SONIFICATION OF EXOSOLAR SYSTEM ACCRETION DISCS

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ABSTRACT

This study investigated the design and evaluation of a sonification, created for an astronomer who studies exosolar accretion discs. User design methods were applied to sonify data that could allow the classification of accretion discs. The sonification was developed over three stages: a requirements gathering exercise that inquired about the astronomer's work and the data, design and development, as well as an evaluation. Twenty datasets were sonified and analysed. The sonification effectively represented the accretion discs allowing the astronomer to commence a preliminary, comparative classification. Multiple parameter mappings provide rich auditory stimuli. Spatial mapping and movement allow for easier identification of fast changes and peaks in the data which improved the understanding of the extent of these changes.

1. INTRODUCTION

This study aimed to investigate how sonification could be applied successfully to astronomical datasets representing accretion discs found in young, developing Exosolar Systems. Accretions discs are ring like dust clouds surrounding a parent star. Light curves represent a star's captured light emissions. Accretions discs are noticeable due to periodic dips in the light radiation. The astronomer in this study wanted to find out whether sonification could help identify similar characteristics between accretion discs from various star systems.

In a previous study [1] the use of familiar, natural sound was considered to be effective when applied to astronomical data related to water vapour found in an exoplanetary atmosphere. It was possible to immediately distinguish between the source and noise signal in the dataset due to familiar, distinct representations, water and white noise. Environmental sounds have a strong associative tie that can be recognised even with limited spectral information [2]. This was advantageous when noise masked the signal, since the astronomer could recognise the latter and its properties despite the interference. Song et al. [3] identified the potential of using spatial separation of two audio streams as a functional method of allowing clear distinction between two signals. The source and the noise signal shared similar spectro-temporal characteristics and spatial separation greatly reduced masking between them [4].

When two signals move in counter direction to each other during moments of increased intensity, it enabled the determination of a new feature in the data previously masked. Spatial separation and timbre can facilitate comprehension of sonified attributes [5].

Changes in timbral qualities of a familiar moving object can enhance perceptual recognition [6]. Added mappings to the source signal, using psychoacoustic elements such as the SMARC effect created the illusion of height [7] making source signal peak values more distinct.

Sound familiarity is considered one of the keys to identifiability [8]. Hermann [9] propounds that a sonification must reflect the nature of the data. Grond and Berger [10] describe the process of parameter mapping as involving the association of information with auditory parameters to ensure that the data is replicated in a comprehensible manner. To mimic aspects of the environment of a given phenomenon, more complex mappings of psychoacoustics cues are required. Studies suggest that the mental processing of environmental sounds is quite similar to those used for spoken language [11]. This could suggest that since environmental sounds are processed as a form of language then by mimicking these attributes this might make the data more comprehensible to the user. Worrall [12] even suggests that there are similarities of listening to a sonification and listening to linguistic speech.

In order for sounds to be recognisable they must have meaning and dimensionality [13]. Sound is a composite of impressions of space, volume, significance, matter, expression as well as the organisation of time and space [ibid]. It is a perceptual entity cognised as coming from a discrete sound source [14]. Awareness of how a sound is created and formed, facilitates its use to replicate sound events [15]. This understanding is essential when designing sonifications and implementing realistic characteristics.

A sound object or event is often perceived as a composite of psychoacoustic attributes but not in isolation [16]. A sound object is not a fixed phenomenon and is never really stationary [17]. On a basic level a sound wave is a series of compressions and rarefactions that occur when travelling through a medium and these vary according to the density or elasticity of the propagating channel [18]. The energy of the generated sound decreases as it moves away from the source and is also affected by reflections and refractions off surfaces that are in the wave's path [19]. The spectral components of reflection from various surfaces are essential in order to perceive spatial dimensions [20]. Fencott and Bryan-Kinns [21] refer to the theoretical framework known as *Spectromorphology* as suggested by Smalley [22]. The harmonic balance and the frequencies present of a sound can change over time, which allows listeners to naturally associate sounds with related materials and actions termed *source-bonding*. This is similar to Gaver's [23] work in relation to the consequential changes in sonic properties of a sound object as it interacts with other objects.

Psychoacoustic properties do not only come into play when utilised to mimic natural sounds but are especially relevant in conveying the properties and dimensions of a sound object. Pirhonen & Palomaki [24] describe how a sound designer's skill to represent elements of a dataset are essential in the design of a sound object. If elements of the dataset can be represented as sound objects, then it is suggested that a sound designer works closely with the user in order to be able to replicate the dimensionality of the data through sound.

A clear understanding of the task that a sonification is supposed to perform is necessary [25, 26]. This means that a designer must understand the specific criteria underlying a user's task [27]. It is not enough to base a sonification on data parameters alone, task description should influence the design [28]. Designers are encouraged to take a step back from preconceptions in order to receive a clear understanding of the design criteria to suit both the specific task and accurate portrayal of the dataset. The users' familiarity or preconceived perceptions of the data should be taken into consideration when designing a sonification [29]. As much as possible task-based design strives to reduce the innate attribute of human error [30]. Iterative design process aims to minimize design flaws as much as possible. An essential part of the iterative process is the evaluation stage where the user tests the reliability of the sonification. The user then communicates whether any changes need to be made to the model to better perform the task [31].

Temporal perception is considered to be more effectively represented by the auditory sense [32], and temporal data is an important aspect of astronomical data which tracks the movements of various phenomena in relation to each other. This means that the data works within temporal-spatial parameters. A sonification with a spatialisation aspect could provide a possible solution. A sonification of an astronomical aspect related to exosolar planetary data was designed and customised from the ground up together with an astronomer. Parameter mapping was tested to find out if it successfully represented the data, its suitability to perform the task as intended by the astronomer and the relevance of the aesthetics chosen to represent the data.

2. REQUIREMENTS GATHERING

A semi-structured interview was conducted with AD, a middle-aged male who has been working in astronomy for over a decade. AD was interested in applying the use of sonification to see whether it would add a new dimension to help classify diverse characteristics of a variety of accretion discs from various exosolar systems. AD studies the development of exosolar systems by observing accretion discs characteristic in younger star systems. Debris from these discs are thought to contribute to planet formation.

The interview covered three aspects: Inquiry about the dataset, identifying how the data can be mapped sonically and gathering information about the design. It lasted about one hour and was based around 22 questions and being qualitative, did not require a pilot study. The interview was audio recorded, transcribed and coded.

Grounded theory was used to develop the sonification prototype without predetermined bias [33]. Grounded Theory uses a three-pass system of coding (initial, intermediate and advanced). The initial stage breaks down the data into smaller segments and compares it to similar data from the same or other sources, forming questions regarding the relevance of the findings to the study. Intermediate coding is where categories are developed, and relationships identified. Advanced coding forms the theory as a storyline providing a narrative for the researcher and any gaps in the theory may be identified [34].

The data represented dips in light from a star that occur due to clouds of dust passing in front of it. The size of the dip is equivalent to the intensity of the dust clouds. Stars influenced by this phenomenon are called dippers. The data is captured roughly over an 80 day observation period. The orbit of the accretion of dust is thought to approximately corollate with the star [35]. It is hypothesised that the differences in the disc's angle of orientation is determined by the stellar tilt axis [36].

Pitch would be mapped by having the dips at a higher frequency. Where dips do not occur represents the light from the star and would be of lower pitch. In imagining an accretion disc rotating around a star, it was decided that the data could be represented on a spatial surround system. To achieve this AD added an extra component to the data. Each measure of time was plotted onto a 360^{o} capacity that allowed the dataset to rotate around the listener in a heliocentric manner.

Coordinates were provided as X and Y axes and Phase data. The phase data was more effective for rotating the sound.

It was suggested that the Flux data should have a familiar sound that could be easily identified, like grains of sand particles being blown around in wind. This would mean that the sonification would need additional parameter mapping to replicate this sound. Apart from just depending on the use of surround sound it was decided that the user would be able to switch between surround and stereo. The use of stereo would allow AD to listen to the sonification on a pair of headphones.

The data was provided in text format and one file would be loaded at a time. The user would control playback speed so that the sonification could be slowed down or sped up and have the ability to choose specific points of interest for more detailed listening. The playback would need the ability to repeat itself using a loop function. The system would require to work both in Stereo and in surround. The interface would have visual elements showing number changes in the data and number boxes would have to be provided. It was also important to have a recording function so that AD could record sonifications.

3. SONIFICATION DESIGN

In order to achieve the differences in intensity of sand grains passing in front of the star other qualities like timbre would have to be used. This would help to give clearer definition to the dimensions of the dust clouds as they move through space. Table 1 gives a breakdown of all the factors that were needed in order to design the sonification of the light curve data.

Table 1 Design criteria obtained from requirements gathering

Procedure	Application	Implementation
Parameter Mapping	One to many mappings	multiple mappings to mimic dust clouds
Time in days	Main mapping Spatial	temporal-spatial
Light Curve	Main mapping Pitch	Low small dips, high large dips
Sound design	Use of familiarity to strengthen association	Multiple mappings to mimic sand particles in a dust cloud
Dips	Enhance peaks in data	Add sharpness and clarity
Spatialisation	Surround sound	Light curve rotates listener
Spatialisation	Stereo representation	Stereo headphones
Recording Function	To record light curves	To listen to the light curves on other devices

The sound design was built using subtractive and additive synthesis. It was initially assumed that additive would be sufficient since it consists of building up a sum of sine waves that constructively add harmonics increasing timbral and tonal features [37]. This could give dips more emphasis through constructive interference which is when two sine waves of similar phase polarity sum up and add amplitude to the third wave (ibid). Real sounds are partly inharmonic and additive synthesis allows the use of non-harmonic frequencies that changes both the amplitude and the frequency of each sonic element [38].

This method of synthesis added harmonics that changed the pitch in a way that falsely represented the data. It was decided to only use additive synthesis to enhance lower frequencies where no light fluctuations occurred and was set to a lower volume. This background drone of non-fluctuating light signified the presence of the star emitting relatively constant light. Subtractive synthesis was adopted to control the pitch and timbre mapped to the Light curve flux. The reductive method used in subtractive synthesis made it easier and more precise to automatically control pitch. Through Pulse Width Modulation and filtering certain particulars could be subtracted from the sound [39].

The Pitch range was set between 65Hz to 9kHz to allow consistency in reproduction between datasets. The frequency range would also be suited to the range of the speaker's lower frequency scale which could deliver as low as 55Hz [40]. The lower range of light Flux would represent the solar light and lower dip measurements. The higher range up to 9kHz would allow dips to reach a maximum range that would still be audible to the listener. Even larger dips would be more audible and distinct when reaching the higher bandwidths between 3.5 to 8kHz which is the span most discernible [41]. The difference limen for frequency (DLF) is the smallest within the mid frequency range than it is in the very low (≤ 250 Hz) and very high (> 8 kHz) where it is harder to hear pitch changes [42].

The additive synth, generated sound by using two oscillators set to full volume. One oscillator was a triangle, the other a square wave. The flux data was mapped to a Cutoff, Hi Pass filter mix, noise intensity and output volume. Cutoff, noise and output increase as the frequency of the flux increases. The Hi Pass Filter and noise intensity decrease as the frequency becomes higher to give more emphasis to lower frequencies and add more noise to the rumbling lower end. Table 2 shows the ranges within which the parameter mappings are changing in relation to the flux data. Within the Max software the full range of the MIDI parameters spans from 0 to 1 rather than 0 to 127 which is the usual convention.

Table 2 Additive synth 1 variable parameters mapped to Flux data

Parameters increase intensity			Parameters decrease intensity		
	Hz	MIDI		Hz	MIDI
Cutoff & Main Volume	65 -1869.86	0.5 – 0.6	Hi Pass & Noise Intensity	6029.68 - 9000	0.1 - 0
	1869.86 – 3642.72	0.6 – 0.7		3041.63 – 6029.68	0.2 – 0.1
	3642.72 – 5430.94	0.7 – 0.8		3041.63 - 65	0.2 – 0.3
	5430.94 – 7317.15	0.8 – 0.9			
	7317.15 - 9000	0.9 - 1			

The subtractive synthesiser affected the pitch consisting of two oscillators, a pulse and a sine wave. Adding overdriven harmonics altered the sine wave making it spectrally richer. The pulse wave gave both clarity and resonance to the sound. Adding ring modulation and overdrive increased volume which had to be compensated for. These two parameters moved conjointly with pitch. As dips became larger, they increased in pitch becoming more resonant and harmonically richer. The added sharpness was important in order to give a clearer idea of the dimensions of the dip. Reverb became more pronounced as the pitch increased to soften higher frequencies diminishing sharp brittle tones occurring in the high frequencies. Reductions in volume on both oscillators was necessary since the amplitude became much louder as the pitch rose. The sub oscillator decreased as the pitch increased since the sub frequencies were more needed in the low end of the scale giving emphasis to lower frequency and leaving the higher frequencies to work within a higher frequency bandwidth making them clearer and more defined. There was also a Hi Pass filter that decreased as the pitch rose cutting off tones that were too brittle and awkward to listen to. Low Pass cut off was reduced too in order to tame occurring resonances, making the sound softer. The amplitude decay increased with the rise in pitch making the tones longer and the sound of the peaks more continuous, allowing them to sound like an object instead of disjointed, short bleeps (see table 3).

Table 3 Subtractive synth 2 variable parameters mapped to the Flux data

		Frequency Hz	MIDI
Pitch	Osc 1	65 - 9000	0.2 to 1
	Osc 2	65 - 9000	0.2 to 1
Increase Pitch	Reverb Wet	65 - 9000	0.3 to 1
	Ring Modulation	65 - 9000	0.3 to 0.5
	Amp Env Decay	65 - 9000	0.2 to 0.8
	Filter Overdrive	65 - 9000	0 to 2
Decrease Pitch	Osc 1 Vol	9000 - 65	0.3 to 0.8
	Osc 2 Vol	9000 - 65	0.3 to 0.8
	Sub Osc Vol	9000 - 65	0.3 to 0.8
	Cut off	9000 - 65	0.3 to 1
	Hi Pass	9000 - 65	-1 to 1

The phase data worked in tandem with the representation of time and gave the accretion disc, it's temporal-spatial properties and dimensionality. Two modes of spatial mapping had to be created: One mode for surround sound, the other mode for stereo sound. The spatial surround system would work on a quadraphonic system where the sonification was presented heliocentrically to the listener.

The user could potentially choose the number of speakers from 2 to 12 to output the signal. For more than 2 channels an external audio interface was required. The selected audio interface could be read by the computer's operating software and listed in a drop-down menu in the sonification interface. The phase data crossfaded from one speaker to another. The volume of each output channel was capped to 75 as a MIDI value, within a range of 0 – 127, to keep the volume of each channel within a safe limit without peaking.

The stereo panning was configured to work by shifting from the right to left speaker in conjunction with a rise in pitch. This meant that sound would move from right (+1) to left speaker (-1) between the frequencies of 65 – 9000 Hz. The dips in flux ranged from 0.678 to 1.316 magnitude of light loss. This allowed the listener to be able to hear differences in the size of the dips according to how far the signal pans to the left headphone speaker. The larger the dip the more the signal shifts towards the left ear. This would act as a form of measurement giving the dips an indicative quantity. At slower playback speeds the movement is more discernible.

Other sound modulations worked within a set range effecting the timbre and amplitude. In synth 1 the oscillators, their tuning, modulation and envelopes were fixed parameters. In synth 2 resonance, envelopes, reverb size, hi and low pass filters and keyboard tracking were also fixed.

The reverb that was being added from Synth 2 was insufficient and the sonification was still too harsh and metallic. By adding reverb from another virtual unit, the dust clouds became more grain like and pleasant through the different sonic complexity. Two virtual reverb units were used to work with both the surround and the stereo outputs of the sound. In the case of the surround system one reverb was routed to cover both the front and back left channels and the other reverb unit covered the back and front right channels. This way the tail of one reverb unit would mix into the attack of the second reverb unit due to a long reverb time of 17.5 milliseconds that was added to both units. In order not to overly muddy the signal and lose its sand grain effect the reverb size was set to a setting of 0.75 and the signal was kept at 50% dry to wet ratio. For the stereo system each reverb unit was connected to each channel of left and right so that the signal would retain its mono characteristics and the output would be a mono signal riding through a mono reverb. This would keep the signal from projecting in stereo if the left and right channels were connected to the same stereo reverb unit.

The interface facilitated the loading of the dataset, control playback speed and select segments of the data to play back on repeat function. The user could control the volume from his laptop. A recording function was included to record the sonifications in WAV, AIFF and FLAC audio files. Some examples of the sonification can be accessed by following this link: https://soundcloud.com/michael-quinton_napier/sets/asteroid-belt-in-an-exosolar

4. EVALUATION

Once the sonification design had been completed the model was evaluated by AD to determine whether any changes needed to be made to the parameter mapping and interface functionality. The sonification was tested on a MacBook Pro with a firewire connection. An eight channel soundcard was connected to the computer so that four loudspeakers could be connected to deliver quadraphonic surround sound. The speakers were at the same height. Two placed in front of the listener, left and right. Two more speakers were placed behind the listener to the left and the right. A distance of one meter was kept between each of the four speakers. The volume was set at a safe, sound pressure level of 65dBA RMS and 100 dBA peak. Listening levels were set at 20 dB below the considered safe level for an eight-hour working day [43].

A 24-inch, external display screen was used displaying the interface on the large screen and any other related software on the laptop screen. Two MIDI controllers were used. One controller allowed the use and control of 40 different datasets simultaneously. The other controller allowed the playback of four datasets that could be altered using the onboard EQ, by adding effects and to crossfade between the different channels. Another two loudspeakers which matched the other four were used to run the audio from this MIDI controller and were placed to the front left and right of the listener.

Interviews were recorded on a portable audio recorder, and subsequently transcribed. Answer sheets and pens were provided. The interviews took place in an acoustically treated auralisation suite. An informed consent form and participatory information sheet were provided to describe the experiment, and the voluntary nature of participation.

The evaluation consisted of three parts. The first part tested the interface, the second part, the efficacy of the sonification design and the third part was an exercise to see if AD could classify details of twenty sonified accretion discs. Each test would last about one and a half hours adding to a total time of four and a half hours. All the interviews were semi-structured allowing extra questions to be asked where necessary.

The first test consisted of two sections. Seven questions were intended to capture AD's initial impressions of using the interface, followed by 32 questions exploring possible extra functions. The second test formed 34 questions that inquired about the efficacy of the sound design and to see whether any changes were required. The third test consisted of playing back twenty datasets that were split into four sets of five. Each dataset was recorded at a playback speed of 1ms. AD would have to listen to each set of accretion discs and to classify them. To assist him in this task he was asked to answer ten questions about each set concerning characteristics of the datasets that he had been listening to. Section 2 consisted of eight questions comparing all the datasets that had been listened to and making a more general classification and to see whether certain patterns or trends emerged from the dataset. The third section asked general questions about the classification process and about all the sonification that he had listened to.

The interview lasted roughly four and a half hours. At the beginning of the session AD used the interface and to explore its functions. This gave him time familiarise himself with listening to the sonification on the quadraphonic surround system and in stereo. He could also load and playback various datasets at different playback speeds. AD answered all the questions in all three sessions and his responses were recorded on a portable audio recorder. The third test was originally supposed to compare forty datasets to each other, but this was cut down to twenty accretion discs, four sets of five datasets.

5. RESULTS

The results have been split into three separate sections that reflect the three evaluations that were used to test the sonification design.

5.1. First Evaluation – Use of the Interface

AD's impressions were that the interface was comprehensive and easy to use. He found immediate associative impressions: *"When I hear a sound, I can sort of picture what's going"*. These impressions were quite strong, and AD was immediately able to hear various characteristics and details that concerned the spatial object impression given by the sonification: *"it feels quite quantitive as well, which is good"*. This sense of quantifiable dimension was advantageous in understanding the depths of dippers: *"The main things to extract from the sonifications, is being able to have a measure of the depth of dips and their regularity*." This level of recognition of a sound object also gave a strong impression of the sense of time of the accretion disc's passage in front of a star: *"Physically that's getting a sense of how regular the passage of these structures pass in front of the star."* AD found the sonification to be informative and the nuances of detail helped to emphasise distinctions between accretion discs: *"There's a bunch of different things, bits of information which tell us a different story about each individual system."*

The second part of the interview consisted of questions concerning the use of the interface and additions or revisions that could be made to improve functionality and workflow. AD had already tried out previous prototypes of the model prior to the evaluation: *"Even on my first, I think it couldn't be a lot easier to use."* He found the interface clear to understand and to navigate. When asked if anything else needed to be added to the interface: *"I think there's everything you need there and not a lot that you don't."* AD felt that the interface was *"...pitched the right way. It's as complicated as it needs to be."*

With regards to changes AD found that the playback speeds could be limited to a range of 5 to 100 milliseconds. Any speeds faster than 5ms were too fast and any speeds slower than 100ms were too slow. AD was more interested in listening to an overall impression of each light curve and hearing the whole data set instead of listening to particular parts in detail. His preferred speed was 10ms which he found comfortable in both stereo and surround. This speed allowed him to hear details like short dips and not take too long to finish playback.

AD found that the cue point selection for playback wasn't something that he was particularly using. Since he hadn't tried it then he couldn't really give a clear judgement about its use.

With regards to extra functions there weren't many that AD wanted added. He was particular impressed when the sonification was filtered using Equalisation (EQ) that had the ability to cut the frequency like a dedicated low pass or high pass filter. When the higher frequencies were cut out AD was able to hear the solar activity much clearer. *"The EQ seems to be a powerful way of isolating something out maybe for comparing things."* It could be useful when comparing two light curve datasets to each other.

AD felt that the addition of a metronome would be useful. It could assist in the perception of rhythmic patterns in a light curve and lags in timing in the frequency of the dips occulting the star. Lags suggest a heavier, denser body like a planet or formed asteroid is crossing in front of the star. The metronome signal was suggested to be kept at a central point while the rest of the sound rotated around the surround field. It would then be easier to determine the signal from the metronome. The last change proposed was a function that indicates the length of the light curve in seconds upon loading. This idea was inspired by the audio files that were loaded into Native Instrument's Traktor indicating the length in minutes and seconds.

5.2. Second Evaluation – The Sonification Design

The second evaluation lasted about 90 minutes. AD felt that the sonification was easily comprehensible and he could comfortably understand how the parameter mapping correlated to the dataset. He could immediately discern dips as they rose in pitch. He was quite surprised by the spatial representations and how the perspective changed when switching between stereo and surround. He found that the pitch range was comfortable to work with. It offered a broad enough range to give clear definition to different dipper sizes. The changes in pitch allowed him to determine the size of the dips clearly and the spatial movements both stereo and surround especially made this distinction more recognisable: *"The pitch and spatial location are the two I'm listening for because I feel like they pretty much give me all the information that I need."* The more subtle mappings of changes in timbre and reverberation helped more with associating the data to sand grains.

The stereo and surround sound options added stronger discernment of the data: *"That's the benefit of having both of them. They tell you similar but different things."* AD found that switching between the two spatial choices allowed a different impression of the dataset, which led to insights about the nature of the accretion disc in relation to the star in terms of size and proximity: *"having both is actually pretty important because they give you a different aspect of the light curve behaviour."* It also offered more information about the sizes of the dippers, their periodicity and frequency. The use of the stereo and the surround sound also meant that playback speeds had to be adapted accordingly: *"For the stereo stuff, you could probably play it faster. For the surround if it's going around too fast then you can't really keep up."*

The stereo representation didn't offer the same level of immersion as the surround option, but it seemed to give a more accurate representation of how the accretion disc is actually observed in space: *"All we're seeing is stuff between us and the star. We're only probing a single point in space."* The stereo sound made amplitude variations of time clearer: *"And the way that the panning works in the stereo that's quite useful for being able to think about, the amplitude variations of time"*.

During playback the surround sound ducked as it moved from speaker to speaker. The crossfading between the speakers seemed to be working smoothly but there was an abrupt cut in the continuation of the sound at some point in the crossfade process. This was noticed during testing of the model before the evaluation and a smoothness factor was increased to make the transition between speaker outputs unnoticeable, but this did not eliminate the ducking. AD who found this distracting.

The sonification allowed AD to immediately hear differences between datasets. He could perceive the regularity of dips between various systems and could discern from the speeds and frequency of the dips whether a system was closer to the star. He could comprehend temporal and spatial dimensions clearly forming an impression of the size of a cloud. The sonification could present quick comparisons between different datasets. AD found it difficult to memorise one dataset from another by its sonic signature. He was however able to get a general impression of the activity or lack of it in a dataset: *"Because there's a lot of information there's more information than I could probably remember."*

When asked about the aesthetics of the sonification AD found that the sand-grain like features made it easier to listen to and that it gave data a certain physicality. The use of a more natural, familiar sound helped in terms of immersion and to strengthen associations. When listening to the sonification AD felt:

"I was sitting with these speakers in front of me and then I move my head in a bit so that they're on either side, but I felt like I was actually a little bit away from the system and it was in front of me."

He added that: *"I can sit there and feel like the system is in front of me and the stuff is going around the star. That is what I found the most immersive, because it's still quantitative."*

There was an important detail that AD added with regards to the aesthetics of the sonification: *"We have models which give us an idea. So, there are no physical pictures that we have to compare to. The sonification gives a picture, in the same way that making a model image gives you an idea."* Most of the visualisations that we see of space phenomena are interpretations made out of scales of the numbers gathered by various technological apparatus.

AD was asked about his likes and dislikes of using this sonification. His overall experience was positive finding nothing to dislike. He had spent over an hour listening to light curves and did not tire or feel the need to switch the audio off. His main comment was that: *"I think that you've done a good job of getting the information from light curve and into the sonification in a way that's useful and allows a reasonable level of quantification."* AD felt the sonification had exceeded his expectations and that dipper data was probably too simple a dataset to use. The sonification clearly and accurately represented the dataset but did not offer new insights. He applauded it as a completely different way of analysing his datasets and he never knew that sound could accurately represent data and give it such a distinct level of quantification.

When asked whether he would use this sonification in his regular workflow AD found this question difficult to answer. Since the sonification did not offer any new insights he wondered whether he would be willing to change the way he does his work. AD felt that sonification would be more effective with a more complex dataset that would entail multiple mappings of various data streams: *"Having learned a bit more about sonification is that it wants complexity because our ears are good at picking out signals from noise which is one of the challenges with data."*

5.3. Third Evaluation – Classifications of Accretion Discs.

The third test was designed to use the sonification to classify a number of accretion discs according to their characteristics. AD listened to four sets of five light curves and classified them according to characteristics he considered relevant. Table 4 gives an indication of the classifications made by AD. The scoring system was set between 1, the lowest score, and 5 the highest.

Table 4 Classifications of light curves

Category	Description	Lowest Score 1	Highest Score 5
Depth	Size of dips in light flux	Smallest size of a dip	Largest size of a dip
Regularity	Light curve sound is more orderly or more random	Dips sound more regular	Dips sound more random
Activity	Number of dips in light curve	Few dips	Many dips
Change	Changes in turning speed of disc	Few changes	Many changes
Frequency	Speed of disc turning	Slow	Fast

Table 5 shows the results of the classifications exercise. Some of the light curves had not been normalised properly and sounded higher in pitch during the playback. This limited the comparisons that could be made. These are marked in dark grey in the line for light curves in Table 5.

Table 5 Results of the Classification of light curves

	Set 1					Set 2					Set 3					Set 4				
Light Curves	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Depth	3	4	4	2	5	3	3	4	5	5	5	3	5	4	4	4	2	3	3	2
Regularity	1	2	2	1	2	3	1	3	2	2	2	3	5	1	2	2	1	2	2	3
Activity	4	3	3	4	5	3	4	4	2	3	5	3	4	4	1	4	2	4	4	4
Change	2	2	4	2	3	2	3	2	5	2	2	2	2	4	4	2	2	2	2	3
Frequency	?	?	?	?	3	4	2	2	3	3	3	2	1	2	?	3	?	2	2	1

There were instances where AD found it hard to distinguish the frequency of the light curves, especially in the first set. This was due to not having anything to compare the first set to. His scores improved once he was able to compare the different datasets and to familiarise himself with the different speeds. AD was able to spot similarities and differences between light curves, hear differences in speed and make out different depths of various dips. He could tell which light curves were not so active, follow a light curves' activity and its depth.

The next section involved finding similarities between the datasets that stood out as different during the first classification process. This was to ensure whether there were also patterns that were recognizable between datasets that stood out when grouped together in sets. It was interesting to note that the only similarities that were found were between two datasets which were the numbers 1 from the first and third sets. They had dippers that sounded of similar depths which were quite deep. They both rotated at moderate speeds. Accretion disc number 4 of the second set had fairly narrow dips. It rotated much faster in speed. These characteristics made this accretion disc quite unique. Accretion disc number 4 of the fourth set was much slower and consisted of larger deep dips that were easier to follow: *"Some of them really short dips are shorter than a day but a lot of the time they are as large as a few days."*

AD highlighted differences in rotation speed between discs and how faster sounding dips were those orbiting closest to the parent star. He suggested that the very deep dips probably consisted of large dust clouds significantly blocking the star out. Objects further away from the star rotate around it at slower speeds. Similar laws of motion govern the movement of celestial bodies in the solar system. These four accretion discs were deeper and bigger than any of the other ones that AD had listened to during the first part of the testing making them more distinguishable. They also consisted of an interesting level of activity that made them more compelling to analyse in detail.

Section 3 was designed to inquire whether AD was able to successfully classify the accretion discs using sonification. AD found that he could discern details from the various sonifications without difficulty. He could sense the depth of dips and understand differences in their dimensions. He was able to understand the substantiality of the dips that were of a deeper nature and relate this to how they could be compared to the parent star in terms of dimension. He could understand the level of activity of a disc instantaneously and could distinguish between the low active discs and the higher active ones without any problems. AD struggled to sense the regularity of the discs dip rate activity due to the speed of the playback where he felt that this was too fast and overwhelming for him to digest these details. AD could easily hear differences in speed between different discs and could tell the faster ones from the slower ones. He found this to be informative since it gave him a good idea of the proximity of the disc to the parent star.

When asked whether any new insights were discerned about the data during the exercise, AD said that he would need more time to consider what he had heard and to listen to these sonifications again, probably at a lower playback speed. During the exercise itself AD felt he didn't really learn anything new. However, he was impressed that the sonification compressed three months of data into 5 seconds and this ease of recall was advantageous when working on multiple datasets. AD felt that with more practice and the ability to listen to the datasets in more detail he could reap more information.

6. DISCUSSION

The sonification mirrored the data accurately. It represented the changes in light flux to the point where AD could perceive quantifiable dimensions regarding the size of dippers and accretions discs. AD felt that the sonification did not present anything new. When seeing how capable it was of representing temporal-spatial dimensions concerning the disc's proximity to the star and the size of the various dust clouds blocking the stars light substantially, suggests that that it did represent these dimensions in ways that a 2D visual graph cannot. A user centred design method seems to be effective. The sonification was designed to see whether the astronomer could successfully classify light curve data, and this was possible and to a certain degree of detail. The sonification fulfilled the task that it was designed for [27]. The task itself determined the sonification design and gave it this degree of accuracy [28].

Worrall [12] compared the similarities in listening to a sonification with speech, this correlation provides a strong basis for a design. For a language to be comprehensible to the user, the designer is encouraged to overcome their own preconceptions [30]. Each designer has to understand what it is they are designing and who they are designing it for [27].

Considering that sonification is listened to in the same way that speech is [12], this is also comparable to environmental sounds which are processed by the same region in the brain [11]. Language is based on a process of learning how a word associates to a concept in order to make sense to a user. This makes the use of environmental sounds similar to the use of language and presents itself as a strong candidate for representing data. The familiarity of the sonified sounds was considered to be evocative when representing datasets [8].

The environmental sounds themselves are sound objects and in being so the user was able to understand their dimensionality with regards to space, volume, matter and relation to time [13]. The propagating sound source was understood [14], on an unconscious level the psychoacoustic coding's that define the proportions and materiality of the sound object were known factors. AD stated that the sonification conveyed quantifiable meaning. He was able to understand the dimensions of the dips in light in relation to the size of the star and the enormity of the dust clouds. Differences in size of dust clouds were easily discerned, creating strong mental images of the discs and how they occulted stars. The size of the dips was conveyed using pitch, with the sharpness of their outline as objects conveyed through timbral changes and spatial orientation. Psychoacoustic factors used to mimic the environmental sounds gave strong definition of an objects' proportions. Since the sound design was based upon the creation of definite sound objects all psychoacoustic elements were cohesive [16].

The use of spatial mapping is often overlooked by sonification designers. Combining this with changes in timbre gives more definition and perceptual recognition [5], [6]. Animating the object in the data strengthens user familiarisation. Sound works in relation to other surroundings, objects, surfaces or materials and due to the intensity of its energy during propagation and dissipation, one is able to experience its temporal relationship within particular spatial parameters. In nature when listening to any form of sound object, its properties are constantly changing [17]. The spectral qualities of a sound vary over time. This is the temporal-spatial relationship that sound manifests. Listeners associate sounds to the related causes [21]; [22]. The use of spatial mapping in astronomy gives life to the celestial bodies and their movement through space. These factors are often temporal, and by giving more emphasis to the temporal-spatial mappings in a sonification it can potentially bring a sound object to life, and more successfully conveying the data. The sonification works more like a sound design employed in film or theatre. The sound is evocative of an object or concept, and this can communicate meaning to a viewer.

The spatial mapping conveyed a new aspect in AD's understanding of the data. He repeatedly stated that due to the speed of the accretion disc, not the playback speed of the sonification, he could tell whether the disc orbited more closely to the star when moving faster, or further away when moving slower. This representation could not easily be recognised when looking at a 2D graph which only represents time in relation to days of observation. When perceiving speed differences, the relationship between the stellar orbital axis and the rotation of the disc was conveyed. The surround spatial mapping made this association stronger as AD could hear the disc revolving around his head and was able to identify this association clearly suggesting that the sonification offered new insights.

Using the three mediums of sonification, visualisation and numerical data could reap unexpected benefits in obtaining a deeper understanding of the accretion disc data. This sonification was considered to be robust as it could work as a stand-alone analysis method or in conjunction with visualisation. AD stated that that the sonification had exceeded his expectations and could represent the data as accurately as visual graphs.

7. CONCLUSION

The results suggest that user and task-based design methods can be effective for designing sonification of light curves. The mimicking of natural, familiar sounds creates strong associations. The use of multiple psychoacoustic properties to animate a sound object can give clear quantifiable dimensions. The use of spatial mapping seems to be effective in conveying data and adding a deeper understanding of temporal-spatial aspects of data. In this specific model spatial mapping allowed the user to understand the proximity of the accretion disc to the parent star and also gave broader definition to the dips in light. This meant that the astronomer could understand the size of the dips in relation to the star more clearly. Even though the sonification did not offer any new insights about the data it did accurately represent the dataset. Although, it was felt by the researcher that the sonification was able to give a more defined temporal and dimensional impression of the quantifiable aspects of the accretion disc and the dippers which cannot usually be determined from a 2D visualisation.

Further work could involve additional testing of the classification process. The playback speed would have to be set at a more comfortable speed ranging between 5 to 10 ms, which could aid the participant to hear similarities in the rhythmical patterns of various accretion discs. All the tested datasets would also have to be normalised in the same way to avoid sounding higher in pitch. The surround sound system would have to be fixed to remove the ducking by programming a gate system similar to the one used in the stereo sound engine that will determine where the signal is outputting in accordance with the numbers in the light curve data. It would also be good to test the sonification with other astronomers who work in the same field to see if there is consistency in the results.

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