Universe (AU) workshops experience could be synthetically made at two levels, starting from the general frame of this initiative to go towards the specific design and evaluation activities.

At a general level, it may be worth noticing, first, that the relative success – or positive reception from participants – of AU2 (in person) was partly due to AU1 (in remote) which already laid a lot of the groundwork to kick off and make progress for the in-person meeting. Then, in this kind of multidisciplinary initiative, one may suggest that having a shorter online version in advance could maximise the benefits of a following, more in depth, in person event. Still from this structural point of view, it may also be worth mentioning that participants highly appreciated the "Flash Talks" and "Show and Tell" format (see Sect. 3.2.1). The informal show and tell interactions around several offices – which have been made possible by the logistical facilities (each participant had their own working space during the workshop) the Lorentz Center organisation offered – turned out to be a key moment, and participants requested additional time for this activity. This was probably the best way to get to know each other, and the projects going on, and was undoubtedly more interesting and useful than non-interactive presentations. Finally, it is important to highlight that the hybrid configuration was very challenging and that some moderators found it difficult to know how best to co-ordinate online and in-person participants.

To address broader issues around accessibility, especially for BVI meeting participants, all written documents and presentations produced for the conference were formatted so that they would be accessible for screen readers using the Microsoft Office suite. This included adding alt-text descriptions to images, using correct text formatting (heading, sub-heading, body text, etc.) and correctly ordering text and items in slides. Information presented in tables was also replicated in more accessible list formats. Attendees presenting at the meeting were encouraged to submit their slides for accessibility checks and assistance before the meeting, and all documentation was made available to attendees before the start of the conference to give them extra time to familiarise themselves with the content. During the meeting, presenters were also encouraged to verbally describe images to the audience.

The main outcomes of the AU2 workshop were tangible improvements on:

• dissemination and sharing of tools/sonifications (e.g. tutorials on the tools shared on a drive, higher awareness of the sonification archive – https://sonification.design/);
• acculturation and knowledge exchange (e.g. the astronomy community became aware of design and evaluation practices, the sound community became aware of the types of data and analysis challenges for astronomers, everyone shared best practices on BVI accessibility, etc.);
• multi-disciplinary networking and teams / projects building.

This resulted in plans to continue discussions through many routes, including: (1) Sonification World Chat (https://sonificationworldchat.org/); (2) a recent grant obtained by the STRAUSS project (a 3 year Early Stage Research & Development UKRI grant to develop the software STRAUSS generally but also paying particular attention to accessibility aspects, and for which the PI plans to incorporate knowledge on design and evaluation acquired during AU2); (3) the multi-sensory Astronomy Festival (https://www.astronomiacastellaro.oapd.inaf.it/) to be held in June 2023 in Castellaro Lagusello (Italy); (4) an audio-visual exhibition curated by astronomers and sound designers that met during AU2; and (5) the astronomical data sonification special session organised at this ICAD'23 conference.

At a specific level, the design sessions' feedback indicates that the participants highly appreciated the presence, in each group, of people with different backgrounds and perspectives. One group, for example, discussed issues around the economic affordability of the final tool, something that was unexpected and that most likely emerged from the diverse points of view present in the room. Additionally, this interdisciplinarity pushed groups towards ideating tools *for all* rather than focusing on hypothetical preferred modalities. The importance of spending time to find a common language for speaking about sound (e.g., the astronomers were not so used to the formalised definitions of some words such as loudness, pitch etc.), astronomy, design, evaluation and listening (e.g. see the confusion that appeared on the different types of listening modes) emerged in most groups' discussions.

Regarding the structure of the sessions and the tools used, one group reported that shorter lectures, and more hands-on preparatory activities (e.g. on the Canvas, methodologies, exercises, briefs) could help develop a better shared ground before the start of the group sessions. Whilst all groups were able to use the Sonification Canvas effectively, some participants found the terminology of some sections difficult to understand.

The listening experience terminology (here divided in Causal, Semantic, Reduced) was the section that sparked most discussions before and during the design sessions. As there is no sound in space, people found it difficult to be able to use the "Causal listening" definition. One group wondered under which listening mode an "Audification" (scaling and playing back the data as if they were sound samples) would fit. And most groups seem to interpret the word "Semantic" as a listening experience that could bring the user closer to the meaning of the data – as opposed to a more abstract, reduced listening – rather than considering the more precise definition of "Semantic listening" as a way of listening and interpreting a sound that uses a specific code, like speech or the Morse code, to convey meaning. While the participants suggested, as a solution, to define the terminology more thoroughly in the Canvas, we put forward that this might not be a sufficient solution. The questions raised during the workshop highlight the fact that listening to sonifications, i.e. sounds often artificially connected to the data they represent and its meaning, might require new, more expanded formulations of listening modes and listening experiences pointing towards the need for more research in this area.

Finally, a few groups reported that they used the Canvas following a different order from the one suggested by its numbers. Although the intention of the authors of the Canvas was not to impose an order on the design ideation process, the numbering seemed to imply it. It is possible that eliminating the numbering and reconsidering the visual position of the sections could improve this aspect of the usability of this tool. Finally, participants explicitly expressed the desire for more sustained interdisciplinary collaborations in the future.

Parallel to this, the feedback on the evaluation sessions provided by the groups globally indicates that formalizing and implementing a perceptual experiment for sonification were found to be a relatively hard and an unusual task for them. The fact that almost no group succeeded in building a preliminary prototype of a pilot experiment may be the consequence of the short time allocated to the evaluation session (1.5 hour), but can also reveal the existing lack of background and experience, within the astronomy community - but to some extent within the sound communities as well, on evaluation methods and measurement protocols that involve human participants. One group specifically reported the fact that the evaluation activity was reliant on the participants' background, that some of them felt rather "lost and unprepared", and finally that they had become aware of "how difficult designing a good experiment is" – even if the process proposed in the workshop (introductory and operating elements, talking, and working group, etc.) had been found to be "very useful". Moreover, the difficulty of designing an experiment could also come from a lack of easy-to-use tools for experimentation (despite the fact that the jsPsych Toolkit was available and potentially supported by tutorials and Q&A with the developer), together with a lack of interoperability of these tools with the sonification tools themselves. In other words, there are no easy solutions for connecting a standalone sonification tool (like Herakoi, STRAUSS, StarSound, etc.) to make it compatible with an experimental protocol that requires controlling a number of variables. At least one group reported having "trouble in exporting the sounds from Sono Uno as needed for the experiments". In that vein, it is particularly worth noting that a large majority of the groups notably focused their experimental hypothesis on affective or hedonic dimensions like pleasantness or acceptability (i.e. an integrated dimension with regards to the sonification tool), instead of mapping sonic dimensions – in fact, only a few elements of all the protocols from the 6 groups could be considered as a systematic / parametric study of the mapping functions between sound and data, or even of the basic sound properties (pitch, loudness, brightness, roughness, etc.) and their effects on detection, identification or performance.

7. CONCLUSION

The Audible Universe 2 workshop was successful in sharing cultures, knowledge and practices around astronomical data sonification issues among participants from diverse fields such as astronomy, sound design, sonification and experimental psychology. The workshop focused on design and evaluations activities; there were instrumental for opening discussions and for planning actions (e.g. planning new developments of the tools). Structured planning for design and evaluation are critical for the successful future development of sonification in this area [1]. The strategies we used to promote communication between participants, to ensure accessibility for the BVI community, and to include online participants were considered to be successful. The tools and methods used in the design and evaluation sessions were popular among participants. They have already been embedded into new research grants by the participants. The tools and methods could be used, with small adjustments, by other interdisciplinary workshops focusing on applications in other areas. On the skyline of the global Audible Universe approach, we plan: in the short term, to disseminate results through a dedicated session on astronomy sonification at the 2023 ICAD conference, with a corresponding set of articles on the conference proceedings; in the mid-term, to contribute to the monthly online meetings of the Sonification World Chat, in order to keep up communications and interactions; and in a longer term, to improve dissemination, expanding the community and sparking further research ideas.

All these ideas aim to promote a more comprehensive cross-discipline sharing of sonification resources (publications, tools, etc.) and a consistent building of collaborative projects that were initiated/discussed during the workshop, including ideas for future PhDs and research grant bids.

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