SONIFICATION OF AN EXOPLANETARY ATMOSPHERE

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ABSTRACT

This study investigates the effectiveness of user design methods to create a sonification for an astronomer who analyses exoplanet meteorological data situated in habitable zones. Requirements about the astronomer's work, the dataset and how to sonify it utilising Grounded Theory were identified. Parameter mapping sonification was used to represent effective transiting radii measurements through subtractive synthesis and spatialization. The design was considered to be effective, allowing the instantaneous identification of a water feature overlooked on a visual graph, even when noise within the dataset overlapped the source signal. The results suggest that multiple parameter mappings provide richer auditory stimuli and semantic qualities in order to allow an improved understanding of the dataset.

1 Introduction

Sonification design can be complex, as it has an open-ended approach which allows creativity. This can be a disadvantage, as experimentation might lead to data misrepresentation, rendering a sonification difficult to interpret [1]. A sonification has to be comprehensible to the user. Designers must consider whom they are designing for and the purpose it serves. Sonification is a form of communication, a language, and needs to be able to deliver accurately the semantics of a dataset. Individual sounds carry strong, associative ties that can act as a narrative [2]. Scalletti [3] emphasised the direct correlation between a dataset and how its meaning must be accurately represented sonically. Barrass [4] defined sonification as a mapping of information into acoustic, perceptual relations for information processing. Sonification has to facilitate interpretation of the data in a communicable manner, easily understood by a user [5]. A useable sonification is designed upon a dualistic underpinning, the source (data), and the target (users). A sonification is determined by the structure of the data and the type of information to be extracted. An effective design easily allows a user to retrieve the necessary information perceptually, physiologically, cognitively and by memory [6].

A designer must work closely with the user to obtain a clear understanding of the necessary requirements and needs [7]. Pioneers in the field, Kramer et al. [8] recognized that sonifications had to be user and task centered. This claim has been supported throughout the years [4, 9, 10, 11, 12, 13]. Users and Designers often have different perspectives and interests, and it is relevant to obtain both viewpoints to make the design more acceptable for an end-user [14]. Sonification design must be a studied approach, built from the ground up in accordance to the task that it is meant to perform [15].

Requirements Gathering is an effective method for obtaining information about functionality, goals, constraints and improvements in future models [16]. The exercise must remain as open as possible so as not to lead a user down any predetermined path laid out by the designers. To overcome such restrictions techniques like Grounded theory, use the data as the foundation to build the required thesis [17] which is a suitable method to design a Task-based sonification. Grounded Theory uses a three-pass system of coding, the initial, intermediate and advanced. The initial stage is used to break down the data into smaller segments and to compare it to other data from the same or other sources. Questions are then asked regarding its relevance to the study. Intermediate coding is used to develop categories and identifying relationships between these categories as the analysis progresses. Advanced coding is used to form the theory in the form of a storyline which provides a narrative for the researcher from which gaps in the theory may be identified [18].

User centered design approach does not guarantee an effective sonification design. Even the most studied methods could fail to convey data comprehensibly when developed the first time [19]. To overcome this, iterative practice is encouraged. Evaluation plays a vital role in identifying shortcomings in the design and allows continuous improvements based upon user feedback. Designers develop a usability engineering life cycle based upon each iteration evaluated by the user. The process confirms the users' requirements, assesses the suitability of the system in accordance to the users' needs and sustainability of the design [20]. A successful interactive system can serve as a template for the development of future products [7].

Multisensory analytics is the idea of using more than one of the five human senses for data analysis [21]. Large, complex, raw data need new methods of analysis so that features lost through one sense could possibly be identified by using another one [22]. Astronomy is a field of study that deals with extensive amounts of data [23] and the use of new methods of analysis are appealing to astronomers who want to dig deeper into their datasets. In a multi-parameter dataset, there is often the possibility that important data artefacts are lost when visually represented on a two-dimensional plane.

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Prevalent visualization methods of time-dependent data are often poor in terms of interactive engagement [24]. The temporal resolution in human hearing is between one to several thousand milliseconds [25]. Sound perception provides a sense of time, space and distinction of subject-object relationships [26]. Humans can identify events that carry semantic information about mass, material, interaction and force [27]. Listening allows the identification of patterns and discernment of things that are perceptually or physically masked, and the ability to localize one particular sound of interest amidst the rich, surrounding sound field [28]. The ability to deconstruct complex acoustic waves to identify specific perceptual objects is known as Auditory Scene Analysis [29]. In the case of speech, a listener is able to easily switch between two different streams of dialogue that are separated between left and right channel on headphones [30]. Such abilities allow a listener to hear distinct details in multiple channels of data and to hear separation. This is especially useful to hear details that are lost when overlaps occur.

Leplatre and McGregor [31] studied the function and aesthetic characteristics of an auditory interface and found that the two properties had to be dealt with in relation to each other. If a user cannot associate with the sound, then it is likely that this will affect their performance when analyzing data. The aesthetic must have some form of association to the data to be able to convey its semantics accurately. Sounds convey strong mental images [32] and possess common, archetypal associations that relay similar messages to many listeners [33].

One of the strongest arguments for sonification is that people are constantly listening to large amounts of data that give them a sense of space, place, time and recognition of various objects. Auditory events can occur from directions where nothing can be seen [26]. This suggests that spatialization could be used as an effective parameter mapping.

Considering that astronomers typically work with visualizations for data analysis it is surprising that sonification is not more prevalent when most astronomical data is temporal in nature. Sonification could add another dimension to data analysis and is not a replacement for visualizations. Human sensory apparatus works together rather than as separate units. Psychophysical evidence suggests that involuntary auditory attention enhances early visual perceptual processing [34]. Data analysis will be more powerful by adding other senses to the process, as long as the Sonification is designed adequately to suit the task.

Various published guidelines suggest how a sonification can be designed effectively. This study tested the efficacy of user-centered design principles in relation to Exosolar Planetary research. Together with an astronomer, a sonification of his work was designed from the ground up.

2 Requirements Gathering

The requirements gathering exercise was conducted as a semi-structured skype interview with an astronomer referred to as WV. The interview took one hour. WV is a middle-aged male who has worked as an astronomer for over 20 years. His field of expertise is Exoplanetary meteorology. His hearing and eyesight are normal for his age, and has no experience working in professional audio or musical training. WV had never used sonification in his work. He believed that sonification could help to identify important, undetected elements of data hidden in overlapping signals depicted in 2D graphs.

The interview was conducted to obtain a clear understanding of the dataset, suitable parameter mappings and gather information about the design. Grounded theory would be used as a method of investigation since this would utilise concepts already familiar with the users instead of introducing them to new concepts. The qualitative data extracted from this process was coded using a three-pass method of initial, intermediate and advanced coding and a theoretical framework developed, based on the data collected and not on predetermined conceptualizations. These codings inquired about the nature of the data, it's extraction, units of measurement, keywords in the astronomer's description of the data, conceptual understanding of the data and finding out more about the astronomer's listening attitudes. The interpretations of the data gathered was then evaluated [35].

3 Results – Requirements Gathering

The dataset relates to the atmosphere of an exoplanet situated within the habitable zone of an exosolar system. This is a hypothetical region in an exosolar system where orbiting planets could possibly host life similar to Earth [36]. Astronomers study these atmospheres by taking a spectral snapshot as the planet transits their parent star. The data is not temporal but spectral. The gases in the atmosphere reflect perceivable colors of the light spectrum as they vibrate at different speeds, according to their chemical composition. This allows identification of atmospheric gases and their quantities. The data gathered are compared to Earth's atmosphere and parallel findings could suggest that the exoplanet hosts life similar to Earth's. The different colored gases vary in the wavelength of light, measured in microns. When light is reflected off a planet's surface and clouds it forms a corona around the planet. The irregularities in landscape and clouds of varying height and size reflect back different amounts of the parent star's light. These measurements are called effective transiting radii, and are measured in kilometers. Figure 1 shows a graphical representation of how the effective transiting radii vary within a wavelength of 20 microns of water vapor (X axis) with the radii (Y axis).

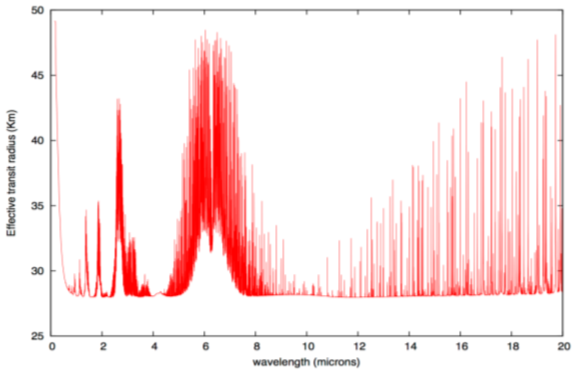

Figure 1. A graphical representation of the source (water vapour) signal

There are two signals, a source (water vapor) and noise. A certain degree of noise is captured by the telescope which comes from light reflected off other celestial bodies, dust particles in space and gases. The source signal is filtered out from the noise. WV wanted to sonify the effective transiting radii of the source, to sonify the noise, to listen to them simultaneously and to explore whether sonification could detect water properties not noticed in the visual representation due to overlaps between these two signals. Emphasis had to be given to the peaks in effective transiting radii to be easily distinguishable from the noise. These peaks represent the highest measurements of radii equivalent to the highest water vapor concentration in clouds in a planet's atmosphere.

Pitch would be the main parameter mapping, with lower radii being lower and higher radii higher. The other mapping would be spatial separation between the two different signals. The water vapor signal would have a water like sound that would strengthen WV's association to it and make it more distinguishable. Noise would be represented by white noise since the frequencies are equally mixed across the human hearing spectrum (20Hz to 20 kHz) [37].

The interface design needed to load two text files of source and noise for simultaneous playback. The ability to manipulate playback speed, select segments in the data, and to repeat allowed scrutiny of particular datapoints. A graphical interface would be useful to identify start and end points. The interface would be used with headphones allowing WV to run it off a laptop. Numerical values of effective transiting radii and wavelength would facilitate data reference and selecting segments for playback.

WV had no formal training in sound or music. Axon et al. [38] found that non musically trained participants were still able to use a sonification without any difficulty. Scalletti [39] argued that a distinction between sonification and music allows the non-musically trained to analytically listen to abstract sounds in order to identify meaningful information without musical overtones that could be potentially distracting.

Many sonifications are made without considering users' mental models in relation to sound [40]. The mental model is about understanding the domain knowledge of a certain context [41]. Ferguson et al. [42] argues that psychoacoustics facilitates the prediction of subjective qualitative response to auditory stimuli. It was agreed with WV that the sonification should have a water like quality to strengthen the association with water vapor.

Parameter mapping was the technique chosen to sonify the data. This gave the necessary flexibility to mimic water droplets by using several psychoacoustic principles [43]. Subtractive synthesis allowed resonant filters to boost or cut unnecessary frequencies [44]. Resonance was used to either excite or generate a raw signal or to vary acoustic properties of a broad spectra [45]. Subtractive synthesis is effective for eliminating undesired noise with pulse width generation to create a high energy partial, periodic waveform at a specific frequency. The bandwidth of the pulse waveform is relative to the ratio of the pulse width compared to the period of the signal. The pulse becomes narrower when the ratio is reduced which creates more energy for high frequency particulars [45] emphasizing the higher frequency radii peaks.

4 Sonification Design

The effective transiting radii was mapped to pitch that varied from 50 Hz to 9 kHz. This range would allow consistency in reproduction between different datasets. Lower pitches would represent lower radii and higher pitches, higher radii. Any changes in the higher frequencies (3.5 to 8 kHz) [46], would be more easily detectible since 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 range (> 8 kHz) where it is harder to hear pitch change [47].

A familiar sound, water droplets in relation to water vapour, could establish strong associative ties. Familiar environmental sounds are identifiable and meaningful without any visual reference [48]. Environmental sounds are comparable to speech and can be considered as a form of language [49], they both require bottom-up and top-down processing using similar cognitive processes [50].

Environmental sounds are subjected to subtle changes in [51], psychoacoustic properties. Sound is time-spatial and occurs in different positions across the spectrum between left and right ear. Movement within space is immediately detectable and causes subtle changes in pitch and timbre known as the doppler effect [52] as an object moves towards or away from the listener [53]. The use of movement could overcome listeners fatigue due to the ever-changing position of things across the stereo field. The movement of the two signals counter to each other will allow clearer spatial representation and distinction. To further enhance the differences in length of the radii an auditory illusion known as the Spatial-Musical Association of Response Codes (SMARC) effect creates the illusion of ascending when pitch and timbre are increased on the vertical axis of hearing in non-musicians [54]. It is suggested that the human cognitive system maps pitch onto a mental representation of space [55]. Effective transiting radius is the measurement of star light reflected from the planet's surface. Smaller radii are light reflected from lower surfaces of the planets irregular landscape and were represented as less clear, lower in pitch and panned to the extreme of one ear. Higher radii are reflected off higher surfaces like clouds and sonically increase in clarity, pitch and move towards the opposite ear.

The source signal was generated using two mixed oscillators that were both set to full amplitude and consisted of saw and pulse waves to produce rich harmonic quantity. The effective transiting radius was mapped to the oscillator pitch controls of both oscillators, to the cutoff frequency, the pulse width amount and the filter envelope depth. Table 1. shows the changes in these parameters in relation to the changes in effective transiting radii measurements.

Table 1. Sonification design for source signal

Effective Transiting Radius Km	Pitch Hz	MIDI	Cutoff (Timbre) Hz	Pulse Width Amount Hz	Filter Envelope Depth Hz
27.9496	27	0 – 0.1	0 - 443.77	2107.97-3154.26	2107.97 - 3154.26
34.3068	1276.38	0.1 – 0.3	443.77 - 1276.38	1276.37-2107.97	1276.37 - 2107.97
38.5383	2107.97	0.3 – 0.5	1276.37 - 2107.97	443.77 - 1276.37	443.77 - 1276.37
49.1171	4187	0.5 – 0.75	2107.97 - 3154.26	0 - 443.77	0 - 443.77

Pitch and cutoff frequency both increase with larger radii measurements and Pulse Width Amount and Filter Envelope Depth decrease. The decreasing pulse width allows the peaks to have richer harmonics. Higher pulse width settings reduce the harmonics in lower frequencies making them more discernible and resonant. The Filter Envelope Depth controls the cutoff frequency. Lower settings have less control allowing the cutoff to affect a wider bandwidth. The higher settings control the output of the cutoff limiting its output.

The noise signal uses a different synthesizer and is generated by using a noise oscillator that increases in frequency with increases of noise measurements. The cutoff frequency also increases with the noise allowing it to become more intense at larger measurements. This replicates more intense noise levels captured by the telescope. Higher noise settings increase in resonance making the signal sharper and more intense. The cutoff allowed the user to choose the type of filter to use on the white noise. This would permit the user to control the sound quality of the white noise signal to allow clearer discernment of the source signal if required. The noise signal also consisted of a random noise generator that would run through an oscillator. The user could choose which wave form to use for playback between a choice of sine, triangle, pulse and square wave. Higher pitched sounds would represent higher noise measurements and lower pitched sounds, lower noise settings.

Source signal radii peaks were enhanced by adding a combination of odd and even harmonics to the fundamental frequency by pushing the pitch of the source radii beyond 4187Hz to 8000Hz. The range between 3500 to 8000 Hz makes peaks more audible and discernible [46, 47]. The 3rd, 5th, 7th and 8th harmonic intervals were added to the fundamental. Table 2 shows how each harmonic was triggered in relation to the fundamental. When the fundamental reached 443.77Hz the 3rd harmonic was added. At 1276.38Hz the 5th harmonic was added to create a triad of tones, the fundamental, 3rd and 5th playing simultaneously. A total of four harmonics were added creating a chord like sound that enhances the source signal in amplitude and tonal complexity. The highest radii peaks being the most convoluted, consisting of 5 composite tones of harmonious relationship to each other.

Table 2. Added harmonics for peak enhancement

Fundamental Frequency Hz	443.77	1276.38	2107.97	3154.26
Effective Transiting Radius Km	30.07030278	34.30688713	38.53834531	43.86222868
Added Harmonic Cents	400 cents (3rd)	700 cents(5th)	1100 cents (7th)	1200 cents (8th)
Resultant Harmonic Range Hz	577.83 – 5582.67	2020.93 – 6629.42	4040.28 – 8025.08	6308.52 - 8374

To give a sense of height to the radii it was decided to use the auditory illusion of SMARC effect. To achieve this the source signal was panned to move from left to right ear as the effective transiting radius increased. The noise signal moved in the opposite direction from right to left ear as it became more intense. Table 3. shows the minimum and maximum frequency ranges of each shift in pan position from one ear to the other for both signals.

Other parameters were fixed to determine the range of the sound modulations which effected the timbre and amplitude of the signal. Table 4. lists these as MIDI values between the range of 0 to 1.

The application of reverberation to the source signal was intended to give a watery quality to the sound. It had to be subtle so as not to blur the distinction between the separate tones. Two reverb units were used. One for the left and right ear respectively. This would retain the reverb as a mono signal which would be better for tracking the movement from ear to ear. A stereo reverb would have projected reverberation onto the signal on both speakers simultaneously and would have muddied the spatial position of the source.

Table 3. Panning movement for Source and Noise signal

Effective Transiting Radius Km	Source Signal Minimum Frequency Hz	Source Signal Maximum Frequency Hz	Pan Position	Noise	Noise Signal Minimum Frequency Hz	Noise Signal Maximum Frequency Hz	Pan Position
27.9496187	27	442.67	-1 (Left)	0.000141	50	444.88	+1 (Right)
30.06471197	442.67	857.79	-0.8	2.938316	444.88	839.97	0.8
32.17701593	857.79	1274.71	-0.6	5.877978	839.97	1234.59	0.6
34.29842905	1274.71	1690.3	-0.4	8.814249	1234.59	1629.78	0.4
36.41310173	1690.3	2106.94	0 (Centre)	11.754596	1629.78	2023.81	0 (Centre)
38.53309845	2106.94	2520.25	0.4	14.686458	2023.81	2419.92	-0.4
40.63617498	2520.25	2942.92	0.6	17.633763	2419.92	2814.63	-0.6
42.78687701	2942.92	3355.92	0.8	20.570556	2814.63	3172.69	-0.8
44.88829637	3355.92	4187	+1 (Right)	23.234784	3172.69	4000	-1 (Left)

The interface would allow the user to load both source and noise signal and play them back simultaneously. Control over the speed of the playback and the ability to select segments of the data that could be played back on repeat function would be needed. Volume and mute controls were included for each channel. A visual representation of the data would provide reference for WV.

Table 4. Static Function Settings from the Synthesizer

Function	Setting	Action
Pulse Width Depth	1	Full range of the Pulse width amount
Filter Resonance	0.6	To add subtle resonant qualities to the sound
Filter Envelope Attack	0.4	The trigger time for the filter increase cutoff
Filter Envelope Decay	0.275	The break point for the filter to reduce cutoff
Filter Envelope Sustain	0.27	The amount of sustained filtered signal
Filter Envelope Release	0.1	Filtered modulation heard after note has stopped playing
Oscillator 1 Amplitude	1	Full amplitude range for Oscillator 1
Oscillator 2 Amplitude	1	Full amplitude range for Oscillator 2
Amplitude Envelope Attack	0.1	The length of time for the note to start playing from inaudible to full audible perception
Amplitude Envelope Sustain	0.25	Length note is heard after being triggered
Amplitude Envelope Release	0.25	Length note plays after the note has stopped playing

Note: - The Amplitude Envelope Decay is not mentioned in this table since it is a variably changing function increasing and decreasing in accordance to playback time.

5 Evaluation

Testing of the functionality of the interface and the user’s listening experience would be conducted separately. The evaluation would determine the effectiveness of the parameter mapping and see whether the sonification was able to offer any new insights to WV.

The sonification was tested on a MacBook. A four channel headphone amplifier allowed the use of two headphone sets for simultaneous playback. The two headphone sets were a matching pair so that sound reproduction for WV and the designer would not differ. 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 [55]. Answer sheets and pens were provided. The interviews were conducted in WV’s office, a quiet environment with sound-proof windows. An informed consent form and participatory information sheet were provided describing the experiment and informing WV about voluntary participation. The interviews were recorded on a portable audio recorder and transcribed.

The evaluation was designed to consist of two parts. The first part tested the interface and the second part, the efficacy of the sonification design. Each test would last about one and a half hours. Both interviews were semi-structured allowing extra questions to be asked where necessary.

The first test consisted of two sections. The first was 25 multiple choice questions based on a 5-point Likert scale. These questions focused on acquiring feedback about the functionality of the interface, it’s effectiveness and the usefulness of each component. The second section consisted of 12 questions about possible extra functions.

The second test assessed the efficacy of the design. Forty four questions were asked about the comprehensibility of the sonification, it’s effectiveness in relaying the data and whether the sound design required any changes. The interview lasted roughly about 3 hours. A demonstration of the interface and the sound design was given before starting. WV signed the participatory consent form and was allowed to explore the interface and the sound design. He then proceeded to answer questions for the first evaluation which lasted roughly about one hour and fifteen minutes. WV decided to go straight into the second test without taking a break. He started by listening to the sonification in more detail and then answered questions about the sound design and the parameter mapping. This test lasted roughly an hour. WV answered all the questions and his responses were recorded on a portable audio recorder.

6 Results

The evaluation of the sonification was split into two parts with the first assessing the interfaces functionality and the second to appraise the sound design. This took an average of three hours. Before starting the evaluation, WV was given a demonstration of the sonification and then left to explore the interface and listen to the sonification. WV had immediately spotted a new water artefact within minutes of using the interface. The first part of the evaluation asked questions about the interface and its functionality. For the second part of the evaluation WV listened to the sonification more thoroughly and answered questions about the parameter mapping and the sound design.

The first part consisted of 25 multiple choice questions about the interface which were set to a five point Likert Scale, ranging from 1 negative to 5 positive. The second part consisted of 12 questions regarding any features that could be added to the interface. The interview was semi-structured allowing further questions to be asked when necessary. WV found the interface easy to use. He could navigate through all the functions almost immediately: *“After the explanation, it was easy for me to follow”.* The ability to vary the playback speed was especially useful to slow down the playback which revealed more detail to the user.

There were a few changes and improvements that would need to be made to the interface. The visualizations lacked the necessary information required to give a clearer indication of the sonification playback in relation to the graphical interface. The selection of cue points in the data would need to be changed to wavelength measurements instead of line numbers: *“Wavelength would be more useful for me than the line numbers because I am more familiar with it”*. WV found that the symbol for the play button ‘X’ was misleading and that it would be better to use the standard symbol ‘▶’.

In the second part of the first evaluation, WV suggested adding functions that aided playback and gave clearer visual information. These would include the addition of other channels so that methane, ozone, oxygen, nitrogen and carbon dioxide can be sonified. Surround sound could enable distinctions between the different gases. The inclusion of a recording function would allow WV to make a copy of the sonification. The addition of rewind, fast forward, pause, jog wheel and scrub functions could facilitate playback.

Before the evaluations had started WV was given a demonstration of the interface and recap about the parameter mapping of both signals. After exploring the interface for about 2 minutes: *“Ok, I found something interesting that I didn’t notice before!”* Upon a second hearing WV announced that he was hearing a new water artefact within the region of 2 to 3 microns of wavelength. WV played the data again and after 19 seconds of listening confirmed that what he was hearing an important water feature within the range from 2.666 to 2.672 microns (refer to table 5). It was sharp, distinct and higher in signal to noise ratio than the broader peak at 5 to 8 microns.

Table 5. Water feature between 2 to 3 microns

Line	Wavelength Microns	Effective Transiting Radii	Frequency Hz	Added Harmonics Hz		
				3rd (400 Cents)	5th (700 cents)	7th (1100 cents)
17,329	2.672	42.3851868	2863.98	3263.98	3563.98	3963.98
17,330	2.671	42.2075746	2829.08	3229.08	3529.08	3929.08
17,331	2.67	37.5151793	1906.89	2306.89	2606.89	-
17,332	2.669	38.4508297	2090.77	2490.77	2790.77	-
17,333	2.668	43.2108538	3026.25	3426.25	3726.25	4126.25
17,334	2.667	39.8899523	2373.60	2773.60	3072.60	3473.6
17,335	2.666	43.0078466	2986.35	3386.35	3686.35	4086.35

The table also shows the added harmonics that pushed the peak above 3 and 4 kHz emphasizing a more distinct, sharp tone making it more noticeable above an increasing noise signal. On a visual graph this peak was masked: *"Using a different sense (hearing) gave me an idea to go back and look at the feature that I wasn't paying attention to before"*.

The next set of questions enquired about WV's listening experience. The peaks were immediately noticeable due to the enhanced harmonics and the cross movement of the source and noise signal along the stereo spectrum as they increased in intensity.

The sonification interface had a total of 9 preset speeds which varied from 1 to 1000 milliseconds. The user could input their own speeds in a separate number box. WV preferred: *"100 to 50 to distinguish between the individual features of the source wave.", "And… to hear a faster impression of the signal and noise … 10 or 5 milliseconds."* The speeds of 1 and 3 milliseconds were too fast to perceive anything. At the slowest speed WV could not make out the source from the noise signal. The speeds of 50 to 250 were the most immersive.

The next set of questions encouraged WV to give descriptions about the parameter mappings. Even though WV was familiar with the dataset he stated that: *"If I don't know anything about the signal, I haven't seen it before, I could understand what was happening because it was clear!"* This confirmed that he was able to understand that larger effective transiting radii were higher in pitch and shifted from left to right ear: *"I could clearly see (hear) that the noise is coming from a different side of the headphones. The pure signal is coming from somewhere else."* It was clear that WV was able to perceive the multiple mappings of the source signal: "*I was able to hear the pitch and amplitude change frequencies."*

The next set of questions enquired about the effectiveness of the aesthetics of the sonification. The source signal had been designed to mimic water-like qualities so that the user could easily identify with a natural and familiar sound. Multiple mappings were used to replicate changes in psychoacoustic qualities similar to what happens in nature. According to WV the source signal: *"It sounded like water! I would say bubbling water, boiling."* When asked whether this aesthetic choice made discernment easier, WV stated the following: *"Definitely! The way you designed the water sound, I was able to pick it up much better than plain audio."* Plain audio refers to the use of a synthetic waveform to represent the source signal. The noise signal used timbral changes in the white noise oscillator and pitch variances in the random oscillator to make intensity more apparent. The noise signal was described as annoying and irritating. This helped WV to block out the noise and to concentrate on the source signal.

The familiarity of the sound design for both the source and the noise helped WV to become more engaged with the data: *"It makes you listen more carefully to things that you might miss. Being more familiar it made me focus more on that particular segment of data."* The contrast in the two signals created a more realistic and credible listening experience. WV was finally asked whether the sound design aided the data analysis process: *"Yes, a resounding yes!"*

The effectiveness of the sonification prompted WV to suggest that it could be used to analyze more data like this. It would add an extra dimension to the data analysis procedure that could overcome masking of certain data elements that is likely to occur when only using two dimensional visual datasets. The designer asked whether atmospheric data could be sonified in real-time, but WV explained that the data had to be refined before it could be analyzed.

7 Discussion

The previous section described how the sonification proved to be most effective. WV immediately noticed a new water vapor feature that had been overlooked when using two-dimensional visualization techniques to analyze the data. This suggests that user centered development is an effective method of sonification design. The sonification should be treated as a method of communication and must accurately represent the dataset [2]. Any parameter mappings must directly convey aspects of the data that are immediately recognizable to the user [5]. To create meaningful sonifications the designer needs to understand what the data is about and the needs of the user [7]. The designer has to resist the urge of putting their own ideas over those that are required by the user. Methods like Grounded Theory allow the designer to build their design theory from the data as the basis for the development of the model [17]. The designer can suggest ideas to the user, but they must be communicated clearly so that the user is aware of how these ideas make the data more comprehensible. Both viewpoints are relevant [14] and when put together effectively it is possible to design an effective sonification.

The sonification was able to offer new insight beyond the limitations of visual representation on a two-dimensional plane. Knowing that each human sense is limited in particular ways suggests that multisensorial data analysis could help users to retrieve more information than usually expected [22]. If multisensorial data analysis methods become more commonplace, then it strongly suggests that sonification designers have to become more versed in their trade. Sonification parameter mapping uses psychoacoustic mappings to convey data and it is therefore important that designers thoroughly understand how human hearing works. One technique that was used in this study was to mimic natural sounds. Humans are highly trained in subject object relationships [26] and can easily extract semantic information concerning mass, material, interaction and force by listening [27]. This suggests that natural sounds are familiar, and the listener is already well trained in understanding the dimensions portrayed by the sound. The environment communicates rich semantic information to the listener allowing them to navigate within a particular space. Such a process creates strong mental associations [28] enhancing the user's ability to understand what is happening. An unfamiliar sound might need more time to be deciphered by the listener and will reduce the effectiveness that strong association is immediately able to convey. In order to mimic natural sounds then multiple mappings must be used to make the sound shape and object more perceivable. More natural sounding sonifications also act more like a language since the same cognitive process is used to decipher environmental sounds [49, 50].

The use of more natural sounding sonification seeks to represent the data more figuratively and can be compared to the way that sound is used in film sound design. Sounds are used to make stronger associations with the visual happenings on screen and sometimes only sound is used to portray certain elements that are not captured in a shot. The audience is able to understand what is happening because they can associate the sound to the object in real life. Even though this approach proved to be most effective in this study it does not suggest that this method needs to be employed for every sonification. In the case of designing water vapor the immediate association to water-like sounds was obvious. The question arises whether this technique would still make sense when designing sound for gases like carbon dioxide, nitrogen, methane and oxygen. These concepts are more abstract and being gases, share similar sonic attributes. The designer would have to produce gas like sounds that are distinguishable from each other and also distinct from white noise. Gas and noise share sonic characteristics. The designer's task is to understand the user's association to these chemicals and to use this as the semantic guideline to convey this affiliation sonically.

As Leplatre and McGregor [31] suggested the function and the aesthetics must be designed in relation to each other. This means that the designer must have a deep understanding of the function that the sonification serves [15]. Sonification design is likely to be more effective if it is task-based [4, 8, 9, 10, 11, 12, 13]. The task and the functionality of the sonification will determine the aesthetic properties that can effectively deliver the dataset comprehensibly.

WV was immediately able to perceive a new water feature, and this was mainly due the movement of the source and noise signals in cross pan to each other along the stereo spectrum. Human hearing is probably the most acute sense for perceiving temporal dimensions. Time works within the context of space and could be considered as time-spatial instead of seeing these two as separate mappings. The idea of speed being measured between distance and time strongly relates time to it's spatial nature. This suggests that spatial mapping strengthens the temporal and other psychoacoustics characteristics of a sound allowing faster information retrieval.

Movement proves to be effective when having multiple sound sources where the listener can either focus on one sound [28] or multiple sounds in relation to each other. Movement portrays a number of psychoacoustic properties simultaneously. It is time spatial, consisting of rhythm, speed and direction. It changes in amplitude, pitch and timbre in relation to proximity of the listener. Movement and spatial mapping allow distinction between one sound and another to be more cognizable. WV was able to distinguish the water vapor signal from the noise even when the latter was relatively high in amplitude in comparison. He had commented on how the movement of the signals made this distinction more apparent. Since both signals moved counter to each other as they became more intense, this left space for both signals to be transmitted without hinderance occurring from masking. Future work could test if the sonification of additional signals would allow clear distinction between them and whether new artefacts will still be discernible between the overlaps. Methods to overcome auditory overload would have to be studied carefully with the user to avoid such circumstances. The complexity involved in adding new source signals with different chemical qualities would need to be determined with the user. Such an approach would require iterative design process and evaluation to fine tune the different sources in their relationship to each other.

Iteration is valuable to the design process since it irons out any discrepancies allowing the designer to improve upon the model [19]. The evaluation conducted suggests improvements to the playback interface. The visual display would need major change since it lacked to provide the information that it was supposed to portray. Other additions include adding a recording device, a scrub tool or jog wheel for immediate playback. The addition of surround sound to the model would be a step worth considering once more source chemicals are to be sonified. The sound design of the source and noise signals needed no further adjustment. It was successful in performing the desired task and providing additional information not perceived when using visual graphs. WV had commented that he could understand the data without any visual reference whatsoever since the mapping was clear in conveying the differences in Effective transiting radii.

Even though multiple mappings were employed to convey the effective transiting radii, but the main mappings used were pitch and spatial movement. More complex mappings, added to mimic water-like sound, such as variances in timbre and amplitude, made increases in radii measurements more distinct without compromising data conveyance. The correct representation of the data overrules mimicking natural sounds and pitch changes had to stand out since they were the main factor conveying the variances in Effective transiting radii.

8 Conclusion

The results suggest that user centered design methods are highly effective for designing sonification of water vapor data for meteorological astronomy. The mimicking of natural sounds creates stronger associations for the listener and makes signal distinction much more effective. This was even the case when the noise to signal ratio was disproportionality high. The use of multiple parameter mappings provides richer auditory stimuli and more semantic information to the user. The use of spatial mapping and movement is a highly effective parameter mapping. It allows for easier detection of sudden changes. It also overcomes masking between signals, enabling clearer distinctions between multiple sound sources.

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