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Sound experts' perspectives on astronomy sonification projects

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The Audible Universe project aims to create dialogue between two scientific domains investigating two distinct research objects: stars and sound. It has been instantiated within a collaborative workshop that began to mutually acculturate the two communities, by sharing and transmitting respective knowledge, skills and practices. One main outcome of this exchange was a global view on the astronomical data sonification paradigm for observing the diversity of tools, uses and users (including visually impaired people), but also the current limitations and potential methods of improvement. From this viewpoint, here we present 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 more well informed, methodological and creative process.

Despite the fact that we are all basically blind to the Universe, astronomers have nearly always opted to represent the data collected with visual images. However, taking advantage of the capacity of audition to complement or supplement vision, different sonification approaches have been recently built for different goals (for example, education or research) and audiences (for example, astronomers or amateurs, blind–visually impaired (BVI) or sighted persons). In this attempt to dialogue between two specific scientific fields—astronomy and sound—it is desirable to come up with shared knowledge, co-constructed ideas, relevant tools and, finally, evaluation guidelines that should be as general, comprehensive and efficient as possible, although potentially dependent on the nature of the goals and/or the audiences.

This Perspective, written by sound design/perception experts, reports on what they saw and understood of current astronomy sonification projects during an interdisciplinary workshop. It aims to strengthen this interdisciplinary dialogue by providing practical advice on how the astronomy community could draw upon the expertise of the sound community to make progress in the approach of listening to the Universe, instead of, or in addition to, just watching it.

Context of this Perspective

A participatory workshop as research framework

The Audible Universe project aims to establish a collaborative framework to share and develop knowledge, ideas and applications concerning sonification in astronomy. It was initiated by a (remote) workshop in 2021 where nearly 50 experts from different scientific disciplines related to astronomy and sound met and worked together[1]. During the workshop 'star people' and 'sound people' shared their respective expertise in an acculturation process of collaborative evaluation and design. The process provided a basis for further development of data sonification as a technique in the handling of astronomical data—whilst also addressing the accessibility issue for the BVI community, which is another key concern of the Audible Universe framework.

The experts in astronomy broadly described the specific nature of astronomical data (light curve, spectrum, image, time series and so on), together with some of the main astronomy-focused sonification tools that are already currently used by researchers in that domain[2]. Detailed information about five of these tools was presented.

- AstreOS (https://astreos.space): a stargazing multisensorial astronomy application based on a standardized visualizer in

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astronomy—Aladin (https://aladin.u-strasbg.fr/)—associated with a sound synthesis engine that mainly maps the brightness value of the RGB components of an image to pure tone audio and haptic clicks, with an additional spatial rendering functionality.

- StarSound (https://www.jeffreyhannam.com/starsound): a standalone application that generically maps any kind of astronomical data to the basic audio dimensions (frequency, intensity, duration) of different types of sound (pure tones, pulses, MIDI (Musical Instrument Digital Interface) instruments).
- sonoUno (http://sion.frm.utn.edu.ar/sonoUno/): another generic application developed methodologically in a designerly way (functionality and ergonomics), based on basic audio parameters (frequency, amplitude and instrument type), with an additional screen reader that uses the speech-based auditory user interface technique[3].
- A4BD (https://www.a4bd.eu/fr/): a didactic application that teaches the use of haptic vibrations to detect different kinds of edge and shape (square, triangle, circle and so on), and audio to detect the colours of an image (hues map to pitches/musical notes and lightness to loudness).
- AfterGlow Access (https://afterglow.skynetjuniorscholars.org/en/): an online application associated with a sky viewer tool (Skynet Robotic Telescope Network) with the main goal of identifying and locating targets of interest (for example, a star in an image) or observing other astronomical information (for example, track saturation). The application is built on the model of a reading head that parses the two-dimensional image as a two-dimensional mapping to audio (time and frequency).

Then, in turn, sound experts described the fundamentals of sound design, sonification, sound perception and psychoacoustics. This basic sonic knowledge provides a shared 'toolkit' for analysis, creation and validation in further collaborative works. Three structural questions, formally based on a conventional three-step design/sound design process[4], were used to motivate discussions between sound people and star people.

1. What can we learn from the existing tools, in terms of sound perception and, more widely, sound experience?
2. Where could we be heading, in terms of designing improved or even new sonification tools?
3. How can we evaluate the usefulness, usability and even desirability[5,6] of existing tools?

Outcomes of the first workshop

This Perspective presents the issues that were raised during the Audible Universe workshop and pointed out during several question and answer sessions and discussions[7]. The perspective of the sound experts on sonification in astronomy applications is presented as an action grid that summarizes the issues and outcomes raised during the live plenary question and answer sessions and later collective discussions.

In summary, the various following key notions, and questions, appear to be definitely noteworthy.

Universality. Could sonification be inserted into a universal design paradigm by taking into account the nature and diversity of its audience, but also by considering feasible solutions for both visually impaired and sighted people?

Standardization. Could sonification standards, or guidelines, for astronomical data be required, and in any case how could they be compatible with a certain level of customization able to ensure adaptability?

Scepticism. What would be the right way to overcome a latent scepticism: better understand the uses and users, propose evidence-based design, raise awareness of the added values of sound (for example, by a gamification approach)?

Multimodality. How could we complement the sound medium with other rendering modalities such as spatiality or haptics, or even through the tangibility of a three-dimensional (3D)-printed mediation object[8]?

Analogy. Could we consider the Universe as a complex sound scene, and therefore transpose auditory scene analysis (ASA) paradigms such as grouping/segregation[9], or acoustic ecology concepts such as acoustic niches[10,11] (spectral and/or temporal zones in the sound spectrum where acoustic energy is preferably located)?

Prototypicality. Could (a certain form of) sonification be seen as a 'quick and dirty process' for auditorily monitoring astronomical data, as visual representations could operate in some way?

On the other hand, it is worth noting that some points relevant to fundamental design were barely (or not at all) discussed, but might remain of major interest for future thoughts and works (they may have been left aside due to lack of time, understanding, reference in the domain…). These include emotions, multiculturality, interactivity, training and importantly artificial intelligence.

From sound perception to sound experience

Basics of sound perception and cognition

Although we can perceive sounds when dreaming or via direct stimulation of our brain, in the majority of cases sound sensation begins when a physical sound wave sets the eardrum in vibration. The human sensation of sounds unfolds along three dimensions (plus one).

The first dimension is pitch, which is related to the sound's frequency, so sounds can be perceived as low or high in pitch (note that auditory sensitivity to frequency ranges from ~20 to as high as ~20,000 Hz, depending on the age and hearing of the person).

The second dimension is loudness, which is related to the sound intensity, so sounds can be perceived as more or less loud as a function of the physical intensity (although in some case loudness and intensity may be partially independent).

A third and more complex dimension is timbre (related to the sound's spectrum composition and its unfolding in time), which enables us to distinguish and recognize the different voices of a mixed sound scene (for example a guitar from a piano) even when they are perceived as having the same pitch and loudness.

Sounds have also a subjective duration, which is, strictly speaking, a sensation not exclusively related to sound but shared by all our senses.

In general terms, sound sensations are categorized in two: tones and noises. Tones give a clear sensation of pitch (for example, the human voice, the sound of a music instrument, the chirping of birds) and can be concatenated in salient pitch patterns (for example melodies). Noises do not give a strong sensation of pitch (for example the fan of the air conditioning) and cannot often produce salient pitch patterns (for example melodies[12]). Although sounds can be described in terms of pitch, loudness and so on, we often describe them by referring to the event that generated the sound and the types of material involved in the sound source (for example, 'hammer on an anvil', 'sound of a waterdrop')[13].

Extension to sound experience

Daily experiences with sounds can be categorized as perceptual, cognitive and emotional experiences[14,15].

In a perceptual experience, psychoacoustics plays an important role in determining how pleasant a sound is: the sharper, louder, rougher and noisier a sound is the more unpleasant it will be perceived to be. Temporal aspects of the sound (that is, duration, repetitiveness) also give rise to event perception and its evolution (for example, car approaching). Furthermore, sound provides cues regarding the physical quality of its source (that is, material, size, geometry and direction)[16].

In a cognitive experience, listeners are able to semantically distinguish their experiences with sounds and categorize them in terms of information regarding the sound event (that is, source, action, location) and its conceptual associations (for example, adventurous, playful).

In an emotional experience, the benefit/harm of the identified sound event to the task at hand is assessed and a sound is appraised by whether it signals a potential threat (for example, fire alarm) or poses opportunities for action (for example, recognizing the bike bell to move aside).

However, not all sound experiences can fit into discrete categories, and all experiences with sound are contextual[17,18]. While we may experience a sound as perceptually unpleasant (for example, a sharp and loud sound of an espresso machine), the context can turn this perceptually unpleasant experience into a functionally acceptable sound (that is, all espresso machines produce such sounds as a result of their mechanical construction) or even a desirable one by means of the circumstantial associations (for example, coffee machines endorsed by famous people) or cultural connotations (for example, the pleasure of drinking coffee in Portugal).

Analysis of sound experiences from existing tools

Overall, when designing sounding objects, the sound creation process can borrow knowledge from the object perception literature that analyses objects on feature, object and scene levels[19,20]. Thus, designers can address the featural aspects of sound to give form to the sound (for example, an incrementally louder and repetitive sound can be perceptually salient by capturing attention, can indicate the evolution of an event and can be perceived as alarming or thrilling). However, designing these physical sound features should give rise to a meaningful whole that can solely be identified as a sound object (for example, audible notification as alarms or approaching footsteps) and the sound object matches the scene it emerges in (for example, medical care or game world). A coherence between the three dimensions of object perception[21] will pose less perceptual/cognitive load on the user, as the sound and its fittingness to the designated function or to its environment will be ensured and sound's capacity to fulfil a user's need will be achieved.

As far as sonification of objects is concerned, all these sensations can be exploited to communicate and represent quantities (as in data representation) and concepts (as messages to be conveyed, such as size, shape, materials). In doing this we map one domain (the auditory sensation) onto another domain (for example, luminances, sizes and so on). Some associations are more natural than others because these associations can be frequently observed in nature. For example, in nature, low-pitch sounds are usually associated with large objects whereas high-pitch sounds are usually associated with small objects[22]. Alternatively, the mapping can be arbitrary and needs to be learnt: we can map pitch with distance (for example, high pitch with large distance) although in nature such a relation does not exist. Pitch is perhaps the most investigated and mapped sensation. The reason for this is that humans are very sensitive to pitch variations (an ability that we can improve with practice), and remember pitch relationships very well. For example, we can remember a sequence of pitches (that is, a melody) after the first time we listen to it, whereas we may forget immediately a sequence of loudnesses[23]. In addition, pitch (but also loudness) often has a spatial connotation: we refer to pitch using the adjectives 'high' and 'low' and this is done in the same way in several music cultures[24].

Astronomers could use sound experience as an approach if they want to create pleasant, meaningful and contextual experiences when sonifying astronomical data (for example, temperature fluctuations in sun observations) and space objects (for example, Milky Way, planets, or galaxies as a whole) or conveying a high-level concept (for example, the stark beauty of a supernova). However, the object identification notion will help congruent acoustic mappings of data to sound and better representations of space objects that fit a designated function, a space mission or research agendas.

From sound design to sonic information design

Basics of sound design and sonification

Designing sounds means "to make an intention audible"[25]. A designed sound is new and constructed, and it represents something other than the sound itself. This can be an object, a concept, a dataset or a system. There are two intentions that need to be audible: form, which relates to sound quality, and function, which relates to what the sound communicates.

In sound design in general, the information portrayed needs to be clearly heard and correctly interpreted for the design to be considered successful. The history of sound design can be traced from Greek and Roman theatre to the development of new audio technology and media (radio, television, cinema, games, virtual reality) in the twentieth century, which generated a great variety of new methods for designing sounds. Recent research taps into this, and into related knowledge and creative practice, to inform new methods for functional sound design, such as sonic interaction design and sonification[26–29].

The invention of the Geiger counter, at the beginning of the twentieth century, is a well known early example of sonification. The further development of electronics, computers and digital technology motivated the need for new ways to display and access information.

Sonification is a type of auditory display and sound design that is defined as aiming to "transform data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation"[30]. The goals include increased accessibility, monitoring of dynamic processes, and data mining, as well as the creation of new artistic experiences for audiences. Applications can be found in assistive technologies[31], health and environmental science[32–36], automotive engineering[37], mobile computing[38,39], intelligent alarms[40,41], technology-enhanced learning[42] and many more fields.

Auditory display techniques have been categorized as earcons (musical motifs)[43], auditory icons (everyday sounds)[44], audification (playback of data series at audio rates)[45], parameter mapping (mapping data parameters to sound parameters such as loudness or pitch)[46] and model-based sonification (mapping the dataset to a digital model that can be excited to make sounds)[47]. More recent methods include acoustic sonification (mapping the dataset to a 3D-printed object that makes sounds acoustically)[48] and stream-based sonification (figure–ground gestalts that form auditory scenes)[49]. Acoustic sonification may be of particular interest to astronomers with visual impairment because the physical object made from the data can be picked up, felt and explored by hand[50]. Stream-based sonification uses psychoacoustic principles to group and segregate data mapped into auditory scenes[9] that are more like the sounds of the everyday world—thus being perceived and understood through experiences of everyday listening[51]—and that do not rely on musical training to hear, analyse and comprehend[52].

Creation of innovative tools for astronomical data sonification

The astronomy tools described in the first section use the parameter mapping technique where data values are played as notes on a musical instrument. Computer music software makes it easy to apply this technique using score-based interfaces. However, although this is a quick and simple technique, short-term auditory memory is only about 2–4 s long[53], which makes it difficult to answer questions about longer sequences of notes.

sonoUno also uses the spearcon technique to support navigation of the user interface by BVI astronomers. Spearcons use sped-up speech to represent menu items and other parts of the interface, similar to the way screen readers can also use sped-up text to speech. There is potential for earcons and auditory icons to also be used to support auditory interfaces for BVI astronomers. Other techniques that have been explored by the data sonification community may be applicable and useful in astronomy. Audification, as used by Robert Alexander et al.[54] for the heliosphere, was employed to play the data at

Table 1 | Basic evaluation methods, derived from psychoacoustics paradigms, described in the section 'Basics of psychoacoustics and experimental psychology'

	Method	Question that can be answered
1	Threshold measurements	Can the user perceive differences between characteristics of different astronomical objects? For example: does the discrimination threshold on the auditory dimension used for the sonification account for the perceived change of a star brightness?
2	Scaling methods	How should one auditory dimension vary for fitting the characteristics of an astronomical object? For example: does the ratio in the auditory dimension correspond to the ratio of the depth of a transit in the light curve (relates to the size of the object relative to the host star)?
3	Dissimilarity ratings	What are the main differences between multidimensional sonified astronomical objects? For example: if several characteristics of stars or galaxies are sonified by sounds made up of several parameters (loudness, pitch, roughness, attack time, ...), what are the most salient dimensions for the comparison? Are they weighted similarly?
4	Semantic scales	What are the auditory profiles related to different words associated with different astronomical objects? For example: stars could be evaluated and compared in terms of sonic profiles—star 1 sounds bright, rough and continuous; star 2 sounds also bright and rough, but discontinuous, which means unstable because of its internal structure.
5	Sorting tasks	What is the most typical auditory configuration for a class of astronomical objects? For example: what are the different and similar shapes of light curves between several transits?
6	Identification tasks	What are the sonic configurations that make it possible to classify different types of astronomical object? For example: what is the boundary between two sound configurations that makes it possible to identify two different chemical fingerprints (related to the presence or absence of certain frequencies)? Does the boundary between two sound configurations allow us to distinguish between a U and a V shape in a transit light curve?
7	Preference scales	Which is the preferred sound model for the sonification of a specific astronomical object? For example: what is the preference between astronomical data played slowly or quickly? What is the most pleasant/efficient among different sonifications—for example, tones versus pulses to explore two-dimensional spectroscopy?
8	Continuous evaluations	Do users detect real-time changes in the sonification of relative position of astronomical moving objects? For example: is it possible to detect changes in the intensity of light emitted by a galaxy by real-time continuous evaluation of its sonification?

Each of the eight methods belongs to a certain methodological category: indirect or direct measurements (1, 2 respectively), dissimilarity, semantic, sorting or identification tasks (3, 4, 5, 6 respectively), preference judgements (7) and—shared with some of the previous ones—continuous evaluation along time (8). For each of these methods, the table contains examples of questions that could be potentially addressed within a validation protocol dedicated to astronomical data sonification tools (inspired by Table 5.1 of ref. [70] and consistently adapted to the present topic).

audio rates so that the human ear carried out the spectral processing, rather than the computer—they found that human subjects were able to hear spectral features that they could not detect in graphic visualizations. The Fourier transform, as used by Bob Sturm[55,56], was employed to sonify spectral data from ocean buoys as short sounds with different timbres. Spectral audification, as used by Joseph Newbold et al.[57], is a similar technique developed for the spectral analysis of chemicals.

These examples demonstrate the potential for astronomers to audify spectral data as timbres rather than note sequences, which may be more perceptually direct. Model-based sonification[58] is another interesting technique that could be applied in astronomy. Thomas Hermann describes one example, called a data sonogram, where the data points are mapped onto a simulated mass–spring system, so for example stars in an image could be nodes in such a system. The user initiates a shock wave that propagates spherically through the spring network, which vibrates to produce the sound of that configuration of stars. An acoustic sonification could be achieved by mapping spectral values onto the parameters of a 3D shape that is 3D printed in a resonant metal so that it vibrates acoustically. Datasets could be held and felt, and differences between entire datasets could be heard immediately by tapping or scraping them. Many astronomical datasets have a lot of noisy background. Stream-based sonification techniques could be used to design auditory scenes where fast transients and weak signals perceptually emerge as auditory figures from the noisy background.

Extension to sonic information design

The design of a sonification to provide useful information requires more than the arbitrary selection of a technique for mapping data into sound. Sonic Information Design is a user-centred method that requires consideration of issues such as the type of data, user task, information requirements and audio display[59]. A designerly approach to sonification that includes stages of ideation, rapid prototyping and evaluation has been developed further[60]. The Data Sonification Canvas provides a design-oriented approach that includes consideration of users, goals, context, functionality, ways of listening and type of sound[2,61].

From psychoacoustics to sonification evaluation

Basics of psychoacoustics and experimental psychology

Psychoacoustics is the discipline that studies the relationships between a sound parameter (for example, sound level) and an associated auditory sensation (for example, loudness) obtained by measurement with human participants. In this subsection, methods are briefly presented. In the next subsection, questions related to astronomical data sonification that can be approached by these methods are indicated.

Traditional psychoacoustical methods are unidimensional, and can be implemented via either direct or indirect methods.

Indirect methods are based on the measurement of thresholds (see method 1 in the table in section 'Validation by perceptual evaluation of astronomical data sonification tools'). Absolute threshold is the minimum detectable intensity of the sensation, whereas differential threshold is the smallest change in a sound to produce a just-noticeable difference. For instance, the just-noticeable differences for fundamental frequency (related to pitch) and spectral centroid (related to brightness) are 0.8% and 4% respectively for musicians, and 1.9% and 5% respectively[62] for non-musicians. The four usual methods to measure thresholds are the methods of constant stimuli, limits and adjustment and the adaptive method[63].

Direct scaling methods (method 2) rely on the ability of participants to assign a number proportional to their sensation, and at the end the obtained relation expresses a direct sensation ratio in relation to the physical parameter. For instance, for a 1 kHz tone, a 10 dB increase leads to a doubling of the loudness[64].

For complex or real sounds, exploratory methods are usually adopted. They can be implemented in three main paradigms.

Dissimilarity ratings (method 3) have been frequently adopted to investigate timbre of musical sounds[65,66] and environmental sounds[67].

Judgements are based on dissimilarity ratings between pairs of sounds, which are then represented by distances in a low-dimensional space using a multidimensional scaling (MDS) technique.

Semantic scales (method 4) are frequently used to assess auditory attributes (loudness, roughness and so on) but also different psychological aspects of sounds, such as appraisal judgements (for example, preference). Judgements are based on direct evaluations on a *k*-point scale (*k* being odd and usually between 3 and 9) defined by a label (for example, 'dull–bright'). It is crucial that the participants correctly understand the meaning of the labels. To overcome any misunderstanding, a sound lexicon ('words4sounds') has been recently developed in the SpeaK environment (https://speak.ircam.fr/en/).

Sorting and identification tasks (methods 5 and 6) are very commonly used in cognitive psychology to address the questions of identification and categorization of sound sources. Listeners are required to sort a corpus of sounds and to group them into as many classes as they want, or into a limited number of classes associated with labels in the case of an identification task. The resulting data are usually formatted in hierarchical structures (dendrogram) that represent clusters of sounds. Sorting tasks have been largely used to study the categorization of everyday soundscapes[68].

Finally, series of tests and analyses have been developed in the field of sound quality[69] to determine preference scales (method 7). In addition, it should be emphasized that the classical psychoacoustical methods have been broadly used to study the perception of short and stationary sounds; however, the fact a sound is time based means the sonification is often more effective when the user is tightly embedded within a real-time evaluation. In this case, methods of continuous judgements can be considered (method 8).

Validation by perceptual evaluation of astronomical data sonification tools

Most of the methods presented in the previous section are precisely detailed in ref. [70]. In this section and in Table 1, a list of specific questions related to the sonification of astronomical data is posed. These questions could be used as a reference and starting point to conceive the perceptual evaluation of a specific astronomy-focused sonification tool.

Conclusion

Finally, the interdisciplinary dialogue originally envisaged as a keystone of the Audible Universe approach began to be established in a rather concrete and fruitful way. A common 'playground', into which both communities—astronomers and sound scientists—brought their respective expertise and know-how, was basically delimited as the frame of a collaborative sound design process.

In this regard, from what inspired them in relation to existing tools, sound experts gave multiple insights to possibly create different design propositions—among which some of them, such as acoustic sonification, could specifically be well adapted to inclusivity—and recommend relevant evaluation paradigms in terms of astronomical data sonification. In fact, basic knowledge in sound perception and cognition, sound design and sonification, and finally psychoacoustics and perceptual evaluation has started to bring new concepts and methods into the astronomy field, and furthermore to open new perspectives on how to observe, analyse, represent or transmit astronomical data, especially since this interdisciplinary approach is specifically based on the assumption that sound can lead to greater inclusion of BVI astronomers. In fact, the reliance of science and scientific education on visualization disadvantages a large part of the population that is BVI. Sound is one possible alternative that can be explored to address this issue[71]. As an emblematic example, astronomer Wanda Diaz Merced, who became blind in her 20s, found that she had to develop her own sonification software (xSonify—https://sourceforge.net/projects/xsonify/) to be able to continue her scientific work[72]. In an interview with *Nature*[73], she highlights how the development of alternative display techniques is not simply a matter of outreach or "learning playfully", but a matter of facilitating equal participation in the mainstream of science and avoiding neglecting human potential for exploration and enquiry. Additionally, as others have done previously—see for example Carla Scaletti's keynote at ICAD2017 (https://www.youtube.com/watch?v=T0qdKXwRsyM)—Diaz Merced points out that sound can, at times, be a better display of the dynamics of scientific phenomena due to its temporal nature together with humans' ability to immediately segregate some characteristics such as signal from noise.

However, as very often in the scientific domain, the Audible Universe workshop and its general approach have opened up more questions than they have practically resolved. Certainly, many other forums and meetings will be required to address some issues raised during the first discussions (universality, standardization, multimodality and so on) and also those that have not been explicitly formulated but are nonetheless of high importance, such as the role of emotions, attention to multiculturality or the reflection on artificial intelligence… to be continued!

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The authors declare no competing interests.

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