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THE POWER OF LISTENING TO YOUR DATA: OPENING DOORS AND ENHANCING DISCOVERY USING SONIFICATION

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ABSTRACT

As a blind researcher, I rely entirely on sound to analyse my data and carry out my research program. To this end I am active in a collaboration that is exploring the use of data sonification (converting data into sound) to enhance, validate, and accelerate discovery. The scope of our program is not limited to enabling blind and visually-impaired researchers to contribute to areas of research that were not previously accessible. Rather, we look also to the use of new multi-modal approaches that exploit the properties of sound to address mainstream challenges presented by trends in modern astrophysics. Using 'real-life' examples, I describe how we are exploring time-series data, spectra, and multi-dimensional datasets mapped to a variety of sonic characteristics such as pitch, amplitude, waveform, pulse repeat rate, tone quality, and distortion and noise to provide additional information on measurement uncertainties. I discuss the application of data sonification to high redshift galaxy research and to our coordinated multi-wavelength observational program to detect and follow up fast transient events. Finally, I outline current research directions involving touch screen and trackpad approaches to examine scatter-plot (non-linear) data representations, shape-based recognition, and the use of combined weighted harmonics to render the information content in multi-dimensional datasets as sound.

RESUMEN

Como investigador ciego, confío completamente en el sonido para analizar mis datos y llevar a cabo mi programa de investigación. Con este fin, participo activamente en una colaboración que explora el uso de la sonificación de datos (conversión de datos en sonido) para mejorar, validar y acelerar el descubrimiento. El alcance de nuestro programa no se limita a permitir que los investigadores ciegos y deficientes visuales contribuyan a áreas de investigación que antes no eran accesibles. Más alla de esto, también buscamos el uso de nuevos enfoques multimodales que exploten las propiedades del sonido para abordar los desafíos principales que presentan las tendencias en la astrofísica moderna. Usando ejemplos de la 'vida real', describo cómo estamos explorando datos de series temporales, espectros y conjuntos de datos multidimensionales asignados a una variedad de características sónicas como tono, amplitud, forma de onda, frecuencia de repetición de pulso, calidad de tono y distorsión. Y ruido para proporcionar información adicional sobre las incertidumbres de medición. Analizo la aplicación de la sonificación de datos a la investigación de galaxias de alto corrimiento al rojo y a nuestro programa coordinado de observación de múltiples longitudes de onda para detectar y seguir eventos transitorios rápidos. Finalmente, describo las direcciones de investigación actuales que involucran enfoques de pantalla táctil y trackpad para examinar representaciones de datos de diagramas de dispersión (no lineales), reconocimiento basado en formas y el uso de armónicos ponderados combinados para representar el contenido de información en conjuntos de datos multidimensionales como sonido.

Key Words: methods: data analysis — techniques: miscellaneous — sociology of astronomy

1. INTRODUCTION

Among the physical sciences, observational astronomy and astrophysics are not alone in their almost exclusive reliance on visual interfaces and visualisation tools in nearly every step of the discovery process. As fruitful as such methods have been, the ability of researchers to visualise data, draw insight, and make decisions is inevitably limited by both human eye physiology (e.g., Schwartz et al. 2005), and the capabilities of the technology employed. There is also the ever-present danger that traditional analysis techniques tend to yield traditional results, and many research insights may remain hidden without the use of new and different data analysis methods (Howell 2014). Moreover, the choice to use a particular analysis method driven by habit, convention, or availability, does not guarantee that it is the most

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appropriate option, or that it provides the greatest opportunity for an individual to work at their maximal skill level (Fluke et al. 2020). Exclusive reliance on visual discovery ignores the potential to use multisensory methods such as data sonification, that can enhance visual representations (e.g. Hansen et al. 2020), lead to new discoveries (e.g., Diaz-Merced et al. 2008), and broaden the accessibility of data analytics for vision-impaired researchers (e.g., Candey et al. 2005; Cooke et al. 2019).

Current challenges in astronomy and astrophysics that demand exploration into new or enhanced analysis techniques and tools include: (i) ever larger datasets and ever increasing rates of data collection from new and future facilities such as the Square Kilometre Array (SKA)[3] and the Vera C. Rubin Observatory and its Legacy Survey of Space and Time (LSST; Ivezić et al. 2019) that surpass the capabilities of present-day technologies to process and interpret data in real time; (ii) increased research activity in real-time and high-cadence observations, such as fast transient searches and multimessenger astronomy that require rapid and reliable source triaging and target identification for follow-up observations; (iii) 'bleeding-edge' observations at the limit of detectability i.e., low signal-to-noise (S/N) data; (iv) multi-parametric and multi-dimensional datasets that strain the capabilities of conventional data visualisation techniques; and, (v) the social imperative of inclusion and accessibility.

Addressing many of these challenges, and realising the potential of current and future data resources, will inevitably rely on automated discovery using machine-learning and artificial intelligence (AI) systems. It is unclear, however, if such systems can evolve sufficiently, or appropriately, to emulate the complex functioning of human cognition during decision-making, especially when faced with uncertainty or equal-valued choices. In addition, automated analysis and recognition algorithms are typically based on known behaviour and phenomena and, thus, not capable of recognising or properly evaluating objects or events outside expectations. As a result, human intervention will continue to be required for the foreseeable future for key roles in data vetting and interpretation including: (i) identifying unexpected 'interesting' objects and events; (ii) determining the significance of outliers; (iii) training machine learning software; and (iv) ultimately deciding what is relevant and important in the data.

Examples of the astrophysical application of data sonification or audification [4] include studies of exoplanet periodicity (Laughlin, 2012)[5], the ionic composition of the solar wind (Alexander et al. 2011)[6], ionosphere plasma bubbles and dwarf novae (Diaz-Merced et al. 2008; Tutchton et al. 2012), and Hansen et al. (2020) developed a software tool that enables application of sonification techniques to the study of intergalactic and circumgalactic media probed using quasar absorption-line spectroscopy. The development of user-centred software and web frameworks for astronomy based on sonification continue apace (e.g., Cooke et al. 2019; Casado et al. 2021; Díaz-Merced et al. 2021), and sonification is now widely applied to present a range of cosmological phenomena such as fast radio bursts (FRBs)[7], gravitational waves[8], and multiwavelength renderings of astronomical objects and phenomena including for example, the Bullet Cluster, the Crab Nebula, and SN 1987A[9]. These efforts have explored only a fraction of the advantages sound can provide to data analysis (see Hermann et al. 2011, for a comprehensive review) and a multi-disciplinary international movement that is exploring the application of sonification in fields ranging from astronomical education and outreach to leading-edge astrophysical research continues to grow[10].

Here we present with real-life applications our proto-type software utilities – `StarSound` and `VoxMagellan` – that enable and augment the analysis of 1-D time-series and spectroscopic data and 2-D images and plots using sound. We propose an approach by which multi-dimensional datasets might be efficiently explored using tone quality (or timbre) as expressed by the superposition of higher-order harmonics, and explore the use of human selective hearing to enable rapid signal identification in low S/N data streams. Finally, we look to future software developments, and the application of multi-

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[3] https://protect-au.mimecast.com/s/bg3FClxwjxs2m70ziGgRzu?domain=skatelescope.org

[4] Sonification is the transformation of data into an acoustic signal for the purposes of facilitating communication or interpretation. Audification is a subset of sonification in which data samples (usually from a natural source) are translated directly into an audible sound by audio signal processing techniques such as amplification, filtering, compression and/or frequency shifting.

[5] "Systemic: Characterizing Planets", (2012), [Online]. Available: http://oklo.org

[6] "Audification as a diagnostic tool for exploratory heliospheric data analysis", presented at the International Community on Auditory Display (ICAD) 2011, [Online]. Available: http://hdl.handle.net/1853/51574

[7] Repeating Extragalactic Radio Signal (FRB 121102)

[8] The songs of spacetime (gravitational waves)

[9] A Universe of Sound

[10] Discovering Sonification [pdf]

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modal sensory perception using ambisonic (3-D) and virtual-reality technology.

2. SONIFICATION TECHNIQUES AND APPLICATIONS

2.1. `StarSound`

The `StarSound` [11] software package is a custom-built sonification tool designed to assist both sighted and non-sighted researchers to quickly identify and interpret trends in complex one-dimensional datasets, e.g., time series or spectroscopic data. It requires no special equipment and can be used on a PC/Mac computer/laptop. Developed using MaxMSP (Puckette 1991, 2020) – a graphical programming environment often employed in the development of real-time musical applications – `StarSound` provides a single graphical interface through which sighted users can configure their sonification environment, and operate the software (see Fig. 1).

Designed from the start with accessibility in mind, `StarSound` can be equally well configured by direct editing of the intuitive text-based configuration file. This capability enables real-time interaction with the software by non-sighted users using any preferred text editor/screen reader combination. The configuration file contains every feature and mappable parameter within the application, and automaticaly updates the current sonification session on editing and saving. Functionality within `StarSound` can be controlled by mouse/trackpad click and drag, or keyboard shortcuts on the client computer, or mapped to external MIDI devices such as the digital audio mixing consoles used by sound and music professionals. Regardless of the I/O interface, `StarSound` features a voice-over accessibility option that reports user actions and the status of configuration settings, and which complements the functionality of OS-based accessibility utilities. Importantly for research applications, this feature also enables the audible reporting of data values on a point-by-point basis.

The sonified output of `StarSound` can be controlled and played in a single channel, or multiple channels simultaneously, with each channel independently rendered using either a tone or MIDI-instrument sound generator. The tone generator uses additive synthesis techniques to create a desired sonic waveform, i.e., sine, sawtooth, or square waves. The MIDI engine conforms to General MIDI (GM) specifications, and supports a library of over 100 different musical instruments. Using either sound generator, parameters in the data file can be mapped to sound characteristics such as: (i) amplitude (loudness); (ii) frequency (pitch); (iii) sound shape as modulated via an Attack/Decay (AD) envelope; (iv) tremolo; and (v) distortion for the rendering of noise (i.e., for data uncertainties). For each channel, the input (data) range to be sonified can be selected by applying a filter function, and the output (audio) ranges similarly set according to user preference.

Moreover, to aid in the sonic rendering and navigation within 1-D data as they are typically plotted, `StarSound` has an option to output the data trace in stereo, a trackpad- or keystroke-activated control to move back and forth in the data stream, and an ability to mark data point locations of interest. These features assist the listener to create a mental image of the data, and enable more rapid and more intuitive interrogation.

2.2. `StarSound` *Applications*

A common 1-D application of sonification in astrophysical research is the interrogation of electromagnetic intensity (light brightness) vs. wavelength spectra (e.g., Hansen et al. 2020). In our own high-redshift galaxy work, we have used `StarSound` for the verification and initial analysis of the rest-frame ultraviolet (UV) spectra of distant ($z \sim 2-3$) galaxies. Rendering the spectral wavelength in time, and the measured photon flux as frequency (pitch), a blind or visually impaired (BVI) researcher is able to: (i) identify steps (or 'breaks') in the spectral continuum; (ii) locate atomic transitions, such as the Lyα emission/absorption feature; (iii) use these spectral features to calculate an initial redshift estimate; and (iv) listen for any unusual behaviour. In the context of low signal to noise spectra that are typical for faint high redshift galaxies, fast scanning through the data can also help validate what is observed (or suspected) by eye.

`StarSound` has also been used in our Deeper, Wider, Faster (DWF) program[12] for the sonification of astronomical transient and variable sources, measuring their brightness vs. time light curves. DWF is a deep, wide-field, and fast-cadenced observational campaign searching for the fastest transient astrophysical phenomena, which vary on timescales ranging from milliseconds to hours, such as fast radio bursts (FRBs), flare stars, kilonovae, X-ray bursters, supernovae shock breakouts, etc. DWF is a multi-facility, multi-messenger program that coordinates over 80 observatories on all continents and

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[11] https://www.jeffreyhannam.com/starsound

[12] https://www.dwfprogram.com/ https://dwfprogram.wixsite.com/home

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Star Sound :: Jeffrey Hannam

config_vienna.txt
test_rr.dat

VIEW: rainbow, superposed, envelope
☐ dim 1
☒ dim 2
☒ dim 3
☒ dim 4
☐ dim 5
☐ dim 6
☐ dim 7
☐ dim 8

StarSound
jeff.hannam@rmit.edu.au
version .10.18

Core Audio	Audio Driver
config_vienna.txt	Active Config
test_rr.dat	Active Data

Star Sound :: Jeffrey Hannam

Tone — Mode: MUTE — sine | tri | saw | square — mod-2

Mapping

On-Off	Dimension			scale lo	scale hi	range lo	range hi
Hz On	#MJD Hz 220.	Frequency (Hz)	A	220.	1760.	0.	7.
Amp Off	MAG dB 1.	Loudness (0-1)	A	0.8	0.8	0.	7.
Attack	MAG ms 10.	Attack (ms)	A	10.	100.	0.	7.
Duration	MAG ms 100.	Duration (ms)	A	80.	800.	0.	7.
Noise	ULMAG dB 0.	Noise	A	0.	0.8	0.	0.3
Tremelo	EMAG dB 0.5	Tremelo	A	0.2	0.	1.	0.8

tremelo — lo - range - hi — tremelo

Instrument

0	AcousticGrandPiano
1	BrightAcousticPiano
2	ElectricGrandPiano
3	Honky-TonkPiano
4	ElectricPiano1
5	ElectricPiano2
6	Harpsichord
7	Clavinet
8	Celesta
9	Glockenspiel
10	MusicBox
11	Vibraphone

StarSound
jeff.hannam@rmit.edu.au
version .10.18

Core Audio	Audio Driver
config_vienna.txt	Active Config
flare_ref.dat	Active Data

Fig. 1. Screenshots of the `StarSound` sonification software interface. (*Top*) The `StarSound` visualisation page. In this example the colour plot shows three discrete data channels being sonified (blue, green and red traces). To the right of the plot are dropdown menus for displaying and selecting configuration and data files, and controls for modifying visual features of the plot. Further right are controls for administering the sonification project, with a selection of features for controlling audio playback below. Along the bottom are pan (stereo) and mute controls for 12 separate channels (*Bottom*) The `StarSound` modules page for mapping data channels to sound and for setting the audible characteristics of the sonified data. The preferred sound generator (tone or MIDI instrument) is selected via a dropdown menu at the top. The data channel to be mapped is selected using the lefthand dropdown menus and sonified output is then tuned using the numeric entry fields to the right. Three other available interfaces (not shown) include a 'Library' for personal files, specific configurations for our 'DWF' research program, and a 'Help' interface.

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in space, making it simultaneously sensitive to radio through gamma-ray electromagnetic radiation and high-energy particles. During a DWF observation run, real-time supercomputer processing of optical images produces hundreds of transient candidates every few minutes. These candidates must be assessed, verified, and prioritised within minutes so that 8–10 m-class and space-based facilities can be triggered to obtain deep spectroscopy or imaging of the events before they fade away forever. The urgency of the data analysis, and the large volume of data that must be processed, motivates investigation into the fastest, most accurate methods of candidate identification and confirmation.

To this end, we have developed a web-based software utility by which the images and light curves of transient candidates can be analysed by a decentralised team of professional and 'citizen science' researchers based locally and worldwide. Data sonification has also been incorporated to enable the participation of BVI researchers and the general public. Specifically, one option for presentation is to assign pitch to the brightness of the object (holding volume constant), such as higher pitch for brighter magnitude, as it is often intuitive to attribute a higher pitch to an upward direction and typical light curves present brighter magnitudes toward the top of the plots. The light curve data are then heard as an even succession of tones in time, as the time of the observations are assigned to the elements of the time series. For example, a light curve representing an object rising and falling in brightness over time is heard as sound rising and falling in pitch over time. The data are presented as a sped-up (time-lapse) version of the data acquisition, which can also be designed to be reflective of data acquired in unevenly-spaced epochs.

2.3. `VoxMagellan`

The presentation of astronomical data on 2-D images and plots has been core to their analysis and interpretation to date, and indispensable in the communication of results. However, the effective interrogation and presentation of information content of 2-D images is frequently challenged by the capabilities of visualisation tools and the limits of human visual perception, even for sighted researchers, and critically so for those among them who are blind or visually-impaired.

It is often the case with multi-dimensional datasets that a number of parameters of interest are analysed, and the results presented in numerous 2-D plots or, in some cases, 3-D plots (with, or without animation). Capturing multi-parametric information is difficult, and typically attempted by varying symbol size, colour, and shape and/or by presenting the parameters two at a time on multiple plots – an approach that leads to presentations that are bulky and inefficient, especially when dealing with more than a few parameters. Moreover, a weakness of such visualisation modalities is the potential to obscure, or overly complicate, connections between the multiple parameters – a significant problem when the ability to recognise these connections is at the core of understanding the underlying physics.

In an attempt to address such challenges, we have developed the `VoxMagellan` sonification tool – a prototype standalone utility that provides users with an accessible touch-based system for exploring 2-D images and multidimensional data using sound. `VoxMagellan` requires no specialist equipment, only a laptop with a functioning trackpad, or any computer with an external touch-based canvas, (such as a WACOM tablet). Using as input either native image files in standard formats (e.g., PNG, JPEG, etc.) or ASCII files of multi-column data, `VoxMagellan` maps the input image or 2-D plot data onto both the screen and the touch-sensitive device in a pixelated grid. The image thus rendered can be navigated by sighted users using the mouse pointer, or by any user with tactile feedback from the touch-sensitive device that correlates the audio output with position on the image. For example, with plots or images scaled to the trackpad dimensions, a BVI user is able to accurately determine the location of a plot data point, or a point of interest in an image, by referencing this position relative to the edges of the trackpad. A key feature of `VoxMagellan` is that the sonic rendering of the image is not limited to the visually displayed information, but can incorporate as many as ten or more channels of data per pixel, thus providing a genuine means to encode and transmit multiparametric information beyond the capabilities of a visual-only approach.

2.4. `VoxMagellan` *Applications*

The properties of sound make it particularly well-suited to render and analyse multiple parameters simultaneously. For example, the human ear can readily discriminate between, and uniquely identify, notes played at the same frequency, volume and duration by a clarinet and a trombone. This ability derives from the overtones, or higher-order harmonics of the fundamental frequency that are produced by the different instruments at differing strengths (see for example figure 2 in Cooke et al. 2019). The

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unique combination of the strengths of the harmonics produces the tone quality, or timbre, of the instrument that can be instantly interpreted by the human ear. The concept we are pursuing is to assign a different data parameter to each harmonic frequency (with appropriate scaling) to generate a single tone (or series of tones) that carry the full information of the multiple parameters of an object of interest. An alternative approach for certain data is to assign different allowed pitches to each parameter (in particular binary-valued parameters) to produce distinct chords.

Our investigation of relationships between the Lyman-α transition of hydrogen and over 10 properties of high redshift star-forming galaxies is one area of research to which we have applied `VoxMagellan` and this multi-parametric approach. Lyman-α has been shown in our, and previous work, to have direct relationships to seemingly unconnected internal and external properties, such as galaxy morphology, colour, kinematics, large-scale spatial distribution, age, mass, star-formation rate, and gas properties (Shapley et al. 2003; Cooke 2009; Law et al. 2007, 2012; Cooke et al. 2013, and Foran et al. 2022a,b, *submitted*). Lyα is the most prominent, and often the only, readily observable feature in the spectra of faint high-redshift galaxies. For this reason, understanding the complicated relationships between Lyα and multiple galactic properties enables a means to probe the very early Universe and elucidate the mechanisms of galaxy formation and evolution.

The left panel of Fig. 2 shows a `VoxMagellan` scatter plot rendering of a dataset from this study. The galaxies are dispersed in colour (y-axis) and magnitude (x-axis), and the plot area mapped to the user's trackpad. No sound is heard when the user touches the trackpad regions corresponding to the white regions of the plot, and different, user-defined sounds are heard when encountering data points of various colours. Overtones can be assigned to different galaxy properties that may, or may not, be rendered on the visual plot, but which can be encoded in the sonic output. The relative strengths of the component harmonics tunes the timbre of each data point, thus reflecting in a holistic way the properties associated with each galaxy. With training, a researcher would be able to identify and characterise multiple relationships between many parameters based on the tonal qualities of a single note or chord, leading to clearer insight into the underlying physical connections.

The righthand panels of Figure 2 show examples of `VoxMagellan` being used in trackpad (or image) mode. In this mode, 2-D images in standard formats are imported and mapped to the trackpad of the client computer on a pixelated grid, and sonified using either a default or user-defined colour map. The colour map can be rendered as pitch, tone pulse-rate, or other sound quality, with the same flexibility as in `StarSound` (see Section 2.1). The astrophysical example shows the interrogation of nebular emission line velocity maps of high-redshift star-forming galaxies derived from integral field unit spectroscopy. Each spatial pixel (spaxel) in the 2-D image contains the full spectroscopic information of the galaxy at that position. One such piece of information is the local velocity of the galaxy relative to the observer (i.e., whether that component of the galaxy is moving toward or away from the observer). This velocity can be mapped, for example, to frequency, with higher pitch representing those parts of the galaxy moving toward the observer, and lower pitch representing regions that are receding. In this example, no sound is heard for the black pixels. Thus, without any knowledge of the visual image, a user can ascertain from the 'virtual image' mapped on the trackpad, not only the location, size, and shape of the galaxy, but also its kinematic (velocity) properties.

2.5. *Other strengths of audition*

Leading-edge research often operates at the limits of signal detectability, resulting in the need to examine low signal-to-noise ratio (S/N) data. Such data, by definition, are difficult to reduce and analyse, and often beyond the capabilities of automated data analysis methods. Writing software to identify and classify signals in low S/N data is very difficult and, to date, inefficient. Moreover, often the aim is to single out a specific signal of interest from a noisy dataset containing numerous other similarly (or more) significant signals, thus requiring intervention by human researchers. In addition, current large surveys are producing data at rates and in volumes that are too great to be examined by humans using conventional methods. Data sonification can help examine low S/N data in ways that enhance the efficiency of visual analysis on is own, speed up the analysis process, and enable the detection of signal that can be missed when only visual inspection is employed.

The human brain is very adept at identifying known or recognisable sounds amidst noise – a phenomenon commonly referred to as the "cocktail party effect" (e.g., Bregman 1990). Humans are capable of selective hearing, i.e., the ability to detect and focus on a desired sound in a noisy environment

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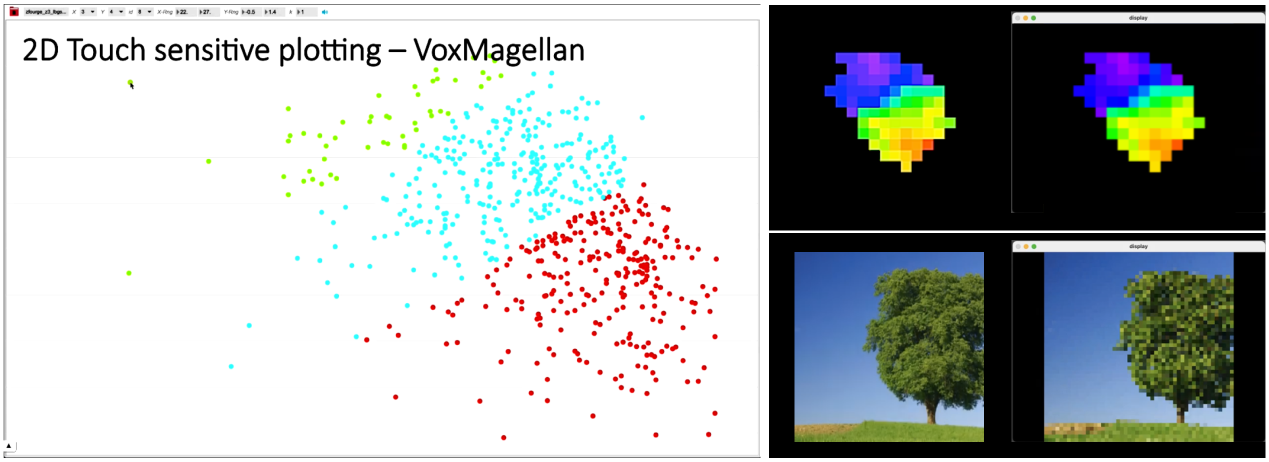

Fig. 2. Screenshots of `VoxMagellan` (VM) in use. (*Left panel*) VM rendering from an ASCII data file a plot of galaxy colours (y-axis) vs. brightness (x-axis) based on selection criteria that identify three populations with different properties (denoted by the three colours). In this mode, VM scales the plot to the size of the user's trackpad and shows the plot in full-screen mode on the visual display. The plot can be navigated using either a mouse pointer or via the trackpad, with multi-parameter data (not necessarily visible) for each galaxy encoded in a single multi-component tone (see text for details). (*Right panels*) VM in trackpad (or image) mode. The input image data are on the right, and the respective digitised VM trackpad displays are on the left for each panel. The upper example illustrates the use of VM to interrogate 3-D integral field unit (IFU) spectral data cube of a distant galaxy. The lower example is similar but shows VM being used to analyse an image of a tree. In both cases, pitch, tone pulse speed, or other sound quality is assigned to different colours, enabling the user to explore not only the physical extent and shape of objects depicted in the images, but also gradients of change. The current level of pixelisation has less resolution for the image of the tree compared to the VM trackpad output, but is more than sufficient to accurately represent the IFU spaxel resolution for research purposes.

consisting of similarly significant, or more significant, sounds. Moreover, our ears have three orders of magnitude better temporal resolution than our eyes. Humans can distinguish between sounds separated by mere tens of microseconds, compared to our relatively slow visual 'refresh rate' of ~ 50 Hz and slower cognitive response. We respond faster to audio stimuli than visual ones – a phenomenon that is already widely exploited in time-critical situations such as aviation safety and military alert systems. Thus, the intelligent application of data sonification can exploit human non-linear listening (Rychtarikova et al. 2016), and other advantages of audition, to enable faster and more sensitive object/event identification from low S/N data streams. We aim to capitalise on these capabilities to identify astrophysical sources in noisy data. Efforts similar to this approach include sonification of fast radio burst data and gravitational wave audification.

3. SUMMARY AND OUTLOOK

It is now well-established that the more sensory modalities that are used to encode and transmit information, the better and faster that information is recognised, interpreted, and remembered. The inexorable rise of virtual and augmented reality (VR/AR) technologies, and the current trend toward immersive interfaces and multi-sensory experiences, speak to the synergistic advantage of interacting with digital information in a way that is closer to how we interact with objects in the real world. It follows, therefore, that a multi-modal sensory approach has potential to address a number of data analysis challenges in modern astrophysics and other disciplines where human intervention continues to be necessary.

Here we have introduced our two data sonification software utilities – `StarSound` and `VoxMagellan` – that have been optimised for the analysis of complex one-dimensional time series and spectroscopic data, and two-dimensional plots and images, respectively. With examples showing their application to real astrophysical problems, we have demonstrated how exploitation of the sensory advantages of sound might lead to faster data management, enhanced analysis capabilities, and improved accessibility to BVI researchers.

In addition, we have described an approach by which multi-dimensional datasets might be efficiently explored using tone quality (or timbre) as expressed by the superposition of higher-order harmonics, and proposed the use of human selective hearing

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to enable rapid signal identification in low S/N data streams.

Areas of our research in which we are implementing data sonification include the DWF fast transient search program (Section 2.2), and the multiparameter investigation of relationships between Ly-α spectral-type and the physical and spectral properties of early star-forming galaxies (Section 2.4). Lessons learned from both these projects will have direct applications to the analysis of large, multidimensional datasets, such as will be produced by the upcoming SKA, LSST, and a large number of other programs. We propose that sonification can not only accelerate, enhance, and validate discovery in such data, it also has potential to reveal new (and unexpected) sources of interest, physical relationships, and insights that would be missed if data analysis relies on automated methods and visualisation techniques alone.

We have demonstrated that sonification has potential well beyond improving accessibility for blind and visually-impaired researchers. Current projects in our group that aim to expand the mainstream use of sonification include work to establish a universal sonification standard to help facilitate the transferability and consistent sonic rendering of data. Of course, a multi-modal sensory approach need not be limited to the augmentation of visual displays with sound. Accordingly, we are also embarking on a project that aims to implement VR/AR technologies with ambisonics (3-D sonification) and haptic feedback to expand the sensory experience into more dimensions and modalities.

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