Sonification of Exosolar Planetary Systems

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Declaration

I hereby declare that the work presented in this thesis has not been submitted for any other degree or professional qualification, and that it is the result of my own independent work.

Michael Albert Paul Quinton

1st June 2021

Date

Abstract

The purpose of this research is to investigate sonification techniques suitable for astronomers to explore exosolar planetary data. Four studies were conducted, one with sonification specialists and three with exosolar planetary astronomers. The first study was to establish existing practices in sonification design and obtain detailed information about design processes not fully communicated in published papers. The other studies were about designing and evaluating sonifications for three different fields of exosolar astronomy. One, to sonify atmospheric data of an exoplanet in a habitable zone. Another, to sonify accretion discs located in newly developing exosolar systems. The third sonification, planet detection in an asteroid belt. User-centred design was used so that mappings of the datasets could be easily comprehensible. Each sonification was designed to sound like the natural elements that were represented in the data. Spatial separation between overlapping datasets can make hidden information more noticeable and provide additional dimensionality for sound objects. It may also give a more realistic interpretation of the data object in a real-world capacity. Multiple psychoacoustic mappings can convey data dimensionality and immediate recognition of subtle changes. Sound design aesthetics that mimic natural sounds were more relatable for the user. Sonification has been effective within the context of these studies offering new insight by unmasking previously unnoticed data particulars. It has also given the astronomers a broader understanding of the dimension of the data objects that they study and their temporal-spatial behaviours. Future work pertains to the further development and creation of a sonification model consisting of different aspects of exosolar astronomy that could be developed for a platform that houses different data related to this field of study.

Publications related to this research

Quinton, M., McGregor, I. and Benyon, D. (2018). Investigating Effective Methods of Designing Sonifications. Proceedings of the 24th International Conference on Auditory Display. (ICAD), Michigan, USA.

Quinton, M., McGregor, I. and Benyon, D. (2020). Sonification of an Exoplanetary Atmosphere. Audio Mostly in Extended Realities 2020, IEM / University of Music and Performing Arts, Graz, Austria, September 2020

Quinton, M., McGregor, I. and Benyon, D. (2021). Sonification of Exosolar System Accretion Discs. Proceedings of the 26th International Conference on Auditory Display. (ICAD), Virtually 25-28th June 2021

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Chapter 1: Introduction

This research is about designing effective sonifications that can be used for scientific measurement of Exosolar Planetary astronomical data. Sonification is the use of non-verbal sound to represent data and this research describes a process of investigation in learning about how to make a sonification comprehensible, informative and able to convey scientific quantities such as planetary size, brightness of stars, speed of planetary orbits and atmospheric qualities for an astronomer working in a particular field of Exosolar Planetary Astronomy. This Chapter gives an introduction to the study and presents the background that motivated this work, the questions that arose, and the aims and objectives related to this research.

1.1 Background

The aim of this PhD was to design sonifications that represented data that belongs to the field of astronomy known as Exosolar planetary research. The night sky reveals countless stars that are visible to the naked eye and if each of these stars are accompanied by a number of planets then this could possibly mean that there are billions, if not trillions of planets in outer space. The hunt for exoplanets brings with it extensive datasets with various temporal-spatial information on each planetary finding. When considering the way that distant planets are detected then one could consider that the data is not a direct observation but is the result of the dimming of the light of a star or the wobbling of a star.

Various telescopy techniques are used to capture exosolar planetary data. With it, a considerable amount of noise, which is the result of light pollution from other stars or sources and dust particles and gases that obstruct observation, is almost always inherent in these datasets. Astronomers and astrophysicists use visualisations, machine learning and numerical representations for data analysis (Long & de Souza, 2014). Johnson (2004) points out that visualisations can be poor representations of time dependent data. Astronomical data is being observed over time which is an important factor in this field. Large amounts of visualised data cannot be effectively represented due to the limitations of being able to fit all the information in one chart (Perkhofer, Walchshofer, & Hofer, 2020). Scientists have to filter the data to streamline areas of interest more precisely for algorithm purposes (Vujcic & Jevremovic, 2020) and this could lead to particular features being overlooked (Diaz-Merced et al., 2011).

Time is related to the measurement of spatial dimensions where the observed phenomena move and co-exist with other phenomena in terms of harmonic ratios (Dainton, 2016). This makes astronomical data temporal-spatial in nature, and there could be discrepancies in the temporal representations of these datasets. Sonification might be a potential medium that is able to remedy this inconsistency. Hearing is an acute temporal sense that can register and analyse changes in sounds ranging from microseconds to minutes (Kopp-Scheinpflug, Sinclair & Linden, 2018).

This research explored these elements to see how an effective sonification could be designed to suit the work of astronomers. It aimed to explore whether sonification could add dimensions that astronomers are unable to perceive using the current methods of data analysis. Sonification has been effectively used in astronomy to represent various aspects of astronomical data but has not become a widely used medium (Tomilson et al., 2017). There is no immediately identifiable reason as to why this is the case, especially when considering the potential that sonification offers as an effective means of representing temporal phenomena. Barrass & Vickers (2011) and Roddy & Bridges (2020) argue that poor sound design is one of the main causes for sonification not being more widespread and accepted as a data analysis technique in the sciences.

Worrall (2011) describes the problems encountered with parameter mappings that produce auditory artefacts that mask data relations and perplex users' understanding of datasets. Others have argued that there is a reluctancy for scientists to alter their modus operandi when it comes to their working methods (Supper, 2012) and are unlikely to adopt sonification in their work if they have never used it before and are distrustful of using their ears for data analysis (Supper & Bijsterveld, 2015). Trepidation towards change is a common tendency (Eagle, 1999) and is an underlying obstacle that sonification designers have to consider. This could be mainly due to the lack of experience that scientists have with auditory displays in their work and have not received any formal education in their use, discouraging them from what could be considered a steep learning curve (Walker and Nees, 2011). When designing an interface for a specific user, a designer is usually encouraged to work with the user (Abras, Maloney-Krichmar, & Preece, 2004). A sonification interface is a communication system (Scaletti, 2018), and a good sonification design should be able to convey the information contained in the dataset clearly and comprehensively. This

PhD explored the relationship between a designer and users, and how to develop a design that encourages astronomers working in the field of exosolar planetary research to use sonification as a data analysis method.

As an underlying hypothesis to this study, it is believed that human hearing offers an acute sense of temporal-spatial perception (Effenberg et al. 2005) which could be an effective platform for use in Exosolar system astronomy. When listening to a dataset a user can selectively listen to a specific aspect of a dataset and easily filter out other sounds that are not relevant to them at that point in time (Lunn & Hunt, 2011). Listeners can also do the opposite and can perceive a dataset as a whole and be able to determine various details simultaneously (Dayé & De Campo, 2006). This allows the listener to go through multiple datasets concurrently, although it could generally be the case that it is difficult to follow more than three continuous sonified data streams (Flowers, 2005). There is also the advantage that data analysis can take place by not necessarily having to sit in front of one's screen (Vogt, De Campo, & Eckel, 2007). This is advantageous when screens cannot be accessed due to the nature of the activity. When a rowing team used sonification to improve their sense of time by listening to changes in the speed of rowing, it was impractical to use a screen on a rowing boat (Schaffert et al. 2012).

This research explores these aspects of designing sonifications and to use them to create effective sonifications of Exosolar planetary data. Through the representation of time, it could be possible to achieve a clearer understanding of the spatial dimensions within which an astronomical occurrence is taking place. Sound is a temporal-spatial phenomenon (Neuhoff, 2011). Celestial bodies move at some point in the empty space of the universe at dizzying speeds (Bataille & Michelson, 1986).

The term *Planet* comes from the Greek word *Planetes* which means *Wanderer* (Thommes & Lissauer, 2005). Planetary movements through space and time of discovered Exoplanets ranges from 0.09 of a day to 7,300,000 days (NASA, 2020) and sound could potentially map the path of a *Wanderer* effectively due to its temporal-spatial characteristics. The dimensions of these celestial bodies could be perceived through auditory perception. A listener can potentially perceive the dimensions of size, mass and length (Carello, Anderson, & Kunkler - Peck, 1998). Lakatos, McAdams, & Causse (1997) found that listeners could tell differences in terms of height and width of two metal bars struck together. In a series of four experiments conducted by Kunkler -

Peck & Turvey (2000) to test how listeners could potentially recognise dimensions of size solely through listening, in the first test listeners could recognise the heights and widths of rectangular steel plates equal in area and weight. In a second experiment participants could determine the material, heights and widths of three plates of steel, wood and plexiglass. Listeners successfully identified circular, triangular and rectangular plates of a single material in test three and different materials in test four.

These different studies illustrate how human hearing can allow listeners to recognise the properties of an object through the sounds that it makes. These characteristics of human hearing can be integrated into sonification design and could possibly offer astronomers a tangible, realistic impression of the data they are listening to. This research intends to explore this possibility in detail. For non-visual information sources to be effectively utilised in human computer interfaces, the designer must be highly adept in the field of psychoacoustics (Visell et al. 2009).

The aspects of this research are especially important when considering the growing interest in multisensorial data analysis systems that are becoming more developed over time (Lee & Wallace, 2019). With the continuous development of VR and AR applied technologies and the ever-increasing size of data, these multisensorial technologies, present new methods of information processing (Lee, 2017). The original Kepler mission which was launched in March 2009 spent just over four years observing more than 150,000 stars within a miniscule frame of the galaxy that exists between the constellations of Cygnus and Lyra (NASA, 2018). This number of stars is dwarfed in comparison with the estimated number of stars in the Milky Way Galaxy which is estimated by astronomers to be roughly between 100 to 400 billion stars (Masetti, 2015). The European Space Agency (ESA) is already attempting to observe a billion stars with the Gaia satellite (European Space Agency, 2016) and with each star that is observed there is likelihood that planets will be found too. This could mean that Exosolar Planetary data will increase exponentially and suggests that innovative methods of data analysis that are fast and efficient will need to be implemented.

This research explored the possibilities of designing sonification interfaces that can be used in Exosolar planetary data. It aimed to design a robust interface that could clearly deliver aspects of astronomical datasets solely through the use of sonification. It inquired to find out the potential that a sonification can offer that cannot be delivered by any other of the useable sense technology platforms. These are the motivations that prompted the following research questions.

1.2 Research questions

1. To what extent can sonification be an effective tool that might be used by astronomers and astrophysicists for exosolar planetary research?
2. What parameters would astronomers be interested in sonifying in relation to exoplanetary data?
3. What would be the most effective methods of sonifying exosolar planetary data for astronomers?

1.3 Aims

- To carry out a literature review: To find out information regarding Exosolar planetary data and about sonification design.
- To contact astronomers who work in the field of Exosolar Planetary research and who would be interested in designing a sonification interface related to their data.
- To Interview other sonification designers to find out more about techniques and design principles that can be applied to create an effective sonification design.
- To use an iterative design approach to broaden the designer’s understanding of the data.
- To evaluate and test sonification techniques that are effective for Exosolar planetary research.

1.4 Thesis structure

This chapter has served as an introduction to the reader ushering them into the motivations, hypothesis and research questions that have arisen with regards to effective use of sonification as a representation of Exosolar planetary data.

Chapter 2 forms the pediment of research for this study by investigating the nature of Exosolar Planetary data, Sonification, its various methods and design techniques and to see how sonification has been used in astronomy before. The chapter explores the process of human perception through hearing and listening.

Chapter 3 is about the first study conducted with sonification designers. The purpose of this study was to obtain a deeper understanding of sonification design, the current trends in the field, the positives and negatives of sonification design. This study was designed to enable the designers to speak about sonification in a much broader context than is usually the case due to limitations in publication space and an interview breaks through the formalities of academic writing going straight to the raw aspects of a sonification designer's philosophy of the field itself and of their own design practice and application.

Chapter 4 discusses the design process of a sonification interface that was created with an astronomer who works in the field of Exosolar Planetary research giving a background of the related research. It describes the data gathering and processing methods used and how these coding's were used to build a sonification model based on these findings. The chapter describes the design process and the evaluation conducted to test the model and concludes by discussing the findings of the evaluation and the effectiveness of the sonification.

Chapter 5 discusses the design process of a second sonification interface created with another astronomer who works in Exosolar science. The background describes research related to the development of this interface and discusses the data gathering process, the results, coding's and findings. The design method describes how the sonification was built in accordance to the findings. The evaluation gives an indication of the testing process of the model and the discussion describes the findings of the evaluation and the effectiveness of the sonification.

Chapter 6 discusses the testing of a third interface designed with an astronomer who has been studying planet detection in an Exosolar system's Kuiper belt. It starts by summarising the findings of the previous chapter and the background research related to this particular study. The chapter moves on to describe data gathering, processing and coding of the findings. The following section discusses the sonification design process which is based on the findings of the data gathering process. The Evaluation section describes the testing of the sonification model which is then followed by a discussion which elaborates upon the findings, draws conclusions about the study and the effectiveness of the sonification design.

Chapter 7 discusses the thesis, the studies that have been conducted, what has been learned from this research and how the findings form a design theory related to Sonification and its use in Exosolar Astronomy.

Chapter 8 summarises the thesis. It discusses the strengths and short comings of the research. The chapter goes on to discuss the contribution to knowledge of this body of work to the field of sonification and how it can be implemented in the context of astronomy related data representations. It also presents future work that can develop on more expansive representations of Exosolar Astronomy and further development of a more studied design theory that probably involves more users and applications.

1.5 Summary

This chapter has given a brief overview of this research by describing the possible potential that sonification could offer as a data analysis tool in Exosolar Planetary research. It has posed research questions that seek to explore the extent of the effectiveness of sonification in Exosolar Planetary research, the data parameters that astronomers would be interested in sonifying and the most efficacious methods to sonify the data.

The following chapter will be giving a more elaborate description of these subjects. It will be looking at the nature of the datasets that astronomers and astrophysicists use in their work in exosolar planetary research. A more in-depth description of sonification and various guidelines and techniques that are used for sonification design will be presented. It will also discuss the nature of human hearing, the process of listening, the relevance of these aspects and their importance in this study.

Chapter 2: Literature review

This chapter will explore the potential of human hearing and how it can be used effectively as a data analysis method in Exosolar astronomy through sonification. It will look at the particular data that is related to this field of astronomy. It will investigate the potential of sonification and how it can be applied and has been utilised before in astronomy. The chapter investigates sonification design, human hearing perception and listening attitudes which are important aspects to be considered in the sonification design process.

2.1 Astronomy & Exosolar Data

Exo or Extra Solar systems consist of planets that orbit around other host stars (Williams, 2015). Astronomers observe these systems in order to achieve a deeper understanding of the formation of the universe. These observations comprise of various aspects of astronomical study. Younger Exosolar systems are observed in an attempt to understand how the Solar system could have developed and how planets are born. Other Exosolar systems that contain planets are observed for similarities and differences to the Solar System. Older Exosolar systems allow astronomers the opportunity to observe planets or even stars dying and studying the effect of this. Another aspect in this field of study is the search for life beyond the Earth. By observing the neighbouring planets in the Solar System, life which is similar to that on Earth has not been discovered since the conditions on these planets is hostile to human existence (Grandl, 2017). For many years astronomers still postulated that human life was unique in the universe (Crowe, 2016). This view seems to be changing since there have been various findings of Earth-like planets that suggest that life similar to that on Earth could exist. All these aspects of astronomical study have pushed the initiative to develop more sophisticated telescopes to observe these phenomena.

Since the late 1980s astronomers were finally able to capture impressions of celestial bodies orbiting other stars and the existence of exoplanets became a reality (Pepe, Ehrenreich, & Meyer, 2014). Periodic observations of hundreds of stars have revealed a few thousand planets of various types. They are predominantly on the mid to large size due to the way that current techniques are only able to capture these types of planets. The information that is gathered with regards to a particular exosolar system is piecemeal since it is harder to detect smaller planets in a stellar system. It could be that smaller planets are missed or are not being detected and that there are Exosolar system models that are incomplete because of this. Exoplanets are not directly observed since they do not reflect enough light (NASA, 2019). Planetary observation techniques focus on capturing variances in light emissions from a parent star and also track any movement of the star that reflects gravitational influence by another neighbouring body (SpacePlace, 2020). Smaller planets might not cause enough light variances or be too small to for its gravitational influence on the star to be noticed.

Astronomical data

There are vast amounts of data in astronomy which amount to terabytes of information each year and this amount is constantly on the increase (Dillon, 2015). To give an example of the unabating increase in astronomical data, the *Australian Square Kilometre Array Pathfinder* (ASKAP) telescope is projected to increase one hundredfold by the year 2025 with an acquisition rate of 750 terabytes/ second (Stephens et al., 2015). Table 2.1 shows how data acquisition will increase annually until the year 2025. The mention of Exabytes which are equivalent to 1000 Petabytes (1000 Terabytes), and Zettabytes that are 1000 Exabytes (Quintero et al. 2015) are immense, and all of this data needs to be processed and analysed. This increase in data pertains to one telescope alone. Similar devices on the ground around the world and in orbit around the Sun in space are collecting datasets of similar magnitude. Once this data is collected it has to be filtered from various noise that is collected from light pollution from other stars and space dust. The filtered signal has to be smoothened using various techniques of mathematical calculation to compensate for any losses in the filtering process (Stark & Murtagh, 2002).

Table 2.1: The projected annual storage and computing needs presented across the data

Data Phase	**Astronomy**
Acquisition	25 ZB/year
Storage	1 EB/year
Analysis	In situ. data reduction ≤ 90%
	Real-time processing
	Massive volumes (quantity)
Distribution	Dedicated lines from antennae to server (600 TB/s)

Note. Data from Stephens et al. (2015) ZB (Zettabytes), EB (Exabytes)

Data mining in astronomy consists of summarisation, classification, regression, clustering, association, time-series analysis and outlier/ anomaly detection (Zhang & Zhao, 2015). The current methods used to analyse all these scientific data are mainly visualisation techniques and various numerical processing (Alexander et al. 2014). There have been many advancements in the application of Machine Learning and Artificial Intelligence that, when applied correctly, are potentially advantageous for data analysis in astronomy (Ball & Brunner, 2010). The bias of human input in Machine learning and AI algorithms limits data processing, and visualisation and statistical methods are still considered to be the first order of preference (Fluke & Colins, 2020). In the case of Exoplanetary research, crowdsourcing has been one of the major contributions in the data analysis process with regards to the confirmation of Exoplanets. Initiatives like the Planet Hunters enterprise, launched in 2008, and initiated by Ariel Waldman from NASA Innovative Advanced Concepts, (Spacehack, n.d.). As of 2020, this initiative consists of about 20,000 volunteers who have been classifying over 280, 000 datasets (PlanetHunters, n.d.). This means that Exoplanetary data archives can be found online so that members of the general public who wish to volunteer can easily access the datasets.

These online Exoplanetary archives consist of about 80 different parameters of data on each individual planet. The data contains information about planetary orbits, mass, size, proximity to the star, axial tilt and information about the star and other related Celestial phenomena (NASA, 2020a). To date roughly over 4,200 planets have been confirmed (ibid) and there are considerable amounts of new data being collected.

Exosolar planet databases

There are two main online database systems that are used for the archiving of Exosolar planetary data. These databases are the NASA Exoplanet Archive (NASA, 2020a) and the Extrasolar Planet Encyclopaedia (Exoplanet.eu, 2020a). There used to be another archive called the Exoplanet Data Explorer, but this site was last updated regularly in June 2018. Since then, the site is only updated occasionally (Exoplanets.org, 2018).

The NASA Exoplanet Archive (NASA, 2020b) consists of a number of interactive tables which represent information on all published exoplanets. Any planet that is discovered is labelled according to the technique and the optical magnitude band used. The findings are analysed and confirmed through a system of peer reviewing. Any information regarding a celestial body that has not yet been confirmed as a planet is still archived in the database. The site also contains various data validation reports and target stellar parameters. There is also information about light curves from the Kepler, the K2, and CoRot missions and from a number of ground-based observations (Akeson et al., 2013) like the SuperWASP, KELT, HATnet (Bakos, 2018) and UKIRT. There is the TESS survey satellite (TESS, n.d.) that was launched in April of 2018 and has been surveying the sky for two years searching for transiting Exoplanets around the brightest stars near Earth. The NASA Exoplanet Archive currently boasts a total of 4,276 confirmed planets on the 05th of September 2020 (NASA, 2020a).

The Extrasolar Planets Encyclopaedia catalogue was established in 1995. It is described by Schneider et al. (2011) as being split into eight different tables which are in accordance to the method of discovery. Data on each individual planet can be accessed in sub-tables that give a more detailed report of information concerning the planet's name, orbit, the method of detection used, its mass, radius etc. The data found in these tables is numerical. Any visualisation of the data can be accessed by going to a dedicated search page that shows Scatter Plot diagrams of the planets. The Extrasolar Planets Encyclopaedia boasts a total of 4,330 planets as from the 28th of August 2020 (Exoplanet.eu, 2020b).

As of October 2020, 60 of the confirmed planets are situated in a particular belt of orbital distance from the parent star dubbed by Scientists as *The Habitable Zone* or *The Goldilocks Zone* (Planetary Habitability Laboratory, 2020). This zone is an area where planets would be far enough and yet not too far for liquid water to exist without evaporating or freezing (Menou & Tabachnik, 2002). Scientists believe that it is highly likely that life similar to that on Earth could be supported on other planets where liquid water is present (ExoplanetExploration, 2020). Zuluaga Callejas et al. (2014) defines the habitable zone as the region where the complex interaction between life and its physical environment produces a degree of equilibrium usually necessary to sustain life.

Exoplanets are much fainter than planets in the Solar system. The distance, angular separations from their parent star and transits which last only seconds makes direct detection extremely difficult, especially at optical wavelengths where the star / planet intensity ratio is sizeable (Perryman, 2018). Due to these limitations a number of techniques can be used in order to detect planets. These are *Doppler Shift* or *Radial*

Velocity Technique, *Transit Observations*, *Gravitational Microlensing*, *Astrometry* and *Direct Imaging* (Wright & Gaudi, 2012). Doppler and Transit Observations detect planets that orbit in close proximity to their host star and are of larger dimensions. Microlensing, Astrometry and Direct Imaging are used for determining planets with a wider orbit. The two different types of planet hunting observations complement each other but the problem is that they are generally not applied to the same sample of stars (Fischer et al., 2015a). This means that information on exosolar systems is piecemeal (ibid).

A star's relative position is influenced by any gravitational bodies that orbit around it. This shift or *wobble* that the star makes due to a planet's gravitational influence can be precisely measured and the proximity of orbit and mass of that planetary body can be determined by this shift. If for example the star has one planetary body orbiting around it then both celestial bodies will move in circular orbits around their common centre of mass. This happens even though the planet is much smaller than its parent star, although smaller planets are still difficult to detect in distant orbits. The centre of mass of a stellar system is known as the *Barycentre*, which is the nucleus point that keeps all the celestial bodies in balance with each other (Wright, 2017).

Exosolar planet detection techniques

The *radial velocity method* can detect these ever so slight wobbles or *reflex velocities* of the star, in a small circle or ellipse, depending on the gravitational pull of the smaller planet. These slight movements affect the star's light spectrum, or colour signature. When the star comes closer to the observer, the colour slightly shifts towards a blueish hue; if it is moving away, it will shift more towards a reddish hue (ExoplanetExploration, 2020b). When a large planet orbits in close proximity to its parent star, the star moves at a faster rate around its centre of mass which in turn causes a larger colour shift in the starlight's spectrum (see Figure 2.1). Larger Jupiter Class planets that are orbiting in close proximity to its parent star are easier to detect (Fischer et al., 2015b).

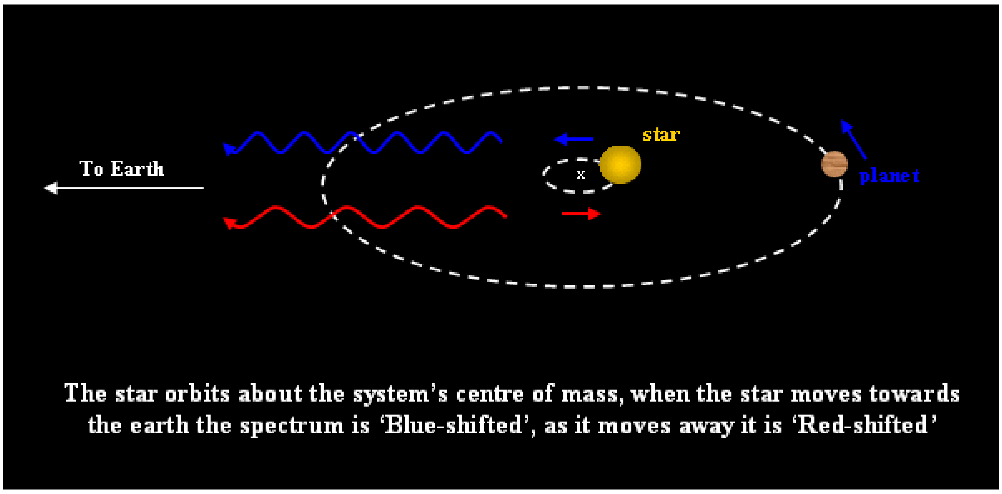

Figure 2.1: Doppler shift planet hunting technique. (Esplanet, n.d.)

Another detection technique is the *Transit method* which is the most successful and commonly used process for planet hunting (Deeg & Alonso, 2018) consisting of about 71% of confirmed Exoplanets to date (Exoplanet.eu, 2020c). If a planet passes between the observer and a star it momentarily blocks out a tiny portion of light reducing the apparent brightness of that star (Taaki, Kamalabadi, & Kemball, 2020). A small planet will not cause much of a dip in light, but a larger planet will (see Figure 2.2).

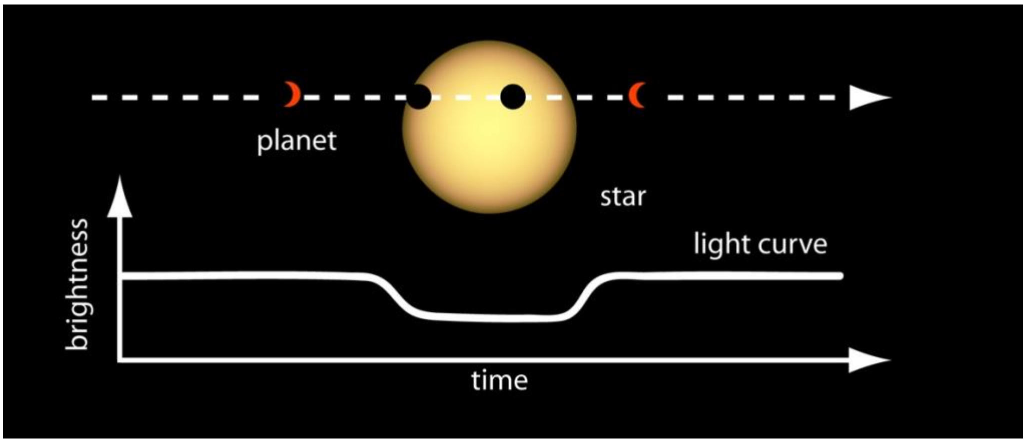

Figure 2.2: Transit method for planet hunting (NASA, 2012)

A transit event can only be observed when the orbital plane of the planet can be seen crossing the plane of the star. Refer to figure 2.3 which depicts when planets can and cannot be observed in transit due to the angle at which the transit is taking place (The Planetary Society, 2019).

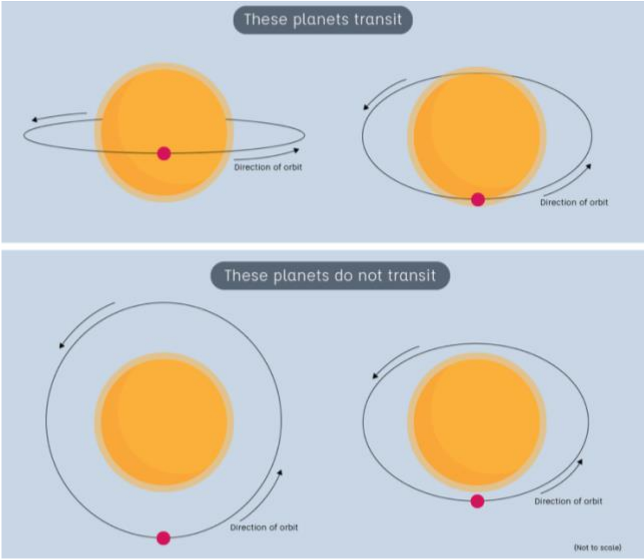

Figure 2.3: The angles at which transits can and cannot be observed (Las Cumbres Observatory Global Telescope, 2020)

The *Astrometric technique* is similar to *Radial Velocity Technique*, as it also measures the wobble caused by orbiting planets (see Figure 2.4). In this case astronomers are looking for slight displacements in the sky by actually having precise positions of the stars compared to other stars around them. Any change, or wobble, that the star experiences indicates that there are possibly exoplanets orbiting around that star causing the wobbling. (Malbet & Sozzetti, 2018).

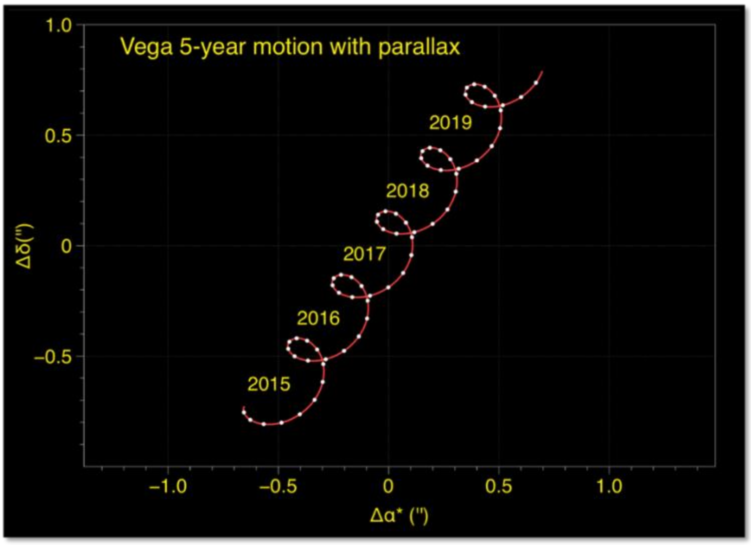

Figure 2.4: Astrometric Technique (IAUS330, 2017)

The *Direct Imaging Technique* uses specialized optic methods to photograph exoplanets. In order to achieve this the brightness from the parent star has to be reduced so that the exoplanets become more visible. This is done by using a technique known as *Coronography* where the brightness of the star is masked by using a huge star shade which is positioned between a nearby telescope and the star that is being observed (see Figure 2.5). Another technique used is *Interferometry* where combined light from a number of telescopes is used in order to cancel out the light from the star by using specialized optics (Pueyo, 2018). An example of how this technique works is animated in a You Tube video presentation by NASA JPL (2014) where the satellite telescope is launched along with the star shade.

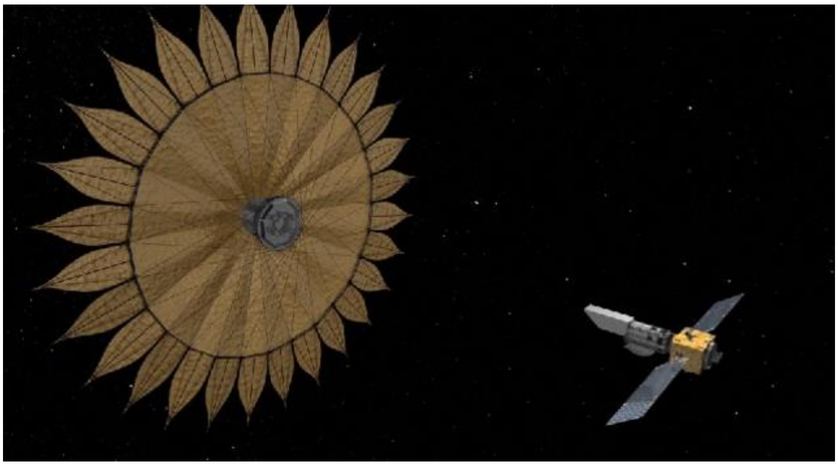

Figure 2.5: Imaging an exoplanet with a flower-power star shade (Timmer, 2014)

Figure 2.6 shows an image captured using the Direct Imaging Technique on the star known as GJ 504, where an orbiting planet was detected and designated as GJ 504b. In the figure it is possible to see how the star light from the parent star has been filtered out to the extent that it appears as a black circle. The planet becomes visible due to the lessening of the star light and can be seen as a bright smaller circle to the right of the black circled star. The light from the planet is the reflected light from the parent star.

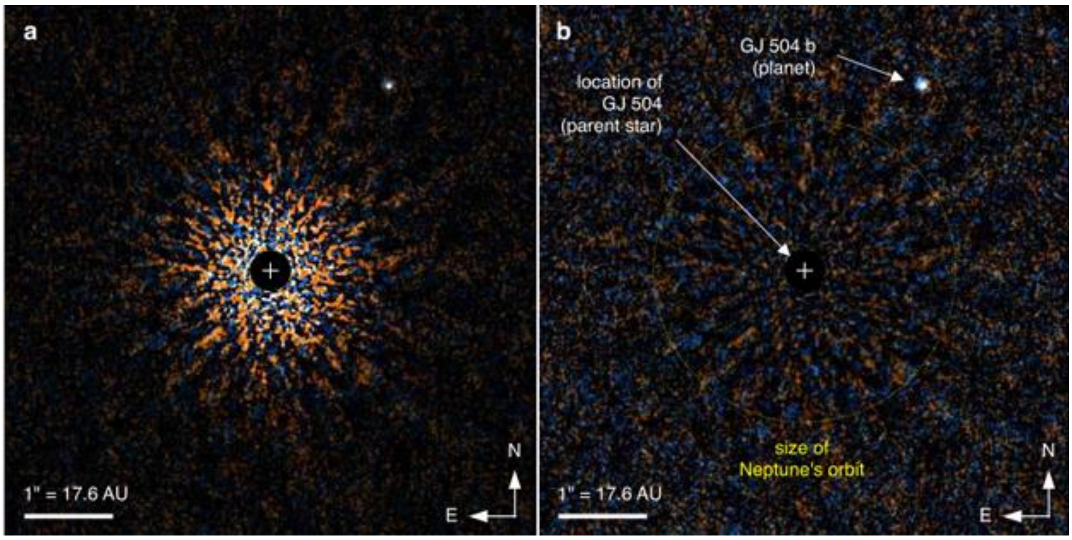

Figure 2.6: Direct Imaging Technique (Spaceref, 2013)

Gravitational Microlensing is the only technique that can currently detect planets that are even more far away from the Earth (Tsapras, 2018). Microlensing is capable of detecting planets at the centre of the Milky Way galaxy which are thousands of light years away (Ban, 2020). It is believed that light travels through space in a straight line. According to Einstein's theory of general relativity gravity actually bends space and therefore also warps light (Einstein, 1936). For this technique two stars are used. One is known as the source star and the other as the lens star. If the source star is situated behind the immediate or lens star its effect is multiplied. The light from the source star envelopes the lens star and this is known as an *Einstein ring*. This creates a single giant disk of light, an enhancement by about 1000 times, which is known as the *Einstein disk*. It is through this light that exoplanets become apparent because the planets gravitational force actually bends the light and produces a third image which is the planet itself. From this resultant phenomenon scientists can calculate the mass, the orbit and the orbital period of a planet from the actual intensity and curve of the light (Batista, 2018). Figure 2.7 gives a graphical representation of how Gravitational Microlensing technique is achieved.

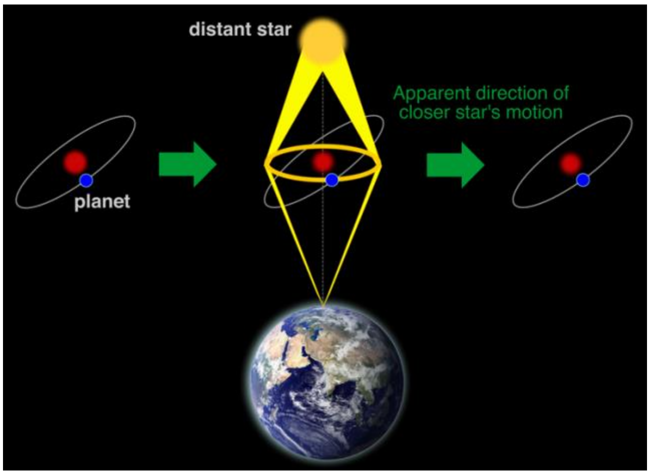

Figure 2.7: Gravitational Microlensing (Microlensing Source, n.d.)

Once an exoplanet has been detected it is relevant for scientists to try and determine what type of atmosphere these planets have. Planets that are found within the *habitable zone* of an Exosolar System could host life similar to that on Earth. Even if planets are located in the habitable zone of any particular exosolar system it does not necessarily mean that they host Earth-like life. If the atmospheres on these planets are either too dense or too thin then the probability of hosting similitudes to human life are unlikely (Seager & Deming, 2010a).

Atmospheric studies of Exoplanets are conducted by using *Spectroscopy* during a planet's transit period (European Space Agency, n.d.). The first Exoplanet to be detected had its atmosphere analysed by using Spectrophotometric Techniques (Refer to figure 2.8) that concentrated on the detection of atomic sodium. While the planet HD 209458b was in transit of its star HD 209458 this caused a dimming of the stellar light. Any sodium quantities in the atmosphere reflecting the remaining stellar light will show up in a particular range of the visual colour spectrum depicted in figure 2.8 as a yellow/orange hue. This allowed the Hubble Space telescope to detect levels of atomic sodium properties in the planet's atmosphere (Charbonneau et al. (2002).

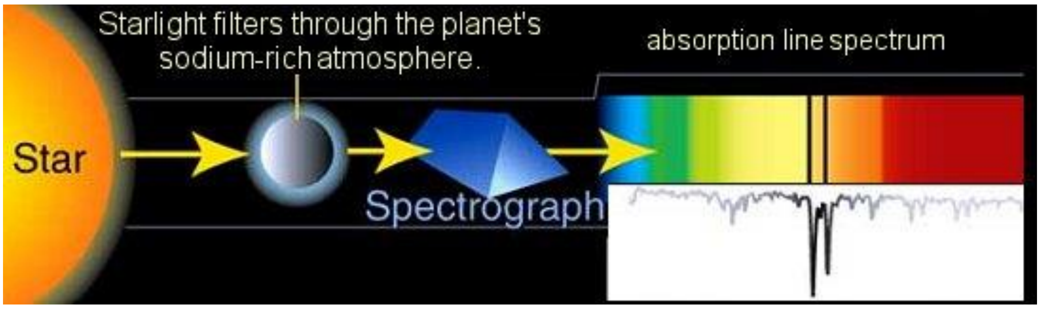

Figure 2.8: An example of how the spectrograph is able to detect atomic sodium properties (James Webb Telescope, n.d.)

Atmospheric conditions on Exoplanets vary according to the planet's position in relation to its parent star and the type of planet, rock or gas. The nature of the parent star and the age of the Exosolar system influence the atmospheric conditions of an exoplanet (Deming & Seager, 2017). There are five types of atmospheres that Astro Scientists usually observe. Table 2.2 describes the five types of known atmospheres.

Table 2.2: Atmosphere classifications observed by astro scientists

Type	**Description**
Dominated by Hydrogen and Helium	Predominantly contain Hydrogen and Helium which was captured from a protoplanetary nebula. e.g. the gas and ice giants of our Solar System
Outgassed Atmospheres with Hydrogen	Hydrogen content not captured from a protoplanetary nebula but from outgassing. Some planets are large enough and cold enough to sustain Hydrogen in the atmosphere
Outgassed Atmospheres dominated by Carbon	Planets like Earth where Carbon Dioxide dissolved in the ocean and become sequestered in limestone sedimentary rocks. The actual planet atmospheric composition via outgassing depends on the interior composition
Hot Super Earth atmospheres lacking volatiles	Hot Earths or Super Earths with temperatures up to 1500 Kelvin, which would have lost Hydrogen, Carbon, Nitrogen, Oxygen and Sulphur, and instead are composed of silicates such as Calcium, Aluminium and Titanium (Schaefer and Fegley, 2009)
Atmosphereless planets	Planets that have completely lost their atmosphere. These planets might have an exosphere like Mercury or the Moon.

Note. Information taken from (Seager & Deming, 2010b) with reference to (Schaefer & Fegley, 2009). Outgassing: the release of gases and water in the form of gas from hot, liquid rock into the air (Cambridge, 2020)

Temporal-Spatial relations between astronomical data and sound perception

Astronomical data consists of information concerning the position of an object in the sky or its change in position over time (Pössel, 2020). Experiments in audition indicate that the time-related features of sound are critical aspects of perception for both localisation and identification (Deneux et al. 2016). Human hearing is acutely refined to hear the temporal resolution between 4.5 milliseconds to several thousand milliseconds (Goudarzi, 2018). This suggests that the use of sound might be advantageous when used to analyse time-based datasets, especially when visualisations of time dependent data is often poorly represented (Johnson, 2004).

In an everyday listening environment, the human ear is constantly receiving a myriad of different sonic stimuli every second. The listener is immediately able to discern the nature of the multiple sounds that are being heard and to determine from what direction these sounds are occurring. The listener is able to focus on one sound amidst the many (Oxenham, 2018). In a conversation, a listener can easily switch between two different streams of dialogue. Cherry (1953) had found that this switching between conversations could easily be done when listening to two separate streams of dialogue, one on each channel of a pair of headphones. He had coined this ability *the cocktail party effect* where the listener is able to home in on a conversation without being distracted by other conversations happening beside them. The propensity to deconstruct complex acoustic waves coming from multiple sources and to focus on one target sound is known as *Auditory Scene Analysis* (Bregman, 1993; Alain, 2007). This capacity to hear particular sounds amongst the many is an important aspect of hearing that allows people to immediately understand the occurrences in their surrounding environment. A novel sound or pattern in the sonic environment is immediately discernible. These unusual sounds peak our attention allowing us to focus, analyse and understand the sound source instantaneously (Horowitz, 2012a).

2.2 Listening

Labelle (2012) describes how sound animates objects. It reflects movement and gives life to seemingly inanimate bodies. It unfolds in time and in space by propagating from its source and reflecting off the surfaces of the surrounding objects. Sound is an event-body in time, with qualities such as spatial coordinates that provide information to the listener (ibid). When sound reflects off various surfaces the spectral characteristics are essential in order to perceive spatial dimensions (Blauert and Lindemann, 1986). These spectral characteristics are ever changing (Schafer, 1994b) giving a sense of time, space, distinguishing subject-object orientation and allowing perception of an object even when it is not seen (Blauert, 1997a). A combination of compressions and rarefactions occur when a sound wave is propagating through a medium and these vary according to the density or elasticity of the sound source (Howard & Angus, 2017). The energy of the generated sound decreases as it moves away from the source as it loses energy when it reflects and refracts off any surfaces that the wave interacts with (Moore, 2012a).

Human hearing can effectively identify these subtle changes that occur in sound propagation. These variances carry semantic information about mass, material, interaction and force (Gaver, 1993). Chion (1994a) discusses how sound perception is not a series of collated perceptions and images, but impressions of actual dimensions of space, volume, significance, matter, expression and the organisation of the adhesive temporal-spatial phenomenon. Shinn-Cunningham (2008) describes sound as a perceptual entity intuitively understood by the listener and cognised as coming from a distinct sound source. Usually in a typical environment there is an assortment of sounds coming from various sources, and listeners are proficient in analysing the soundscape to determine the sound sources in that environment (Shinn-Cunningham et al. 2007). If any sounds have been masked by other sounds, then the concealed frequencies are perceptually restored allowing continuity of perception of the masked sounds (Darwin et al. 2002; Warren et al. 1994). There are three forms of restoration that takes place and are listed in table 2.3 (ibid).

Table 2.3: Restoration of masked properties of source signal

Restoration Type	**Description**
Homophonic Continuity	The restored sound source and the potential masker are the same sound but have different amplitude levels
Heterophonic Continuity	The restored sound and the potential masker differ in spectrum
Contextual Catenation	The restored sound differs not only from the potential masker and is enhanced if the potential masker is acoustically similar

Source Warren et al. (1994)

Human hearing perception consists of physiological effects that influence the psychology of perception and this is known as psychoacoustics (Yost, 2015). Perception is an interpretation of the property content of sensation. The chemical, physical, excitation of sensation produces a physiological reaction in the form of a neural signal, hence, as an interaction with the environment (Schneider, 2018a). The main characteristics of hearing perception are loudness, pitch, temporal recognition, the perception of space and tone or timbre which is also referred to as sound colour.

Loudness

Loudness is the perception of variations in the intensity of sound which varies from the softest to the loudest discriminable, ranging from 1 to 1012 dB (Carlile, 2011). It is the subjective effect of the ear and the brain, and of the amplitude and frequency of a vibration (Smith et al. 1996). Loudness depends on frequency as well as intensity (Moore, 2012b), on the sound pressure level exerted by the stimulus, the frequency and its bandwidth and duration (ISO 16832:2006). Different frequencies are perceived at different levels of loudness and sounds in the midrange of the perceivable frequency spectrum (20Hz to 20kHz). These seem louder than frequencies in both the lower and the higher ranges at the same sound pressure level (Farnell, 2010a). The midrange frequencies of a range of 300Hz to 3kHz are usually the bandwidth where human speech is perceivable (ibid) and evolutionary influence on the human hearing faculty emphasises this range. Any changes in the Mid frequency range are more distinguishable since the difference in limen for frequency (DLF) is smaller than it is in the very low and very high bandwidths where changes in pitch are harder to hear (Moore, 2012c).

In order for frequencies to be perceived at equal loudness to each other various compensations in the amplitude of the frequency have to be made. For practical purposes used in engineering and acoustics a subjective scale relative to loudness is required. Fletcher and Munson (1933) had formulated a means of calculating loudness in relation to the intensity and loudness of stable sounds. These loudness to frequency relationships are depicted in figure 2.9 in what is known as the *Fletcher Munson curve*.

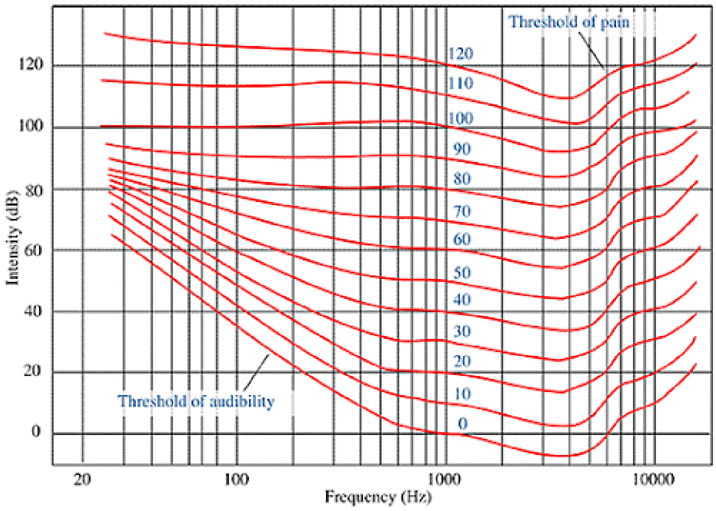

Figure 2.9: Fletcher Munson Curve of equal loudness contours between audible frequencies in the human hearing range. (Source: System One Audio, 2012)

As can be seen from the graph the amount of amplitude required for the midrange frequencies require less energy or amplitude in decibels (dB). At around 5000Hz more amplitude is needed to make the High range frequencies more audible. The equal loudness contour standard has been revised (Suzuki & Takeshima, 2004) numerous times by various scientists (Robinson & Dadson, 1956; Churcher & King, 1937; Zwicker & Feldtkeller, 1955; Suzuki et al. 1989; Takeshima et al. 2002).

Pitch

Pitch is purely a psychological construct related to actual frequency (Levitin, 2011b). Frequency reflects the number of times that a wave is vibrating within a medium and pitch is the sensation that is experienced from vibration of this wave (Moore, 2012d). A main characteristic of pitch is associated to spatial orientation in relation to distance, interval, a rise or inclination (Schneider, 2018b). The temporal and spatial attributes of pitch can be seen with the Doppler Effect. Movement within space is immediately detectable due to changes in pitch and timbre (Thoret et al. 2014). The pitch rises as an object moves towards the listener and decreases as it moves away from the listener (Gupta et al. 2012). Figure 2.10 shows how the perceived pitch of an ambulance siren changes as it moves closer or further from the listener.

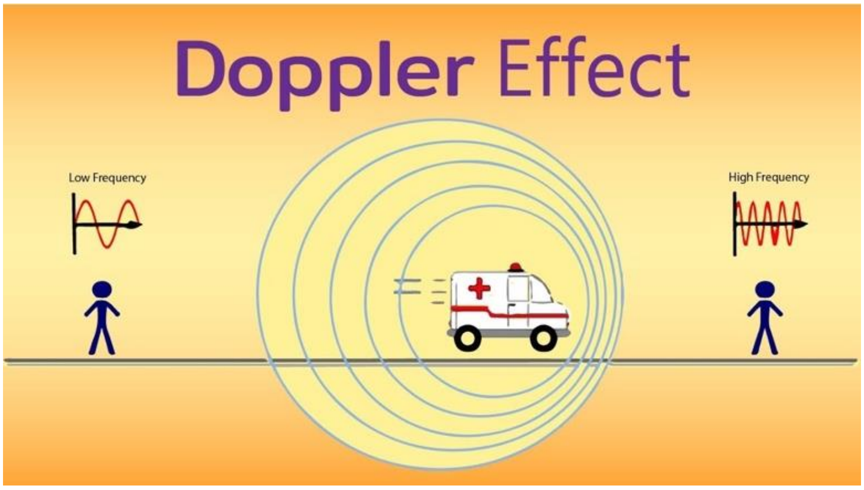

Figure 2.10: The Doppler Effect, perceived pitch changes as ambulance moves away and towards two listeners. (Source: Kannadascie, 2018)

Pitch is probably the most common parameter mapping in an auditory display (Neuhoff et al. 2002). It is easy to manipulate, any changes are immediately detected, and it is less influenced or masked by any environmental sounds (Walker and Kramer, 2004). Pitch perception is relative to a wide variety of tasks (McPherson & McDermott, 2017). In sonification Pitch has been representative of temporal-spatial characteristics such as localisation, size, orientation, velocity, motion and distinction (Dubus & Bresin, 2013b). The periodic nature of pitch is measured using two approaches. The *Spectral* approach utilises Fourier analysis to look for a spectral peak and use its position as a prompt for pitch. The Second approach, *Waveform*, analyses the stimulus waveform where its periodic properties are reflected in its consistent repetition (Cheveigné, 2004). These two approaches have to take into consideration whether the sound sources are *Pure tone* or *Complex tones*. A pure tone is simply defined as sinusoidal pressure variation over time and a complex tone is a sound consisting of multi-frequency components that arouse pitch sensation (Plack & Oxenham, 2005).

Timbre

Timbre can be defined as sound quality or characteristics such as dullness, shrillness, softness or brightness (Schneider, 2018c). Through these features it is possible to recognise differences in events or objects using sound alone (Handel, 1995) (refer to figure 2.11). Timbre is the attribute that allows for object representation and definition through sound and it is not merely a stimulus feature (Handel & Erickson, 2004). It is essential to language enabling the identification of phonemes or phoneme clusters which allow comprehension of what is being said (Houtsma, 1997). It also allows recognition of one person's voice from another (Bizley & Cohen, 2013). When pitch, loudness and duration of different sound sources are similar, timbre allows immediate distinction between them (Caclin et al. 2006). Timbre primarily correlates to the spectral profile of a sound (Meyer et al. 2006). It also relates to the temporal aspects of sound as a dynamic system changing over time (Balzano, 1986; Griffiths, 2001). It has been described by Toiviainen et al. (1998) as being a multidimensional property of sound and is associated with its time-varying spectrum.

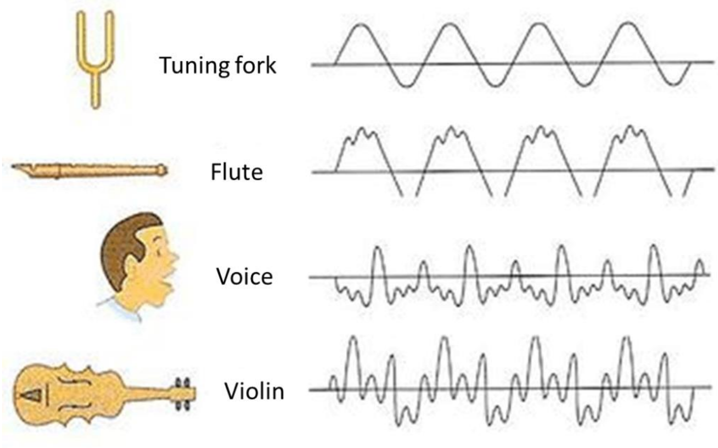

Figure 2.11: A depiction of timbre and how human perception can determine one object from another through sound. (Source: Musician Tuts, 2020)

Timbre is also an important component of sound localisation (Blauert, 1969). The human ear is an effective amplifier due to a combined effect of diffracted signals around the head, captured by the pinnae (outer ears) and resonated in the auditory canal where sound pressure is greater than outside the ear. Signals received in the auditory canal at various angles of incidence create differences in timbre (Weiner & Ross, 1946). The spectral cues responsible for timbre are shown to also influence the location of sound (Batteau, 1967; Blauert, 1997b; Butler & Belendiuk, 1977; Hebrank &Wright, 1974).

Spatial Perception

Orientation and localisation of sound sources assists human and animal survival. The direction of sound sources in space are measured in relation to the head as illustrated in figure 2.12.

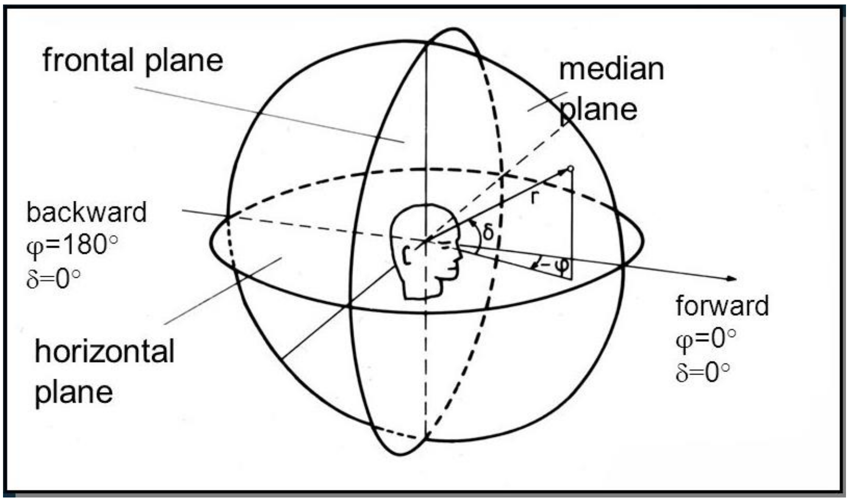

Figure 2.12: Sound localisation as a spherical perception sense (Source: Blauert, 1997c)

Sound is perceived from multi-directions allowing the listener to register sounds that are happening behind, above, below and out of sight. The diagram shows three planes of perception. The horizontal plane is in line with the upper part of the outer ear and the lower margins of the eye socket. The frontal plane is at right angles to the horizontal plane intersecting the upper parts of ear canal entry. The median plane is equidistant to both ears. These three points intersect at the centre of the head (Moore, 2012e). Interaural time and level differences give the primary cues in Horizontal localisation and monaural spectral changes, the Pinna provides vertical localisation, primary cues (Middlebrooks & Green, 1991; Carlile, 1996; Wightman & Kistler, 1997). Potential localisation cues are the physical aspects of waveforms reaching the listener and altered by changes in position of the source (Wightman & Kistler, 1997). All sound must traverse the head and the torso, and changes in amplitude and phases are measured in relation to the head and pinnae. These variable amplitudes and phases, when represented as a function of frequency, represent the transfer function. When these transfer functions happen as a result of being impeded by the head then they are known as a *Head Related Transfer Functions* (HRTF) (Yost & Dye, 1997). This means that the shape and size of the head, pinnae and torso of the listener effect the HRTF (Algazi & Duda, 2002).

Temporal Perception

Time is a crucial aspect of hearing since it gives humans the ability to perceive events and space. Audition is a much more suited sense in duration perception than vision (Ortega et al. 2014; Welch et al. 1986). The human auditory system is effective in its ability to perceive temporal resolution at such fine detail, 4.5 milliseconds to several thousand milliseconds, in an order of magnitude greater than any other sense (Griffiths et al. 2001). Auditory temporal perception gives an indication of spatiality, localisation and identification of the object or event being perceived (Lewis et al. 2004; McBeath & Neuhoff, 2002; Nelken et al. 1999; Theunissen & Elie, 2014; DeCharms et al. 1998). Sound and loudness perception are only possible through a temporal dimension since both attributes unfold over time (Ferguson et al. 2011). This suggests that auditory temporal perception effects all the other characteristics of hearing as the sound unravels through time and varies them according to the energy of intensity, its dissipation and the sound's contact with other mediums and surfaces. Figure 2.13 shows how sound propagates through time and space and changes accordingly in relation to a tuning fork.

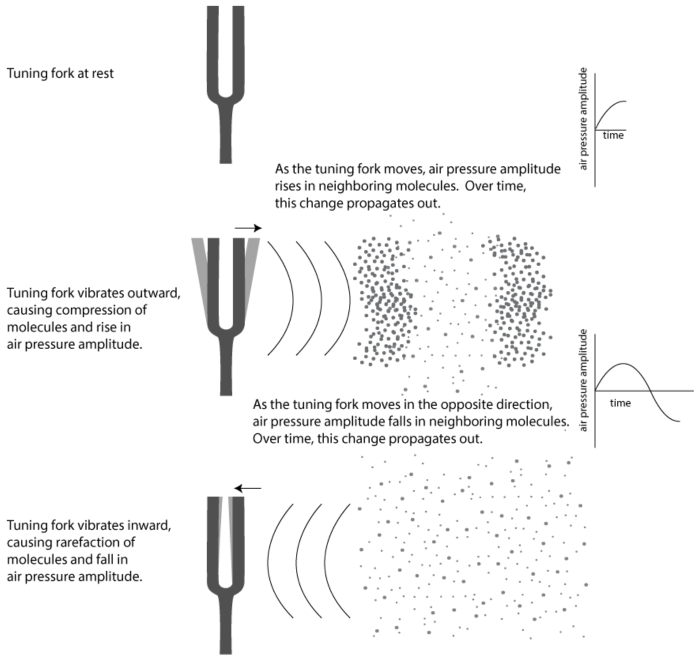

Figure 2.13: Shows sound propagation over time through space & the changing psychoacoustic properties of pitch, timbre & amplitude as energy dissipates, thus changing the qualities of the sound. (Source: Digital Sound & Music, 2014)

Moore (2012f) makes a distinction between *temporal resolution* (acuity) which is the ability to perceive alterations in stimuli over time, and *temporal integration* (summation) where the auditory system adds up information over time which enhances stimuli detection and discernment. In order for information to be added to stimuli then forms of recognition and memory are needed as reference points. Pattern recognition in Auditory temporal perception assists survival and the acquisition of speech (Warren, 1988). Auditory patterns are the temporal succession of sounds.

This recognition of time happens in three ways: *Presentation rate* which is a function that recognises that timing of a sequence. *Relative timing* is the analysis of the distribution of different durations. *Rhythm* looks at the total time that it takes for a sequence of events to unfold (Jones, 1978). The duration of individual components in a sequence are thought to affect the ability to properly perceive a pattern. Two tones of a duration shorter than 15ms are more difficult to distinguish the individual components thus effecting the overall pattern recognition (Hirsh, 1959). Pattern recognition does not rely solely on the processing of temporal complexities of a sound, but spectral analysis is also required (Espinoza-Varas & Watson 1989). This means that Auditory temporal processing also involves auditory filtering processes such as hair-cell based compression and adaptation and binaural cross-correlation which form part of the mechanism that processes patterning and behavioural data (Hartung & Trahiotis, 2001).

The descriptions concerning the various factors of human auditory perception indicate that these psychoacoustic attributes of auditory sensation do not work in isolation but overlap and influence each other (Moore, 2012c). A good understanding of how sound is created and shaped in the world is needed in order to know how to use these properties (Bregman, 1994). The sound designer must be quite proficient when developing a sound design for a specific output and must obtain an understanding of the way that sonic representations are interpreted by a user (Pirhonen & Palomaki, 2008).

Sound and Meaning

The complex mechanics behind the human auditory system are one aspect, but sound also conveys meaning which varies according to context. Acquiring an understanding of the semantic dimensions of sound is probably more abstract due to the multitude of dimensions of meaning unfolding in a human listeners brain (Hermann & Ritter, 2004). This may suggest that the meaningfulness and social significance of an object needs to be studied in depth in order for an effective sound design to be created (Hug, 2008). Listening is a more personal experience, it is the process of giving active attention to extract information and meaning from the sonic environment (Tuuri & Eerola, 2012). Deep listening occurs at an expanded level. It attempts to grasp the interconnectivity of the environment and the intelligence, ideas, feeling and memories that sound carries with it (Oliveros, 2005). Cesaro (2014) similarly explains listening as an act that goes beyond the perception of the ears and should be felt by the whole body. This level of engagement of listening looks for meaning, understanding associations brought about by sound and even looks beyond the immediate associations in actually listening to the characteristics of the sound. A deeper level of listening allows the perceiver to grasp the omni-directionality, the relationship to time and how different sounds move within the temporal-spatial environment and not just spatialization, identification and localisation but also the meaning of the sounds (Liljedahl & Fagerlönn, 2010).

Chion (2012) devised three modes of listening in 1994 and was influenced by Schaeffer's four modes of musical listening: *Comprendre* listening to the communicative meaning of a sound, *Écouter* a process of information gathering using sounds as an index of real-world events or objects, *Etendre* to select particulars of interest to listen or attend to and *Ouïr* is a passive mode of listening that acts as a global scan of whatever is happening (Kane, 2007). Chion's (2012) first mode is called *Casual listening* which is the most common form. The intention of this mode is to gather information about the cause or source which could either be visible or invisible. In the case of the latter, the origin is identified by knowledge or prognosis. *Semantic listening* This mode of listening extracts meaning from symbols or lingual communications. *Reduced listening* focuses on the characteristics of the sound itself regardless of cause or meaning. This form of listening is focused on the physical properties of the sound object free from precognitive interpretations or meaning.

Tuuri et al. (2007) had added five more modes of listening to Chion's (2012) three modes. *Reflexive listening* is a reflex reaction to a sound that immediately captures one's attention. *Connotative listening* is concerned with the immediate associations gathered pre-consciously, made in relation to similar past experiences before any function of reason is prompted. *Empathetic listening* focuses on the emotional cues present in a sound. *Functional listening* analyses the purpose of a sound in relation to a specific function. *Critical listening* is analytical and is used for judging of aesthetics and interpretation.

Vickers (2013a) had fashioned four modes of listening that were an extension to Schaeffer's four modes of musical listening and modelled to suit sonification. These modes from Vickers (ibid) are based on *Subjective*, *Objective*, *Concrete* and *Abstract* sounds. *Direct Concrete Objective* listening (DCO) which complements Schaeffer's *Écouter*, is where the sound works as a key of a visible or present cause. In sonification, it would apply to Model-based and interactive parameter mapping sonification. *Direct*

Concrete Subjective (DCS), complimenting *Ouïr*, is a passive mode of listening related to a visible cause where in an audio-visual display the auditory component is pushed to the background and acts as a complimentary factor. *Direct Abstract Subjective* (DAS), complimenting *Etendre*, is the resultant emanated sound caused by user interaction that becomes a unit of interest to the user. *Direct Abstract Objective* (DAO), which complements Schaeffer's *Comprendre*, is the most common direct mode of listening where the cause of the sound is visible or present. This mode would be used in model-based interactive auditory displays as it allows immediate confirmation of interpretation of the sound.

Sound has strong associative ties that act as common archetypes that give meaning to people (Chion, 1994). These archetypes convey mental images to the listener (Minghim & Forrest, 1995). These aspects of sound, when integrated into a design are powerful tools. An effective sonification design easily conveys information perceptually, physiologically, cognitively and by memory (Worrall 2019a). The power of the mental image evoked by a sound should not be overlooked and should also be taken into consideration with regards to sonification aesthetics. Users have often criticised sonification designs since they could not associate the data with the sound. That is why the task function of the sonification has to be a determining component of the sonification aesthetics (Leplaitre & McGregor, 2004).

Listening attitudes in sonification design

Ferguson and Brewster (2018) have found that many sonifications are made without considering the users mental model in relation to sound. The study of the *mental model* is a means to understanding the domain knowledge that a person has in relation to a certain context (Gentner, 2001). This means that the sound itself could be a symbolic representation of an event rather than being an exact representation of that sound in nature. In more established platforms of sound design like film sound, a principle known as *idea-associative comparison montage* is where sounds can be chosen that work in harmony with the event on screen. These sounds could be apparently disassociated, yet conceptually related events that strengthen a concept (Zettl, 2013). Trying to represent abstract concepts is not always easy. Human beings are adept in recognising realistic sounds but struggle to understand unrealistic ones. This factor was experienced by Lopez and Pauletto (2010) who had created the concept of a new form of film called an *Audio film* which is a story that is narrated through sound, not by visual elements and not even through narration. The narrator is the sound design itself. When the concept was tested it was found that the narration worked with realistic sound, but the unrealistic sounds compromised the narrative.

Sound has strong associative and emotional ties. Various theories suggest that when emotions are processed, they also cause reaction in the body of the listener which is thought to affect how the emotional information is processed (Niedenthal, 2007). Emotional interpretation of sound does not depend solely on the physical attributes of sound but also on listeners identification to it (Tajadura-Jimenez, 2008). When users cannot identify with a sound design or find it unpleasant then they are likely to actually switch off the interface (Sorkin, 1988). This suggests that sound designers have to take these factors into consideration and to apply this when investigating user's perceptions and attitudes towards the data. The listener's associations towards the data could be the direct way to understand how to sonically furnish a sonification design in line with the user's affiliation to it. Vickers (2013b) has been a strong contender of implementing the use of familiar sounds that would strengthen associative concepts related to the data.

Familiar sounds already mean something to the listener who even has an unconscious idea of the spectral characteristics of these sounds. This makes familiarity one of the keys to identifiability (Cycowicz and Friedman, 1998). Environmental sounds are familiar and are consciously identifiable and conspicuous to the point that no visual reference is needed (Kirmse et al. 2009). Obviously, the strength of association comes from the listener having previously experienced and learned the associations related to these sounds (Schirmer et al. 2011). The ability to cognise environmental sounds is considered to be a primordial ability that humans had acquired before the evolution of language (Gygi, 2001) making it a highly evolved constituent of the human cognitive system. Ballas and Howard (1987) suggest that the perception of environmental sounds is comparable to speech making it akin to a form of language which could suggest that environmental sounds could possibly communicate data more clearly to the user. Various studies have suggested that environmental sounds are processed by a similar cognitive process as that used for spoken language (Dick et al. 2016; Leech & Saygin, 2011) where both require bottom-up and top-down processing (Hendrickson et al. 2015).

Worrall (2019b) suggests that there are similarities in the way that users listen to a sonification and listen to linguistic speech. This supports the claim that the use of environmental sounds or the mimicking of these sounds would be a strong means of communicating data to the user of a sonification. Environmental sounds are also fluid and ever-changing creating an aesthetic advantage where users do not feel irritation or alienation that can be caused by not so natural sounding sound designs.

Fencott and Bryan-Kinns (2009) refer to the theoretical framework known as *Spectomorphology* that was suggested by Denis Smalley (1997). This refers to the way that the spectral qualities of sound change over time. Smalley suggests that listeners are naturally inclined to associate sounds with related causes and calls this *Source-bonding*. The idea of bonding between the sound and the source is likely to create immediate associations and the spectral changes are unconsciously known factors that the listener is used to deciphering without giving much thought to it. In sonification design various practitioners have used natural and familiar sounding qualities in their sonification design reaping positive results (Blanco et al. 2020; Wolf & Fiebrink, 2019; Mauney & Walker, 2004; Vickers et al. 2014; Nees & Walker, 2009).

The strong associative factors related to environmental sound have the advantage of being perceived and recognised even when there is limited spectral information available (Gygi, Kidd & Watson, 2003). Spectral interpretation could also draw advantage from spatial separation allowing frequencies to have their own space for propagation and eliminating further possibilities of masking. In the natural environment sounds are constantly modulating and part of that modulation is attributed to localization and spatial representation.

Emotional reactions to sound are also influenced by spatial representation and movement which give us signals about how to react to a given situation (Hagman, 2010). When talking about the psychoacoustic properties of sound there is an intricate connection between the temporal and spatial properties which are usually treated as adhesive components. Considering that sonification is a strong representative of time then this does suggest that the spatial element must be considered as a complimentary factor as an information provider. The spatial dimension also adds more credibility and dimensionality to environmental sounds. It has been found that sonifications do tend to be less effective when a complex dataset is represented through a linear audio signal (Rosli et al. 2015).

Spatiality provides required depth to an otherwise flat, sonic representation (McLeran et al. 2008). Space could also be represented on a vertical axis through using the audio illusion known as the *Spatial-Musical Association of Response Codes* (SMARC) effect which creates the illusion of ascending when pitch and timbre are increased on the vertical axis of hearing in non-musicians (Pitteri et al.2015). This adds yet another dimension and measurement to sounds that are supposed to be representing vertical inclined datasets which is a likelihood in astronomy. Sound propagates and interacts with an environment and in doing so provides directionality and exact source location (Nasir and Roberts, 2007). Sound instinctively evokes reactions from listeners to seek the locality of the source Chowning (1971).

In the case of complex datasets spatial mapping would be especially effective at unmasking sound sources. Song et al. (2007) had identified the potential of using spatial separation of two audio streams which was a functional method allowing clear distinction between the two signals. Spatial separation allows for similar spectro-temporal characteristics between two signals to remain distinct and unobstructed (Best et al. 2005; Ebata, 2003). Timbre is another psychoacoustic element that works cohesively with spatial separation thus facilitating discernment of sonified attributes and enhancing distinction between multiple signals (Song & Beilharz, 2007). Spatial dimensionality gains more attention through movement of the signal and related changes in timbral qualities which further enhance perceptual recognition (Kronland-Martinet & Voinier, 2008). Spatialization of sound sources and movement of signals would be applicable to surround sound environments that add more context to sound object definition and give a clearer representational platform to mimic movements of object through space thus giving the listener more auditory data (Childs and Pulkki, 2003). This use of extra spatial dimensions of sound representation could also help to enhance the temporal representation of objects moving through space. Pitch representation in a broader spatial field could enhance recognition of sonic properties and spatial understanding since the human cognitive system maps pitch onto a mental representation of space (Rusconi et al. 2004).

These factors that contribute to enhancing the listening experience of a user of a sonification interface are possibilities that could be implemented in a design that represents astronomical data. By using familiar attributes and by mimicking their behaviour in a spatial medium then this could possibly give further access to an astronomer's dataset and enhance and add meaning to their analysis.

2.3 Sonification

Sonification can be defined as the application of non-verbal sound to represent scientific or other forms of data (Barrass & Kramer, 1999; Hermann, 2008a). It is a subset of Auditory Displays, which is broadly defined by Walker & Nees (2011) as any display that uses sound to convey information. There have been a number of successful sonifications such as the simple apparatus known as the *Geiger counter* which used short audible pulses that could indicate increases in radiation levels by simply becoming more frequent and raising in pitch. This straightforward device served its purpose in relaying radiation levels without the need for any visual aids (Cook, 2011). Sound triggers or alarms can invoke immediate attention from a listener to pay attention to their surrounding environment and relay information regarding the nature of the issue. A simple example is a proximity car alarm which is used for parking. The sound becomes more intense in frequency and pitch when a car is too close to another object thus warning the driver to stop reversing (New Electronics, 2010). In medical technology, health monitoring equipment aids nurses or doctors to immediately recognise the slightest changes in a patient's condition just by hearing variances in the frequency of bleeps from various machines (NHS, 2019). A cardiac monitoring machine would be one example, where any changes in heart rate can immediately by heard by an increase or decrease in the speed of the pulses that represent heartrate.

Throughout recorded history sound has been used to represent the physical world (Dubus & Bresin, 2011). A typical example of relaying information by using sound would be the simple measurement of time from church bells. The bell would mark out the hours of the day, seasons, the special days attributed to various festivals and celebrations. It warned of any danger approaching the town and gave off the alarm signal for people to seek refuge. The changes in the bell's melodies would signify what kind of activity would be taking place at the church. People were so used to these patterns that they could tell what event was happening just from the particular bell toll (Schafer, 1994a).

Sound is a temporal-spatial phenomenon (Neuhoff, 2011). It conveys power and energy that deliver information (Hartmann, 2004) regarding coordinates that allow humans to navigate safely through space and time. Through hearing, the listener is immediately notified to potentially perceive the slightest crack of a twig, rustle of leaves, grass or any sudden change in the pattern of the cognised environment (Prochnik, 2010). The human hearing mechanism monitors the surrounding environment faster than any other sense. Humans and animals can detect and respond to a myriad of complex sounds in less than a millionth of a second over hours of listening. Sound is processed by the brain at a much faster rate than light, which travels faster than sound, but processed is at a much slower rate. Vision is capable of processing 15 to 25 events per second whereas hearing can detect vibrations oscillating 20 to 20,000 times per second. At a perceptual level changes in auditory cues can be heard 200 times per second or more (Horowitz, 2012b). The response to a vibration goes through the auditory faculties in the ear and is then distributed to about 10 different synapses to reach the cortex, the centre for conscious behaviour. Yet the ability to recognise what the sound is and where it is coming from only takes 50 milliseconds or less (ibid).

Fast sound events and sound object recognition is advantageous and is a benefit that sonification could present to speed up data analysis processing in astronomy. This quality could potentially allow for immediate pattern recognition which is one of the many assets that sonification propounds (Barrass & Kramer, 1999). There are various techniques of how to sonify data. In the context of this study the narrative will concentrate on the two most commonly used sonification techniques in astronomy which are *Audification* and *Parameter Mapping Sonification*.

Audification

Audification is the simplest form of sonification. It is described by Kramer (1994), cited by Dombois & Eckel (2011) as the direct translation of data waveform into sound. The waveform itself might not even belong to the sound domain. Any alteration in pitch to a sound recording can be defined as audification. This technique is probably one of the most common forms of sonification found in astronomy. Since most astronomical data is in some form of electromagnetic wave, the direct pitch translation of these waves is a faster and a more direct approach. Audification can be done by astronomers without going into the complexities of mapping data to various hearing parameters or actually designing the sound in any kind of way. Audification can be achieved by either slowing down electromagnetic waves that are faster in frequency than the human hearing range of 20Hz to 20kHz (Levitin, 2011a) and this is done by pitching the wave down. To speed up waves that are slower than 20 Hz the process is to pitch the wave upwards. Audification has been classified by Dombois & Eckel (2011) into four different groups of data: (1) Sound Recording Data (2) General Acoustical Data (3) Physical Data (4) Abstract Data. Table 2.4 sums up these four aspects of audification.

Table 2.4: Audification Types

Audification Type	Definition	Example
Sound Recording Data	Sound recording considered to be an audification if recording is amplified and reveals aspects that were unheard before. When a recording is time-stretched or time-compressed it is possible to hear frequencies that are beyond the human hearing range of 20 Hz to 20 kHz (Levitin, 2011).	Any sound recording can be considered to be a data series in today's realm of digital recording.
General Acoustic Data	The progation of mechanical waves are waves through a medium. The speed of the wave is determined by the elasticity or inertia of that medium.	Stephoscope, Sonar, Sounding-boards
Physical Data	Waves that exist outside the domain of mechanical waves that can also be audified	Electromagnetic Waves
Abstract Data	Data that does not originate from a physical system or in the form of a wave	Stock Exchange

Note: These classifications come from Dombois & Eckel (2011)

There are various examples where audification has been used. One classic example was when audification was used for seismological research to determine underground nuclear explosions from natural earthquakes. The researcher Speeth (1961) had transposed the seismic signals, which are usually within the range between 0.3 Millihertz to 20 Hertz, into the audible range using a digital signal processor (DSP) converting a sampling rate of 10 samples per second to 1000, 2000, 4000 and 8000 samples per second using an IBM 7090 computer (Volmar, 2013).

Audification is being tested as a means of localising point-source sounds similar to echolocation used by bats but being developed for blind and people with impaired vision. Transmitted, ultrasonic signals between 26 – 40kHz are pitched down to the audible range using digital conversion (Davies et al. 2012).

In medical application audification has been used to facilitate EEG data to identify seizures and seizure lateralisation in which signals were converted from a range of 1 to 10 Hz to 60 – 6000 Hz (Khamis et al. 2012). Temko et al. (2014) had also used audification to identify seizures in neonatal children by pitching up 0.5 – 13 Hz to 0.5 to 13 kHz allowing 1 hour of EEG playback to be reduced to 6 minutes of listening time. Temko et al. (2020) have gone on to patent a real time audification platform for neonatal EEG signals to detect seizures built upon the previous research done in this field.

Plants emit transpiratory or hydraulic sounds that are water and air circulation activities which lie within the ultrasonic range in particular plant species. Audification was used to down-pitch these ultrasonic frequencies into the human hearing range allowing researchers to hear the trees transpiratory activity (Maeder & Zweifel, 2016).

Parameter Mapping Sonification

Parameter mapping is another form of sonification technique that is often used in astronomy. It describes when data values are ascribed to various acoustic attributes (Pitch, Amplitude, Timbre, Rhythm and Spatial Dimensions). Considering the multidimensional characteristics of sound, parameter mapping sonification could be particularly well suited for representing multivariate datasets. Mapping decisions should be determined by the data source and available synthesis parameters. Appropriate understanding of the data and its preparation influences the sonification's success, especially with a multivariate dataset. Dimension reduction techniques generally have to be implemented, or complementary derivatives can be added. Data Dimension Reduction is influenced by two factors. The dimensions of synthesis parameters should be utilised as fully and efficiently as possible. Noise or distortion resulting from the parameter mapping needs to be eliminated to ensure accurate perception. The mapping procedure poses two challenges. The first, to warrant that a proper formalization connecting factual data to the elusive nature of human perception has been achieved. The second, is to guarantee that there is good mapping accurately representing the data through appropriate synthesis (Grond & Berger, 2011).

Parameter mapping sonification has been studied in particular detail when used as a method to train elite rowers where pitch was mapped to the speed of rowing. The rowers could immediately hear if they were starting to slow down by hearing the pitch going lower or speeding up if the pitch went higher than a nominal range of pitch. This way the rowers could adjust their stroke to get back to the nominal level (Schaffer et al. 2009; Schaffer et al. 2010; Schaffer et al. 2011; Schaffer et al. 2013; Schaffert et al. 2015; Schaffer & Mattes, 2016; Schaffer et al. 2017;).

Sonification has also been applied to maps and spatial data exploration. In a study conducted by Schito and Fabrikant (2018) they used three methods of parameter mapping. In method A, the origin point of coordination was set to the lower left corner of the auditory display rendering the X Axis to the left ear and Y axis to the Right ear. When moving away from the point of origin pitch rises on each ear by an octave indicating the maximum distance from the start point. Elevation was represented by duration of the sound which would be shorter on higher elevations and ranging from silence to 200ms in duration. In Method B pitch was mapped to duration and location was mapped to panning on the xy-plane. Pan was also added to the y axis using two distinct waveforms where participants could determine their orientation by comparing any sonic changes when moving away from the origin point. Method C was similar to Method B but could also allow the participants to choose an acoustically rendered elevation point between two points of choice within the field. Pitch was effective at representing continuous spatial elevation data. It was also found that with a more immersive soundscape participants were able to interpret sonified terrain more effectively.

Walker and Cothran (2003) had created the Sonification Sandbox which was a multipurpose sonification platform. The software allowed users to map datasets from various fields of study to timbre, pitch, volume and pan allowing them to create auditory graphs.

Barrass and Zehner (2000) had used sonification for oil and gas exploration and was used to interpret multi-attributed data from well logs. The sonification consisted of using samples of three different musical instrument sounds with varying timbre characteristics to allow the user to hear differences between rock and gas. The cello represented an aspect of the dataset known as gamma data which measures natural radioactivity, the trombone which represented neutron data which represents porosity of the rock, and the bassoon which represented density which is measured by bombarding gamma radiation and recording the gamma returned by the electron density in the atom.

Granular changes in timbre were used as the main mappings of each dataset. The sonification worked as a kind of Geiger counter that increased and decreased in intensity according to the readings of the data. After testing successfully, the oil company asked for the sonification tool to be developed further but no publications related to this development were found.

In research conducted by Metatla et al. (2016) reference markers were auditory graphs and were sonified to enhance non-visual point estimation tasks. Three methods of parameter mapping sonification were used which were pitch-based: Pitch-only, one-reference and multiple references were designed to provide information regarding distances from an origin point. The pitch-only mapping consisted of sonifying a point that was assigned to a sine tone to the points Y coordinate on the positive scale. The tone of the pitch changes with the movement of the point on the Y axis with a rising in pitch when moved up and a decrease in pitch when moved down. This was set at a scale using exponential function at a range between 120Hz (-15 on the graph) to 5,000Hz (+15 on the graph). The one-reference mapping consisted of the same pitch mapping and included a tone to convey the reference point of origin. The reference point represented the midpoint on the scale at 774Hz (At 0 position) and lasted 100ms in length. This way the listener could hear the differences in movement in the pitch-only and compare it to the origin point of the one-reference. The multiple-references mapping used the same pitch-only mapping with the difference of hearing multiple successive reference tones with varying pitches that represent all the points between the current and origin point. These tones lasted 50ms and consisted of a delay of 50ms. To estimate the position of the point in relation to the reference the listener can judge the pitch difference at that point compared to the subsequent points and the length of the tones of the sum of successive tones that distinguish it from the origin. A longer distance results in a longer succession of tones. The points below the origin point ascend in pitch while the one above the reference tone descend in pitch. The sonification was tested and showed that the added reference tones increase the user’s accuracy, and that multiple-references mapping are effective at conveying the points that are positioned midway on a given axis.

In the realm of medical research sonification was applied to Electrocardiography (ECG) data by Kather et al. (2017). A system of polyphonic sonification simultaneously represented 12 different ECG channels each assigned to a different note of the musical scale of D minor, for aesthetic reasons, over two octaves. Each channel was mapped to volume and half a semi tone or 3% in frequency variation was assigned to voltage changes. Higher voltage was louder and higher in pitch and lower voltage would have a lower volume and pitch. The sonification was tested and the users were able to classify differences in the ECG datasets accurately. Sonification has also been considered as a tool to aid blind and visually impaired people.

Presti et al. (2019) had created a sonification device called *WatchOut* which could monitor obstacle distance, width and height in horizontal position to the user. The sound design consisted of a sine wave that would decay within one second, coupled with percussive filtered impulse sound. The sine wave was chosen since it is not found in nature and would be easier for the user to distinguish it from surrounding environment sounds. The sensors used the same system as parking sensors which are intermittent with nearby objects having a higher repetition of pulses in contrast to a faraway object where pulses are less frequent. Panning was used to convey obstacles to the left and right. Pitch was used to convey the size of objects with larger objects being lower in pitch than smaller objects that were higher. Panning was effective at conveying obstacle distances and positions, but pitch was less effective at projecting the dimensions of objects.

Sonification was used to map calcium imaging of neurons in the brains of Zebrafish larvae by Verrier et al. (2020) for the purposes of enabling more effective representation of temporal and spatial and synchronous activity between different neurons. Regions of interest of neurons were mapped to FM synthesisers. Four parameter mappings were used. Amplitude represented the fluorescence value. Activity in neurons creates a rise in calcium levels and when the calcium binds with a GCaMP protein it increases its level of fluorescence or light emission. More loudness would mean increased fluorescence. The inverse harmonicity ratio was mapped to the rate of change of the fluorescence. Modulation Index was mapped to Region of interest Group Parameters to provide feedback to the users regarding the categories that they have made. Panning was used to map the location of the particular Region of Interest. These mappings helped to enhance and clarify the neuron activity that was not being clearly represented using visualisation.

2.4 Uses for sonification in astronomy

Lunn & Hunt (2011) state that essentially there is much more astronomical data than there are astronomers to process it. The use of sonification in astronomy is not novel but it has not been as widely used. This is possibly due to the lack of theoretical foundation in the creation of many sonifications (Diaz-merced, 2013). Candey, Kessel, & Plue (1998) claimed that sonification will add to astronomer's research capabilities. It could be useful in the context of complex multi-dimensional and multiple data set research concerned with Earth and space sciences. It might potentially complement visual displays and help identify new phenomena not noticed when using visual and numerical data analysis techniques. Barrass (2012) argues that though there are scientists inclined towards more traditional methods of research, there are many that are using new techniques such as sonification. There are a few examples where Audification and Parameter Mapping Sonifications have been created purposely for the analysis of astronomical data.

Audification of astronomical data

The most numerous and eminent examples of audification in astronomy are found in the work of Donald Gurnett. His work was mainly based on the measurement of *Plasma waves* and he worked on more than 25 projects on NASA spacecraft including the two voyager missions (Gurnett, 2020). In order to study the nature of plasma waves he used Audification as a means of understanding them better. Space craft are equipped with scientific instruments that detect and record radio waves which are then Audified (University of Iowa, n.d.). An extensive list of the audifications made by Gurnett compiles recordings of the Earth's Radiation activity, the atmosphere of Jupiter, various recordings made by the Voyager 1 & 2 spacecraft, Cassini recordings of Saturn, Sun rings, Magneto Spheres and heliospheric activity (University of Iowa, 2020). One example of Gurnett's work is an audification of Jupiter's auroras. As the spacecraft Juno flew by Jupiter on August 27th of 2016 the ship's waves instrument received radio signals associated with the planets auroras which are known as *Jovian Kilometric Emissions*. These wavelengths are up to a kilometre in length and range from 7 to 100kHz. They have been pitch-shifted down into the audible frequency range and compressed in time to fit 13 hours of observation into roughly 25 seconds (Space Audio, 2016). No further details were provided as to how the audification was processed. The audifications were used to obtain a better understanding of auroras that occur in Jupiter's magnetosphere and how they differ to the ones that happen in the

Earth's magnetosphere. The study of auroras shows the relationship between the sun and the planets that have magnetospheres and how corona mass ejections cause changes in the atomic and chemical composition of a planet's atmosphere (Aurora Service, 2021).

One of the most recent and notable examples of audification in astronomy is the LIGO gravitational wave detection. The collision of two black holes that took place over a span of billions of years created a gravitational wave that was detected on Earth. A sophisticated device of an L-shaped configuration consisted of laser light reflected off mirrors that were slightly displaced. The measurement of this displacement, four one-thousandths of the diameter of a proton (Overbye, 2016) created a phase that was translated into a sine wave of sound that slid in two tenths of a second up from 35 to 150 Hz. This rising intonation created a chirp-like glissando that represented the gravitational wave created from this collision (Helmreich, 2016). Probably the most relevant aspect of this study in relation to sonification was the comment made by Professor Brian Greene, renowned Astrophysicist who stated that sonification is: *"the future of studying the Cosmos"* and that it was the only way of discerning certain aspects of the universe (The Week, 2016).

Asteroseismology utilises audification in order to hear the sound frequencies that are produced by stars. Sound waves cause the star to swell and contract and also affect the temperature of the star in terms of it becoming hotter or colder (Aerts et al. 2010). These stellar sounds are resonances that are created from turbulence in the outer layer of the star. These frequencies oscillate at speeds that are too slow to be perceived by the human ear, so they are sped up to the audible frequency range (Tootell, 2011).

Lunn & Hunt (2013) used the technique of audification to sonify astronomical data collected by SETI (Search for Extraterrestrial Intelligence). The data consisted of white noise sources extracted from the setiQuest radio observations of the moon. The sample data was converted to audio wav files of 30 seconds in duration at 44.1kHz, 16-bit resolution. There were also a set of pseudo signals that had been selected by SETI of signals that could be transmissions from intelligent life from other planets. These were in the form of spectrograms that were converted by using a C++ program that would synthesise the tones, and a series of pulses and squiggle waveforms were generated using vOICe, a Java application used to convert images to sound. These audifications were made to test whether users could distinguish between phantom and authentic signals with white noise type data, and it was found that listeners heard illusory tones along with genuine signals.

Archer et al. (2018) used audification to study Ultra Low Frequency (ULF) magnetohydrodynamic waves which transfer energy from outside the Earth's magnetic shield to regions inside it and thus influence space weather. These frequencies are too low to be heard, as the name suggests, and have to be sped up in order to be audible. The data comes from the Geostationary Environment Operational Satellite (GOES). Each year of data at 512-ms resolution was sonified, reducing the time frame for analysis. These audifications were then analysed by various citizen scientists from a London high school who were able to determine an event of narrow-band waves of decreasing frequency spanning over several days.

Jodrell Bank (2014) have been using audification to convert various pulsars into sound. The rotation periods for these pulsars vary within a range of 1.30 to 173.7 Hz. The slower frequencies have to be sped up so that they may be heard. There is a list of Pulsar sonifications where the signal pulsating from these rotating stars was converted into sound using Audification (ibid). The audifications have also been filtered in order to eliminate the white noise also captured along with the radio wave emissions.

Tutchton et al. (2012) had used audification to sonify light emissions from various stars and to understand differences in orbital periods between two stars in a cataclysmic variable system. This is a system where two stars orbit around each other and that can be measured from the resulting light fluctuations. The light curve data of these orbital periods had to be sped up to be made audible and were translated to sample rates of 11,025Hz and 22, 050Hz. The findings suggested that similarities exist in the fluctuations of light emissions of two-star systems which were heard as similar amplitude and pitch changes.

Winton et al. (2012) had sonified Kepler telescope data related to exoplanet hunting. The data related the fluctuations in brightness of stars. A dim in this brightness could possibly indicate that a planet has passed in front of that star. These dips in light magnitude were audified and the sound was filtered to remove noise from the original signal. Bandpass filters were applied to remove frequencies outside the range of 150 –

800 Hz in order to give a tone which would sound more celestial and heavenly since planetary bodies were being represented in the dataset. Finally, a 3-CurveFitting filter from Matlab was added to make the tone more pure and containing less noise. This was the only audification that was found in this study that was related to Exoplanetary data.

Robert Alexander was involved in various works related to the sonification of solar wind (Alexander et al. 2011; Landi et al. 2012; Alexander et al. 2014; Alexander, 2015; Wicks et al. 2016). Alexander's work had led to a new discovery described in Chapter 3 when he had realised that it was more efficient to you use Carbon in the analysis of solar data (Worrall, 2016). Alexander had also worked with other astronomers like Jian who then went on to use audification in her astronomical work related to solar winds (Jian et al., 2015).

Parameter Mapping Sonification in Astronomy

Parameter mapping sonification is another widely used technique in astronomy. Unlike audification, parameter mapping does not directly convert any given wave into sound. A number of acoustic attributes such as amplitude, pitch, timbre, rhythm, tempo and spatial dimension can be mapped to various data parameters.

Diaz Merced has been able to practice as an astrophysicist through the use of sonification. She had lost her sight and has been motivated to improve the use of sonification in astronomy so that visually impaired and sighted practitioners can benefit from this way of analysing data. Over the years Diaz Merced and other colleagues have been developing a sonification interface, dubbed *xSonify*, that allows astronomers to input various datasets that are immediately sonified into musical sounds (MIDI) of their choice. This tool has been in development over the years (Candey, Schertenleib, & Diaz-Merced, 2006; Diaz-Merced et al. 2011; Diaz-merced, 2013; Garcia et al. 2019). Data that is sonified using xSonify are mapped to the parameters of amplitude, pitch, rhythm and tempo. The interface has been used to sonify X-ray and solar data that are two-dimensional, time-series sets.

The Bell3D system, a sonification tool developed for visually impaired astronomy students, can convert star data into audio signals. Astronomical particulars from the SIMBAD (Set of Identifications, Measurements and Bibliography for Astronomical Data) database (Wenger et al., 2000) such as magnitude, size, location and distance from the Earth have been sonified using this system. These features of the data are mapped to volume, pitch and the star's equatorial coordinates are mapped and spatialised to be perceived in three-dimensions that is projected from different directions around the listener's head. This allows the user to understand the position of the star from a geocentric perspective (Ferguson, 2016).

West et al. (2018) created an interactive virtual reality performance that used sonification to enhance aspects of the astronomical database that was used for the performance. Granular synthesis was used to sonify time-series photometry (light curves) from the AST3 (Antarctic Survey Telescope 3) multi-band wide field survey camera. Data from astronomical objects from within the Large Magellanic Cloud, within a game-engine based virtual environment, were mapped to various ambisonic spatialized coordinates on a 7 - channel speaker array, so that the listener would be able to sense the position of the stars. The software retains the possibility of binaurally outputting the signals across a stereofield. Timbre descriptors for sound grains were achieved through the analysis of audio files. These analyses were then mapped to the star field data with similar audio descriptors for granulation.

Alexander et al. (2010) had used parameter mapping in his early investigations of representing heliospheric data. A total of eight different components related to solar wind were sonified. There were different mappings for different chemicals. Helium density and speed were mapped using loudness for density with louder amplitude settings for higher density and cut off filter changes on a band pass filter for Helium speed. Solar wind was amplified by adding distortion whenever the wind was more intense. The different charge states of carbon used 6 different pitches of female voices. The 6+ carbon was higher in pitch and the 4+ and 5+ ones lower in pitch. Panning was used for further distinction between these charge states. The higher voices corresponding to charge state 6+ was panned to the left. The lower set of voices were panned right. As these charge states increased in intensity, they became louder. The scientific team involved in this project could easily follow how the sonification worked in conjunction with the data, but it didn't present any new insights. This led Alexander to use audification in later projects related to the sonification of solar winds, where more successful results. When Alexander began to listen to the audified versions of carbon 6 to 4 he realised that they presented aspects of the data that was being overlooked by astronomers who used oxygen as the main element for analysis. Through his discovery astronomers changed their working methods and were able to make new findings concerning differentiations between solar winds (Alexander et al. 2011).

Parameter mapping in astronomy has been utilised in the context of public outreach and various sonifications have been designed to convey scientific data to the general public. Sonifications for planetariums like the prototype designed by (Quinton et al., 2016) where a model of the 8 planets of the solar system was created. Planet size was distinguishable through the mapping of pitch, lower pitches for larger planets and higher pitches for smaller ones. Each planet's orbit speed was represented by different timings of surround panning. Timbre and amplitude were used to represent proximity to the listener who was placed in a heliocentric position. Other mappings such as LFO timings, added resonance, white noise and VCA and VCF envelopes were used to represent different climate conditions, gases, temperature and other planetary characteristics. The sonification was tested with 12 participants, 11 members of the general public and a representative from the planetarium, who were able to discern many of the planetary characteristics in the sonification design without any visual reference.

Tomilson et al. (2017) created a sonification of the solar system for a planetarium. Pitch was used to convey the mass of each planet and the resonant frequency filter was centred in accordance to each mass. Orbit year was determined through spatial mapping. A day on each planet was represented by using a VCA envelope that increased in amplitude as time proceeded to the end of the day. Brown noise was used to create the sound of each planet and a resonant filter was applied with a central frequency scaled proportionately to the mass of the planet. This project was evaluated by the public who were asked to give their feedback about their experience. The researchers inquired about the publics user experience by evaluating the performance on helpfulness, interest, pleasantness, comprehensibility and relatability of the mappings. The design was comprehensive, helpful and engaging.

Sonification of astronomical data has also been used for Public outreach in films like Rhythms of the Universe. Ballora (2014) created a sonification for the various aspects of astronomical data that were portrayed in the film. Various mappings and sonification techniques were used to represent the different astronomical phenomena of Pulsars, Planets of the solar system, gravitational waves, helioseismology, solar winds (aurora borealis), extragalactic background light and cosmic microwave background radiation. Ballora (ibid) used various mappings to represent pulsars. Eight sine waves were tuned differently by using additive synthesis. The intensity of the data was represented by a VCA envelope that would increase in loudness accordingly. Each of the eight oscillators were panned across the stereo field and reverb was added. The eight oscillators were accompanied by two detuned wavetables that were routed through a bandpass filter and panner. These added harmonics were tuned two octaves below the oscillator frequencies. The beating rate frequency was mapped to the zenith data and routed through a filter bandwidth matching this data. The azimuth degree was mapped to pan. These mappings created a pulsing, quivering sound that gave a clear rendition of how a pulsar rotates on its own axis. No formal assessments were done of the effect of these sonifications.

Garcia Riber (2018) was working on a sonification system that could make Exoplanetary data from the online archives accessible to the public. The sonification would be done by using a virtual interactive synthesiser created by Garcia Riber which he called the *Planethesizer*. It uses vector synthesis which uses Csound’s Planet computer operation code to generate planetary coordinates of a planets orbiting a binary star system (Redfern, 2008). Each planet has a dedicated synthesiser to create the sound. Delay is used to reproduce eclipse sequence cadence introducing planets at different times expressed in days. By restarting the system, it initialises the eclipse sequence. The delay can be switched off allowing planets to be synchronised. There is also a global tempo which controls the speed of the planets’ orbits. There is also a global zoom button that brings planets to the forefront giving them more audibility. The model can also be controlled using a MIDI keyboard.

Garcia Riber (2019) also worked on another virtual synthesiser which he called the *Sonifigrapher* which is used to sonify Exoplanetary Light curve data that is available to the public at the NASA Exoplanetary Archive. Once again Csound’s opcodes were used and an algorithm written to control the output of the signal. Filtering, panning, reverberation and global tempo settings are mapped to control the variances in the light curve data. Additive synthesis was used to generate sound by adding up a sum of sine waves that constructively add harmonics, increasing timbral and tonal features (Cipriani & Giri, 2010a). The colours Red, green and blue from the light curves are extracted through the opcode. The monophonic output is low or high pass filtered and sent to a quadraphonic matrix and reverb processor to affect the output on the four channels of the quadrophonic sound system. Both models are interactive and have been created as a public engagement tools to teach non astronomers about Exoplanets. Users can also tweak the sonified parameters accordingly.

Snook et al. (2018; Snook et al., 2020) has been developing a modular musical scientific instrument that sonifies astronomical data which has been called *Concordia*. It has been built for musicians to create music that uses harmonica and geometric relationships of the planets of the solar system. It is being built in extended reality (XR) which is a combination of Virtual Reality (VR) and Augmented Reality (AR), also known as immersive computing. Concordia aims to sonify and visualise celestial harmonies designed for VR headset and headphone use; the main emphasis will be on the audio representations of the data. It is being designed to be played as a musical instrument making it interactive for users. Mappings will concentrate on the use of timbre, envelope shaping especially with Attack settings. It will use Multichannel 3D spatialization for localisation of signal to image projections. Table 2.5 summarises the examples of audifications and parameter mapping sonifications used in the context of astronomy.

Table 2.5: Examples of Sonification in Astronomy

Audification	Scope	Source	Parameter Mapping	Scope	Source
Jupiter's Auroras	To better understand auroras	Space Audio (2016)	Sonification interface called xSonify – General Astronomy	Converts astronomical data into sound	Candy et al. (2006)
Gravitational Waves	To detect gravitational waves	Hemreich (2016)	Sonification interface called xSonify – General Astronomy	Converts astronomical data into sound	Diaz Merced (2011, 2013)
Asteroseismology	To measure the size, temperature of stars & their surface activity	Tootell (2011)	Sonification interface called xSonify – General Astronomy	Converts astronomical data into sound	Garcia et al. (2019)
Signals from possible alien civilisations	To test between phantom & authentic signals with white noise type data	Lunn & Hunt (2013)	BELL3D sonification system – Star data sonification	Sonifies star data for blind astronomers	Ferguson (2016)
Magnetohydrodynamic waves	To study Ultra Low Frequency (ULF) magnetohydrodynamic waves which transfer energy from outside the Earth's magnetic shield to regions inside it & influence space weather	Archer et al. (2018)	Virtual Reality performance instrument sonified data of the Large Magellanic Cloud	An educational performance tool for public engagement & interaction	West et al. (2018)
Pulsars	The speed of rotation of these stars on their own axis	Jodrell Bank (2014)	Solar Wind data	To learn about the different aspects of solar wind	Alexander et al. (2010)
Cataclysmic Variable Systems	To measure similarities in fluctuations of light emissions of two-star systems heard as similar amplitude and pitch changes	Tutchton et al. (2012)	Sonification of the solar system	For a planetarium	Quinton et al. (2016)
Exoplanet Hunting	To search for Exoplanets	Winton et al. (2012)	Sonification of the solar system	For a planetarium	Tomilson et al. (2017)
Solar Winds	To learn about the different aspects of solar wind	Alexander et al. 2011, 2014, 2015	Sonification of astronomical data	For a film	Ballora (2014)
Solar Winds	To learn about the different aspects of solar wind	Landi et al. (2012)	Sonification interface for Exoplanetary data	For public engagement	Garcia Riber (2018)
Solar Winds	To learn about the different aspects of solar wind	Wilks et al. (2016)	Sonification interface for Exoplanetary data	For public engagement	Garcia Riber (2019)
Solar Winds	To learn about the different aspects of solar wind	Jian et al. (2015)	Musical interface using planetary harmonics	For musical composition	Snook et al. (2018)
			Musical interface using planetary harmonics	For musical composition	Snook et al. (2020)

The design process in sonification is characterised by having a broad and open-ended approach (Choi, 2018), not pinned down by rules but only assisted by guidelines which have been developed over the years. This allows sonification design to be creative and experimental, although Ibrahim et al. (2011) had noticed patterns in the way that practitioners map their parameters. Since sonification is based on non-verbal sonic representations of data then this allows certain design approaches to take a more musical aspect than merely a pure sound design implementation. Whether one approach is better suited than the other is overridden by the importance to facilitate interpretation of the data for the user (Barrass & Kramer, 1999). This means that sonication design is determined by the nature of the data and by the nature of the users.

It has been noticed in certain examples of sonification literature that it is sometimes unclear for whom the sonification has been created, how they have been created, how the data was converted and whether the sonification had been evaluated (Maeder & Zweifel, 2016; Verrier et al. 2020; Space Audio, 2016; Heimrich, 2016; Tootell, 2011; Jodrell Bank, 2014; Tutchton et al. 2012; West et al. 2018). This could be a disadvantage for researchers who are new to the field and are learning how to create sonifications. One of the main points mentioned by Hermann (2008) is that a sonification should be reproducible and this why these details of information would need to be reported in more detail.

2.5 User Centred Design

The user centred design process follows a series of procedures. The first step is to study and understand the people that the product is being designed for and to achieve deeper insight into their activities and behaviour in relation to the particular technology being designed (Benyon, 2019). This can be achieved by working with the users (Dix et al. 2009). Understanding the user’s requirements should take precedence over the designer’s preconceptions to ensure that the interface is more intelligible for the user (Kirwan, 1994). The next step is to have a good grasp of the technologies and the benefits and limitations. This process is followed by a step called *ideation*, which is to come up with solutions for the technology and to base it around the purpose of the technology’s use in the context of the people and their related activities (Benyon, 2019). At this stage the designer and user learn about each other's processes and to integrate this into the design (Foster & Franz, 1999). The designs are then evaluated by the users, and a number of iterations and are made based on the feedback and research that is conducted until all the issues have been solved (Benyon, 2019). (Refer to figure 2.14.)

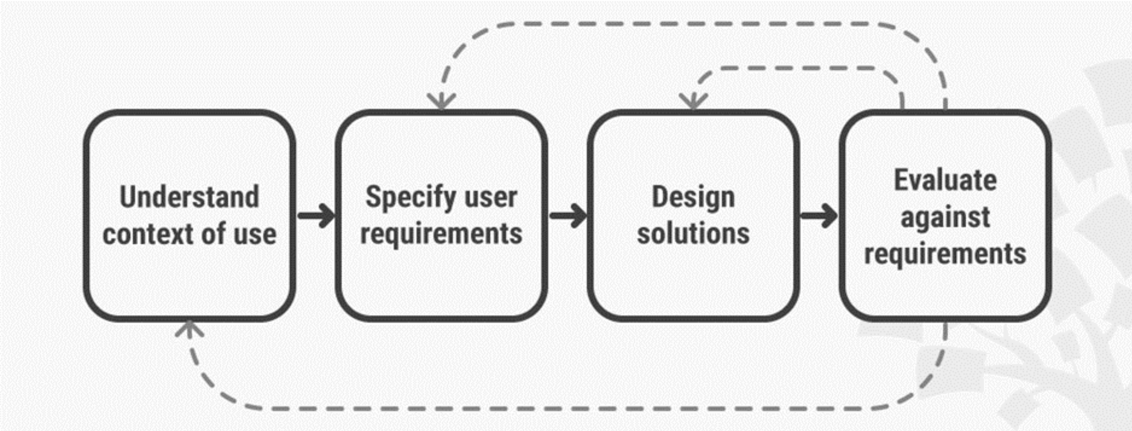

Figure 2.14: User centre design life cycle (interation-design.org, n.d.)

Iteration allows for the development of a usability engineering life cycle (Mayhew, 1999; Seffah et al. 2005) of communication to-and-fro between the designer and the user to fine tune and tweak the model based on the feedback from this interaction (Xiao et al. 2020; Kirwan & Ainsworth, 1992; Sebillotte, 1995). This process helps to create an effective user interface which is unlikely to be achieved through the first design (Nielson, 1993). The evaluation stage confirms the users' requirements, assesses the suitability of the system, examines whether it meets the users' needs and checks the sustainability of the model (Stone et al. 2005). During the evaluation the user tests the model rigorously and communicates any changes that might be necessary to make the model more effective (Hartson et al. 2001; Peres et al. 2008; Benyon, 2010).

Csikszentmihalyi and Halton (1981) have argued that there is a kind of symbiotic relationship between humans and the tools that they use which reflect the nature of the user and becomes an extension of them. Interfaces that are designed in such a way are like an extended reality comparative to the relationship between an audience and a theatre stage (Laurel, 2013). Bødker and Klokmose (2016) refer to the procedure of creating more natural and intuitive user interfaces by applying Fauconnier and Turner's theory of *Conceptual Blends*. This theory is about creating a qualified match between two mental spaces and that selective components from these two inputs are blended together into a third mental space. The *Mental Space* is described as minute partial concepts formed from thought and dialogue for purposes of understanding and action (Fauconnier & Turner, 2003). MacDonald and Stockman (2018) had created an Auditory display for autonomous driving using this method of blending. User design methods were blended with film soundtrack composition and drew clear parallels between the different compositional processes. Table 2.6 shows these comparisons.

Table 2.6: Conceptual blends between user centred design methods and film

Auditory Interface Stages and Development	**Soundtrack Composition Stages and Steps**
Stage: Requirements Gathering - Scenarios and task analysis with users/ actors/ characters, events, objects, actions, context	Stage: Spotting the scene - stories with characters, actions, objects, transitions, locations
Stage: Conceptual Design - thinking about interface arrangement, parts that need sonifying and how it is laid out	Stage: Arranging ideas and cues, sketching, establishing and iterating ideas
Stage: Detailed design - mapping events to audio	Stage: Composing/ Designing original music and sourcing sound samples to map to the cues/ events
Stage: Evaluation	Stage: Evaluation

Source: MacDonald and Stockman (2018)

The importance of user centred and task-based design methods in sonification design were immediately recognised by Kramer et al. (1997) who suggested that sonification was naturally task dependent. This report also highlighted the importance of accurate data portrayal which could be achieved through user centred design methods. Sonification was also seen as a complimentary element that could be used in conjunction with other display units such as visualisation, haptic feedback or multisensorial interfaces (ibid).

The use of the five senses for data analysis enhances data exploration in many new ways (McCormack et al. 2018). The advantage of using a multisensorial dataset means that one sense could identify features that are lost through the limitations of another sense (Malikova et al. 2017). It is also the case that one sense compliments and enhances the behaviour of another, especially since the senses work in unison and not in separation to each other. Involuntary auditory attention has been found to enhance early visual perceptual processing in a study conducted by McDonald et al. (2000).

These types of interfaces are more complex to design due to the risk of information overload (Zheng et al. 2020). Requirements Gathering is effective for obtaining information regarding the functionality and goals with regards to how an interface will work in relation to the data and for the benefit of the user. It also has a more sustainable effect in the way that it can highlight possibilities and constraints that can be improved upon in future models (Silhavy et al. 2011).

Sonification design is about mirroring the meaning of the data as clearly and as comprehensively as possible in sonic terms (Dubus & Bresin, 2013 citing Scaletti, 1994). Data carries semantic meaning to the person who utilises the information in their work. It is a narrative that reports information about the phenomenon or phenomena in question and gives it shape through measurement of related variables. In visualisation a practice known as *Data Driven Story Telling* is becoming a most popular means of relating data in the most comprehensive and efficient way (Carpendale et al. 2016). Segel & Heer (2010) describe how they used seven different genres of narrative visualisation including: magazine style, annotated charts, posters, flow charts, comic strips, slide shows and videos to facilitate user interfaces by crafting data stories.

User centred design in sonification

Barrass (1996) used the same ideas in relation to sonification since he was also aware of the potential that storytelling offers in conveying solid principles that can be easily absorbed and reproduced. Barrass (ibid) created a method of requirements gathering for auditory display design that was based on the use of storytelling. This process was broken down into four steps listed in table 2.7.

Table 2.7: Auditory display requirements gathering through storytelling

Design Step	Description
Situation description	A short story describing an activity in the user interface which is then followed by identifying the key points in the story.
Situation analysis	An analysis of the Situation Description identifying the task, information and the data structure in the form of questions that can be answered, with the answers themselves being key identifiers in the design process
Example Lookup	Identifies similarities between the description and analysis processes from the previous two steps.
Design Synthesis	Uses examples found in the third step as the basis for the interface design

Source: Barrass (1996)

In publications by Anderson (2005), Walker and Nees (2011), Flowers (2005), Sanderson et al. (2000), Peres and Verona (2016), Lenzi et al. (2020), Verona (2017) and Verona and Peres (2017), there is particular emphasis on Task-Based design methods where the requirements gathering is designed to extract a clear understanding of why and for whom the interface is being designed. Barrass (1997) had come up with a method of Task-Based design theory which he had coined as TaDa (Task-oriented, Data-sensitive method for Auditory information design). Table 2.8 describes this method of Task-oriented data gathering and design.

Table 2.8: Task-oriented, data sensitive method for auditory information design (TaDa)

Step	Description
Scenario Description	A short narrative, in the form of a research question, describing the information process activity that the sonification is designed to support
Requirements Analysis	Requirements must be in line with the research question. It must provide an answer that can be analysed and from which data is characterised from the requirements process
Representation Design	Data acquired from the requirements process that are essential to the task and true to the data
Realisation	The design of the sonification interface based on the findings of the requirements gathering exercise

Source: Barrass (1997)

All these methods are focused on conveying the semantic properties of the data in the most effective and comprehensible means possible. Each one of these chosen methods is also a study of user behaviour. This emphasises the importance of understanding who the system is being designed for and what purpose it serves in conveying the data to the user. Sonification design is an exercise in communication to create a useable, effective and communicable system. Hermann (2008b) had put this into the context of sonification by developing four design guidelines that emphasise the importance of effective and communicable sonifications. Table 2.9 lists these guidelines.

Table 2.9: Sonification guidelines

Process	Description
Input	The sound reflects objective properties or relations in the input data
Transformation	The transformation is systematic. This means that there is a precise definition provided of how the data (and optional interactions) cause the sound to change.
Reproduction	The sonification is reproducible: given the same data and identical interactions (or triggers) the resulting sound has to be structurally identical.
Sustainability	The system can intentionally be used with different data, and also be used in repetition with the same data

Source: Hermann (2008b)

These guidelines reflect the user centred design approach in the way that they emphasise the importance of the sound design mirroring objective properties of the data. The other guidelines suggest that an iterative process takes place to ensure that the user clearly understands how the data has been transformed, that the sonification is reproducible and that the system is sustainable.

User and task-based design are encouraged in sonification design but since there are no hard rules with regards to the design process, then practitioners can use different approaches as long as they sonify the data effectively. When analysing a number of publications in relation to this study it was noted that a small number of publications had spoken about designing sonifications based on information that was learned through reading about design methods used in other studies. Sonifications designed by Boschi et al. (2015), Brewster & Murray (2000), Gionfrida et al. (2016), Kather et al. (2017), Dyer & Rodger (2016) all shared the practice of not conducting any user or task-based requirements gathering. Each one of these designs claimed effective results and the sonification suited the purpose that they were designed for.

Different methods of sonification design can be effective but not necessarily fail-proof. Worrall (2010) had spoken about the difficulty of data mapping in relation to acoustic characteristics and listeners' attitudes. The complexities of human perception and cognition are likely factors for design failure (Roddy & Bridges, 2020).

2.6 Summary

This chapter has looked at the nature of astronomical data that is captured and analysed by astronomers that work in the field of Exosolar Planetary data. It has also discussed a detailed analysis of sonification and its application in astronomy, design factors that are practised in the sonification field. It has also looked at human perception and how psychoacoustics are the tools of understanding the sensory world through audition. It has then explored the aspects of listening which is the extended component of hearing that is used for extracting meaning from sounds. This was also discussed in the context of how listening applies to sonification design.

In the next chapter a more detailed exploration of sonification design will be presented in the form of a study of sonification design trends. During the process of collecting information regarding sonification design in this chapter it was felt that the literature did not always clearly convey sonification design practice. It was decided that by interviewing sonification designers it might be possible to obtain more detailed information regarding this process that would help in the sonification designs for this study.

Chapter 3: Investigating Effective Methods of Designing Sonifications

This study aims to provide an insight into effective sonification design. There are currently no standardized design methods, allowing a creative development approach. Sonification has been implemented in many different applications from scientific data representation to novel styles of musical expression. This means that methods of practice can vary greatly. The indistinct line between art and science might be the reason why sonification is still sometimes deemed by scientists with a degree of scepticism (Goudarzi, 2018) since sound is often regarded as being a more immersive and emotional medium rather than being objective like vision (Supper, 2014). The gathering of information from the literature on the subject was at times vague since various publications were unclear about their design methods. The literature reported positively about the outcome of various testing, but this led to the question of why sonification is not used more if it seems so successful. It was sometimes unclear as to what a sonification was being designed for. The purpose of the sonification design was not properly defined leaving questions as to whether the sonification served any purpose beyond testing. There were also publications that contained vague descriptions about the data gathering process before the actual design procedure had begun. Some well-established practitioners argue that it is poor design that renders sonifications meaningless, in-turn having an adverse effect on acceptance. Due to these questions that arose during the investigation concerning sonification design it was decided to conduct a study to try and understand the process much better. To gain a deeper understanding about sonification research and development 11 practitioners out of 18 who were contacted on the basis of their work and on having met them personally at the International Community for Auditory Display (ICAD), were interviewed. They were asked about methods of sonification design and their insights. The findings present information about sonification research and development, and interesting views regarding sonification design practice.

3.1 Rationale

The purpose of this study was to investigate effective methods of designing and evaluating sonifications. Guidelines have been developed to facilitate practitioners in their work, but sonification design also enjoys an open ended and creative approach (Hermann, 2008). This also leads to a certain level of obscurity for the newcomer or the layman who is trying to understand the underlying principles for good sonification design. Brazil (2010) argued that it was hard for new practitioners to understand how to design auditory displays due to guidance being limited and scattered across publications. It is often unclear for what purpose the sonification was designed and for whom. Sonifications are often restricted to contained studies without further development.

In the literature review there were some of the publications that lacked clarity in describing methods of design (Maeder & Zweifel, 2016; Verrier et al. 2020; Space Audio, 2016; Heimrich, 2016; Tootell, 2011; Jodrell Bank, 2014; Tutchton et al. 2012; West et al. 2018). There is often little information about any requirements gathering that had been conducted prior to the actual design stage of the sonification as was found in various publications (Bidelman, 2017; Hinterberger & Baier, 2004; Plazak, 2017). Frauenberger (2009) had analysed 82 submissions that were published in the ICAD proceedings of 2007 and found that only 23 of the publications described the design of an auditory display. Descriptions of the data sets are often oblique. Sonification techniques employed are often described in a complex and inaccessible manner, without even describing the aim and purpose of the sonification, or if it was utilised beyond the testing period. This paucity of information can leave researchers in doubt as to whether sonification has any scope as a method of data analysis. In order to reap a deeper understanding of the sonification design process it was thought necessary to interview practitioners about projects that they had worked on and to investigate their design processes.

Attitudes towards sonification

Dubus & Bresin (2013) citing Scaletti (1994), state sonification only becomes relevant if it is communicating original information comprehensibly. There is often an open-ended approach to sonification design, but patterns are noticeable in the way practitioners map parameters (Ibrahim et al. 2011). In the sonification community a Sonification Handbook was collated by Hermann and Hunt in 2011 (Hermann and Hunt, 2011). It contained the ideas of leading practitioners in the field and established definitions, terms and guidelines to assist practitioners and help bring about an established code of design practice. This was an attempt to standardise sonification and to try to establish it as an accepted method of data analysis similar to visualisation (Supper, 2012a; Alexander, et al. 2014).

Sonification design has been compared to visualisation and argued that well established visual practices are partly to blame for sonification's restricted appeal amongst scientists. Listening to scientific data has been criticised as being broadly subjective and deemed unscientific (Supper, 2016). The immersive and emotional qualities of sound seem to reinforce this claim negating sonification being recognised as an accepted scientific method and seen merely as an art (Supper, 2014). Instead, Scientists utilise sonification as a promotional tool for public outreach. Supper, (2012b) gives an example of this by describing how "*the sound of a star*" is played to audiences in public talks on asteroseismology. This gives an idea of how stellar oscillations work. The scientists consider this an effective way of conveying such ideas to the public but doubt the scientific accuracy or the reliability of auditory displays for their day-to-day work. People are also often reluctant to try out new ways of doing things (Eagle, 1999), which can seem counterintuitive in a scientific setting. Goudarzi, (2018) had found that scientists would not use a sonification framework unless they could program it themselves with their own computer. Sonification is a relatively new method of representing data and it will take more time for this technique to become common practise. Barrass (2012) argues that there is always a degree of scepticism towards new methods. Even though there are many scientists who prefer more traditional methods of scientific research, there are also a number of scientists that are using new techniques such as sonification.

The comparison between sonification and visualisation does not only reflect differences but also similarities. Any form of design practice methods in sonification, visualisation or HCI design are a constant learning process that evolve over time. Advances in technology and social trends determine the way that design evolves. Accumulative, collected, knowledge acquired is usually compiled to reflect the design practice within a field and to establish codes of practice or methods.

There are however various publications about sonification research that tend to lack relevant information about the design approach used in the study. Verona and Peres (2017) identified that many sonifications had not been empirically evaluated adding further lack of understanding of how to design sonifications for specific tasks. Many sonifications have been created without involving end users. This means that the user is unaware of what elements of the data the sonification parameter mappings are representing. This has led to a lot of sonifications being considered undecipherable, potentially making them redundant (Diaz Merced et al. 2013).

The Importance of Requirements Gathering

The importance of a thorough investigation and understanding of a dataset is also echoed in Barrass's (1997) sonification design method *TaDa* (Task-oriented, Data-sensitive method for auditory information design). This method is based on four design principles. The first is *Scenario Description* or a short narrative, in the form of a research question, describing the information process activity that the sonification is designed to support. The second step, *Requirements Analysis*, means that requirements must be in line with the research question. It must provide an answer that can be analysed and from which data is characterised from the requirements process. The third principle is about *Representation Design* acquired from the requirements process that are useful to the task and true to the data. Once the investigation and understanding of the data has been established the *Realisation* of the sonification can be fulfilled. The importance of appropriate data gathering, and implementation of task analysis methods has been emphasised in multiple sonification papers (ibid), (Anderson, 2005; Walker & Nees, 2011; Flowers, 2005; Sanderson et al. 2000; Peres & Verona, 2016).

Designing for End-users

The involvement of the end user in the sonification design is at times under-reported or unclear as was found in the following publications: (Poveda et al. 2017; Poirier-Quinot et al. 2016; Boschi et al. 2015; Laughner & Kermit Canfield Dafilou, 2017). This gap in the literature is likely to downplay the effectiveness of sonification mainly due to giving the false impression that sonifications are not designed properly. This leaves a negative impact on the field of sonification and its implementation as a scientific method that can be used for data analysis. Black et al. (2017) describes how the use of auditory displays in image guided intervention has been largely neglected despite its benefits. Future work could include working more closely with auditory display designers to create more meaningful displays (ibid).

The problem of not including end users in the design process was a factor that was immediately identified by Kramer et al. (1997) and has yet to be fully resolved. He stated that sonification research needs to be user centred. Although it had been successful in a broad range of applications as described by Worrall (2016) who reports various examples of scientifically utilised sonifications, it was still not clear as to how to design an effective, working sonification for a specific task. This could be a reflection of open-ended design approach and not a failure in the design process. Kramer suggested that progress in sonification would require specific research directed at developing predictive design principles or design guidelines. Sonification is naturally task dependant, requires adequate representation for data portrayal and user interface interaction. The report describes a number of considerations that should be taken into account when designing a sonification (see table 3.1).

Table 3.1: Guidelines for designing a sonification user interface

Considerations	Descriptions
Control	Parameter controls for sound parameters that are efficient, effective & accessible
Mapping	Provides flexibility & the ability to design new sonification mappings allowing the user to have intuitive control over data dimensions in relation to sound parameters
Integrability	To allow the different formats of data from different disciplines to be imported into the system and then sonified
Synchrony	To allow easy integration with other display systems like VR systems and other visual or assistive technologies
Experimentation	To integrate a perceptual framework for testing overall mapping functions and sound synthesis

Source: Kramer et al. (1997)

Sonification has been applied to quite a wide spectrum of diverse applications and designed by different people who have used various approaches to create their interfaces. For the purpose of this study, it was decided to explore a portion of sonification works that reflected this diversity to analyse how these interfaces were created.

The Study

A total of 22 publications representing a wide range of diverse applications and design methods were chosen and analysed to explore sonification design. The selection was based on literature that was being analysed at the time when this study took place. There were publications about sonifications that were created for the same field of study, showing different design approaches taken by various practitioners to represent similar aspects of data. The sample of publications chosen were considered sufficient to give an impression of different applications of sonification and different design methods.

The study would look at the requirements gathering methods, the parameter mappings used, evaluating the methods used to test the sonifications, the actual test methods and results of each of the publications chosen for the analysis. Eleven out of the 22 publications had not been tested and the papers only discussed their sound design methods (Ness et al. 2010; Ben-Tal et al. 2002; De Campo & Daye, 2006; Kadkhodaie & Rezaee, 2017; McGee & Rogers, 2016; Polli, 2005; Strum, 2000; Vogt, n.d.; Winton et al. 2012; Barrass & Zehner, 2000; Baier et al. 2007). The other eleven publications (Boschi et al. 2015; Brewster & Murray, 2000; Janata & Childs, 2004; Quintero, 2013; Gionfrida et al. 2016; Kather et al. 2017; Dyer & Rodger, 2016; Schaffert et al. 2012; Valery et al. 2017; Jamieson & Boase, 2017; Verona & Peres, 2017) were evaluated by investigating their methods of data gathering, whether they chose audification or parameter mapping, if there was training prior to testing, the testing procedure itself, the results and any mentions of further development of the sonification.

Requirement Gathering Methods

Effective methods of practice typically follow a rigorous investigation to learn about the data. Most sonification designs are constructed by first obtaining information from relevant literature (Boschi et al. 2015; Brewster & Murray, 2000; Gionfrida et al. 2016; Kather et al. 2017; Dyer & Rodger, 2016). Other sonification designs were based on conducting interviews with the proposed end-users (Janata & Childs, 2004; Quintero, 2013; Schaffert et al. 2012; Valery et al. 2017; Jamieson & Boase, 2017; Verona & Peres, 2017). Two publications did not explain clearly how the requirements or data gathering processes were conducted. These publications were *Not Informative* (Janata & Childs, 2004; Quintero, 2013). Two studies gave detailed explanations about the type of information that was gathered but were vague about how it was gathered. These publications were *Partly Informative* (Schaffert et al. 2012; Jamieson & Boase, 2017). There were two publications that gave a clear explanation of the data gathering investigations, which were *Informative* (Valery et al. 2017; Verona & Peres, 2017). Requirements and data gathering were often under-reported in publications. Out of the 6 reports that conducted interviews or involved an end-user in the design process, only two gave descriptive information about these procedures. Some publications gave ample information about the data but were scarce on reporting how it was obtained (See table 3.2).

Table 3.2: Requirements & Data Gathering Exercises

Author	Data from Literature	Interviews	Task Analysis	Process
Bosci et al. 2015	X			
Brewster & Murray 2000	X			
Gionfrida et al. 2016	X			
Kather et al. 2017	X			
Dyer et al. 2016	X			
Janata & Childs 2004		X		Not Informative
Quintero 2013		X		Not Informative
Schaffert et al. 2012		X		Partly Informative
Valery et al. 2017		X		Informative
Jamieson & Boase 2016		X		Partly Informative
Verona & Camille Peres, 2017		X	X	Informative

Parameter Mapping Techniques

Parameter Mapping descriptions are occasionally not accessible or easy to grasp. Table 3.3 gives an indication of mappings that were found in each of the publications that had some form of testing. The most common parameter mapping is the use of pitch which was used in 9 of the studies listed in table 3.3. Most of the sonifications analysed for this study involved multiple mappings where more complex representations of the data were required. The exceptions Brewster & Murray (2000) who only mapped pitch to movements in stock prices and Schaffert et al. (2012) who mapped pitch using Middle C as a zero point and notes above and below being higher or lower to that point. It is noticeable that spatialization has not been used as a mapping in any of the studies listed in table 3.3. Spatial mapping is an effective parameter mapping and sound is a temporal-spatial phenomenon but none of the studies listed have considered to use this as a parameter mapping.

Table 3.3: Parameter mappings from various publications

Authors	Data	Mapping Technique
Brewster & Murray (2000)	A month of trades from a Swiss bank	Pitch - up (higher) down (lower)
Janata and Childs (2004)	Sonification of Real-time Financial data	Multiple Mappings - Pitch, Tremolo, Note length
Quintero (2013)	Sonification of oil and gas wireline well logs	Multiple Mappings - Pitch, Tone, Amplitude
Gionfrida et al. (2016)	Sonification to enhance the diagnosis of Alzheimer's & Dementia	Multiple Mappings - Pitch, Rhythm, Tone
Kather et al. (2017)	Sonification of Electrocardiography (ECG) data	Multiple Mappings - Pitch, Amplitude, Harmonics
Dyer et al. (2016)	Sonification of movement for motor skill learning	Multiple Mappings - Noise, Pitch, Rhythm
Schaffert et al. (2012)	Sonification as an asssting training guide for rowing movement	Pitch - Middle C = zero point. Notes above 0 = high pitch and vice versa
Valery et al. (2017)	Sonification for piloting aircraft	Multiple Mappings - Pitch, Rhythm, Tone, Syllables
Jamieson & Boase (2016)	Exploring logged interactional data through sonification	Multiple Mappings - Tone, Note Length, Rhythm, Amplitude
Verona and Camille Peres (2017)	Sonification of Surface Electromyography	Multiple Mappings - Pitch, Amplitude, Panning, Filter

Test Methods and Results

Table 3.4 gives an indication of how the various sonifications that have been listed were tested. The number of Participants ranged in each study from 2 to 45 with of a median of 23.5. Each publication gives various information regarding the participants. It is noticeable that out of 11 sonifications 8 of these designs required prior training before the actual testing took place (see table 3.4). It is interesting to note that all the sonifications provided positive results. Negative results were only reported by 5 of the designers. Seeing how positively all the sonifications had tested could suggest the effectiveness of sonification. This could also signify that by giving a more positive overview it could be portraying a false indication of the general effectiveness of sonification.

Table 3.4: Test Methods & Results

Authors	Participants	Training	Positive Results	Negative Results
Brewster & Murray (2000)	12 aged between 20 & 45; 9 male, 3 female	Yes	Participants spent less time referring to visual graphs leading to significant reduction in the workload	None
Janata and Childs (2004)	12	Yes	Increase in 8% accuracy when sonification was triggered with 2 note sonification. Sound significantly reduced the number of missed significant events.	In the 4th and 8th stream conditions detection accuracy was not significant
Boschi et al (2015)	10 Geologists, 4 Sound Technicians, 10 Acousticians	Yes	11 participants sorted the data into similar criteria	None
Quintero (2013)	12 Engineers & Geoscientists	No	Pitch Modulation achieved better results than amplitude modulation	Takes longer for user to learn how to understand the pitch related sonification than the amplitude related sonification
Gionfrida et al. (2016)	2 radiologists, 1 more experienced than other	Yes	The sonifications helped to improve results when added to visual display. Sonification added information to the visual display. Sonification strongly helped to discern different cases of AD and induce confidence in made diagnostics	Sonification was found to be unpleasant to use by the participants
Kather et al. (2017)	10 medical students completed cardiology course or 1st - 3rd year clinical practice. 7 medical students before completion of cardiology course. 5 undergrad students with no knowledge of cardiology	Yes	Group 1 scored highest, Group 2 2nd and Group 3 last. Values above expected baseline. 13 participants had musical training achieving higher scores. Premature Ventricular Contractions most easily detected, 89% correct classifications due to rhythmical deviance.	None
Dyer et al. (2016)	45 participants, undergraduate students, split into 3 groups of 15 participants each	Yes	Melodic sonification proved to have the lowest average error scores than the temporal and Control Conditions.	Temporal condition did not improve test results
Schaffert et al. (2012)	23 athletes, 18 male and 5 female. Average age 17.8 years	Yes	Boat Velocity: - Substantial improvements for all boat categories, Boat Acceleration: - Improvements in recovery phase and execution of front reversal, Sound Sequence: - More controlled movement from the athletes determined by the sonification	None
Valery et al. (2017)	9 visually impaired & 8 sighted pilots	Yes	Both pilot groups showed acceptable maneuver precision through using the sonification.	Sonification led to a mitigated responisveness to other additional auditory stimuli as task difficulty increased
Jamieson & Boase (2016)	The sonification was analysed by the research team in a number of different ways	No	Sonification successful at identifying patterns, also effective for hypothesis generation.	Sonification alone not feasible for testing hypotheses among the whole sample of data
Verona and Camille Peres (2017)	Students, 27 males, 16 female, ages 19 - 59	No	Task Designed Sonifications more effective than data designed sonifications.	None

Obtaining more information about Sonification design

To obtain more information about sonification design it was decided that it would be worth interviewing sonification researchers and designers. Publications tend to be limited since they were written for conferences or had particular restrictions where information is usually selective and certain details could be briefly described or left out. By speaking to people directly it was thought that a lot more detail could be obtained about different sonifications and their design processes. The interviews would allow the discourse to explore people's opinions about the usefulness of sonification and how it is being applied in real world applications, which is information not usually found in publications.

The following section will describe the method used to find participants for this study, the number of participants that took part, and information about how the interviews were created and conducted.

3.2 Method

After analysing different sonification studies, it was noted that the language used to describe design methods was occasionally vague and unclear. This has a detrimental effect on aspiring sonification designers who find it hard to learn about the sonification design process. Sonification reaps positive results during testing but there is no mention of further development of it after this period. This could mean that sonification, although effective, is only remaining within testing parameters and has no scope beyond this point. Interviews were conducted to ask sonification designers for what purpose they were designing their sonifications, about the design, testing, the results and, finally, the outcome of the study. Semi Structured interviews were conducted to ask practitioners about the purpose of their sonification, the design, testing, results, and the outcome of the study.

Participants

The 11 people who participated in this study had designed sonifications for a variety of applications. Some of them have developed guidelines on how to improve the sonification design process and were also active members in the ICAD community. Participants were recruited by email which was considered to be more effective by establishing a more personal contact and also building networking relationships with people in the field. Their age or gender were considered not relevant since their identities were not anonymised. After much deliberation it was decided to reveal the identities of the participants in line with Supper (2014) where a similar approach had been practised. This is due to the inherent openness of the auditory display community and it would allow future sonification designers to approach individuals which is the part of the collaborative culture of this community. All participants that were contacted were advised during the initial call that their identities would be revealed for the study.

Eighteen people were initially contacted and 14 replied. Contact details were obtained from ICAD publications (Alexander et al. 2010; Walker & Cothran, 2003; Ballora, 2014; Peres & Verona, 2016; Gionfrida et al. 2016; Dyer et al. 2016; Barrass & Zehner, 2000; Nesbitt, 2004; Hogg & Vickers, 2006;). In the case of Jeon (Philart) his contact details came from a business card that was collected at ICAD 2016 and Ferguson's contact details came from a journal publication not affiliated with ICAD (Ferguson, 2016). ICAD is an abbreviation for the International Community for Auditory Displays which was established in 1992 and acts as a forum for presenting research on the use of sound to display data and the provision of enhancing interfaces for virtual reality platforms and computers (ICAD, 2021). A variety of participants were chosen with different degrees of experience in the field. One side of the scale consisted of well-established members who have heavily contributed to the field. The other side were people just starting in sonification research and development. This was done with the intention of obtaining a rich spectrum of different perspectives, knowledge and ideas concerning sonification design.

The University ethical procedures were followed. This included the provision of a participant information sheet and an informed consent form. The questions were based around the design processes of specific projects and sonification design in general. A different set of questions (refer to Table 3.6 and Appendix B) were asked to one participant who was interested in talking about sonification design guidelines. This participant did not consider himself to be a sonification designer, but he had worked on sonification guidelines and suggested that he could provide information about sonification design from this angle. There was initially someone else lined up for the interview but at the last minute was unable to participate and other people who had been contacted for similar interviews had not written back. The data collected from this one interview was still considered valid since a lot of the answers were similar to answers given in the other interviews and many interesting insights came from this particular interview. The only difference was that there was no discussion about actually designing a specific sonification. These questions were aimed to learn more about the effectiveness of sonification guidelines, how these assist practitioners and whether or not they are being applied (Refer to Appendix B).

Materials

The interviews were conducted on Skype and were recorded on a portable audio recorder. All the participants were provided with the necessary ethics forms that were sent to them by email when they first agreed to sit for the interviews, and these were signed and sent back before the interviews took place. The interviews were roughly one hour in length with some running for shorter time and others running beyond the time limit.

Design

The interview consisted of 23 questions about the sonifications designed by the participant (refer to Table 3.5) and they functioned as reference points to guide the conversation to find out more than is usually explained in sonification literature (Refer to Appendix B). Other questions were asked in accordance to participants responses when points of interest arose or certain aspects needed more clarification. There were certain elements that were noticed while conducting research in the field. The lack of certain information brought up the question as to whether sonification is used beyond the realms of lab testing. Language used in various publications was also an issue. Quite a few studies lacked clarity when describing their sonification design methods. The language was often cryptic, and it was hard to understand the exact procedure of how the sonification was made. This is a disadvantage for people who are new to the field. One other factor that was noticed in a lot of the literature is that the scope of the sonification is not made clear. The testing methods were often focused on a one-time project. The results did often produce positive results, but this led to the question as to whether sonification was being positively reported but that it had no further continuation beyond the limits of the study. There was barely information about whether the sonification was ever used after it had been tested.

Table 3.5: Questions Investigating Sonification Design

Questions	Description
Participants	Who the designer was, who they were designing for
Requirements Gathering	How information was gathered by the designer concerning the data
	Whether the investigation procedure and overall design was influence by any existing guidelines or techniques
	The involvement of the client (if there was one)
	A detailed description of the dataset
Sonification Design	About the data inputted into the system and how was it mapped to various sonic attributes
	Whether any aesthetic considerations were made in the sound design of the sonification
	The software platform or technology used to produce the sonification and why this choice of platform
	The method of synthesis used and why
Testing	The testing method and the reasons why it was tested this way
	The reaction of the participants and their ability to discern information from the sonification
	The positives and negatives of the sonification
Results	Whether any further iterations of the model were made based on the feedback obtained from the results and how many were made and tested
Outcome	Whether it led the users to any new insights or discoveries
	Whether the sonification was ever used after the testing period

Table 3.6: Questions Investigating Sonification Design Research

Questions	Description
Desription of the Research	Describing the participant's research in auditory display design.
Influences	What previous research influenced the pariticpants work?
Changes in the field	What standards have changed in auditory displays have changed over the years.
Design Efficiency & Aesthetics	The description of an efficient and aesthetically pleasing sonification
	How to design an efficient and aesthetically pleasing sonification
	The importance of Aesthetics in Sonification design
Requirements Gathering	The description of an effective requirements gathering approach
	Existing methods, techniques used for requirements gathering
Testing	To discuss effective methods for testing sonifications
Drawbacks of Sonification	Can sonification hinder the traditional methods of data analysis?
Success	Is sonification being utilised successfully as a data analysis tool in Scientific research?
Standardisation and Guidelines	Whether there should be standardisation of guidelines that should be used for sonification design
Literature	Does current literature on sonification accurately reflect current practices?
Outcome	What would make sonification more mainstream as a data analysis tool?
	What is the future of auditory display design

Procedure

The interviews varied in time between 50 minutes and an hour and a half, but most were approximately one hour long. Due to qualitative approach of the investigation no pilot study was conducted, allowing the interviews to evolve and be adaptable to each of the interviewees. Participants were asked questions about sonification design according to the outcome of the interview. Some people spoke about a specific project. Others discussed various projects giving details on how each sonification was designed. Discussions about the general impact of sonification and its relevance also came up with various participants who had diverse views concerning the impact that sonification is having as an instrument of scientific research.

Each interview was transcribed and coded. The coding procedure passed through three different phases of extraction and refinement. The first phase was to obtain an initial set of codes and descriptors from the participants' responses. The second phase was to refine the codes and definitions and to see what was meaningful or redundant. The third and final phase was to check for consistency in the results.

3.3 Results

A total of 11 people were interviewed about sonification design. Participant's experience in sonification design varied, four of them had worked on sonification of astronomical data. The more seasoned sonification designers seemed to have a more global perspective about the workings of sonification design. Those who were newer to the field often spoke more about their sonification projects and the experiences encountered during the design processes.

The method of analysis for this study was inspired by Ground theory, collecting the data and then studying and compiling through an analytical process (Khan, 2014). The analysis of the findings aimed to construct a theory that would emerge from the data using a qualitative coding method focused on the findings and by-passing any pre-existing conceptualisations. This allows any social trends or processes in the data to emerge, these are organised into categories and integrated into a theoretical framework (Charmaz, 2006; 2012).

As described in the previous section 3.2 subsection *Procedure*, a three-pass system was used that was for the data analysis that was based on the descriptions of coding described by Mills & Birks (2014). The *initial coding* stage was used to get a general picture of the main components or patterns that arose from the interviews. It was interesting to find that there was a general picture that had already started to emerge. In most of the interviews the 23 questions that had been formulated were not always asked and in most cases the interviewers answered them without actually being asked the questions. During the initial phase it could be seen that people spoke about the subject of sonification and then related that to their own projects. At this stage one could see that all the participants believed that sound could be used as an effective data analysis tool and that they were fascinated by it, but some were not convinced that sonification design is being done properly.

In the *intermediate phase* of coding the emphasis was to pull out a more detailed structure that had emerged from the initial stage of coding and to see if any subcategories of the general attitude were present. In this stage evidence of a divided opinion about sonification and its effectiveness started to emerge more clearly. There seemed to be those that had a strong belief that sonification is effective as a data analysis tool, that it has evolved and is being applied more. There were those that believed that sonification was not achieving this level of expected reliability and that there were still a lot of issues with sonification design in general. There was a third group that had worked on one project as part of their research and they critiqued sonification in relation to their personal experience and the results they got from their own testing. In this phase more details started to emerge about the various techniques of audification, parameter mapping sonification, about their effectiveness or non-effectiveness. Design trends like iterative processes, changes to designs, aesthetics, testing methods and difficulties that emerged started to indicate that people's individual experiences are shared by their fellow designers and that there is a pattern in the approaches that people take. From the findings it seemed that even though sonification allows an open-ended approach there does seem to be a design trend that was reflected by the participants and there are particular general considerations that designers are using in their sonification designs.

The third phase or *advanced coding* was organised into a form of narrative that had evolved from the previous two phases and was organised to reflect the theory that had emerged from the interviews. In the sonification community it has long been argued that there is a lack of vocabulary when compared to visualisation which is often deemed as being more standardised. This argument emerged in these interviews but there was another reflection that become apparent. Even though sonification as a field might be lacking in having specific terminologies or techniques when compared to visualisation, but from these 11 interviews one could see that there was a sonification design trend that all the participants seemed to follow. The subsection titles in this section are the final coding that had emerged from interviews. They give an overview of how sonification is understood and practised by certain people in the community. The number of participants is small and there are other aspects of sonification that have most probably not been captured but these interviews helped to obtain a clearer of sonification design that influenced the sonification designs in this PhD. Figure 3.1 shows each of the three phases and the codes that emerged in each phase and the interconnection between the themes in the different stages. In the initial stage indicated in dark blue, the intermediate phase in green and the advanced phase in dark orange. The arrows indicate the relationships between the first and second stages and the light blue, light yellow and light grey boxes show the relationships between the second and third stage.

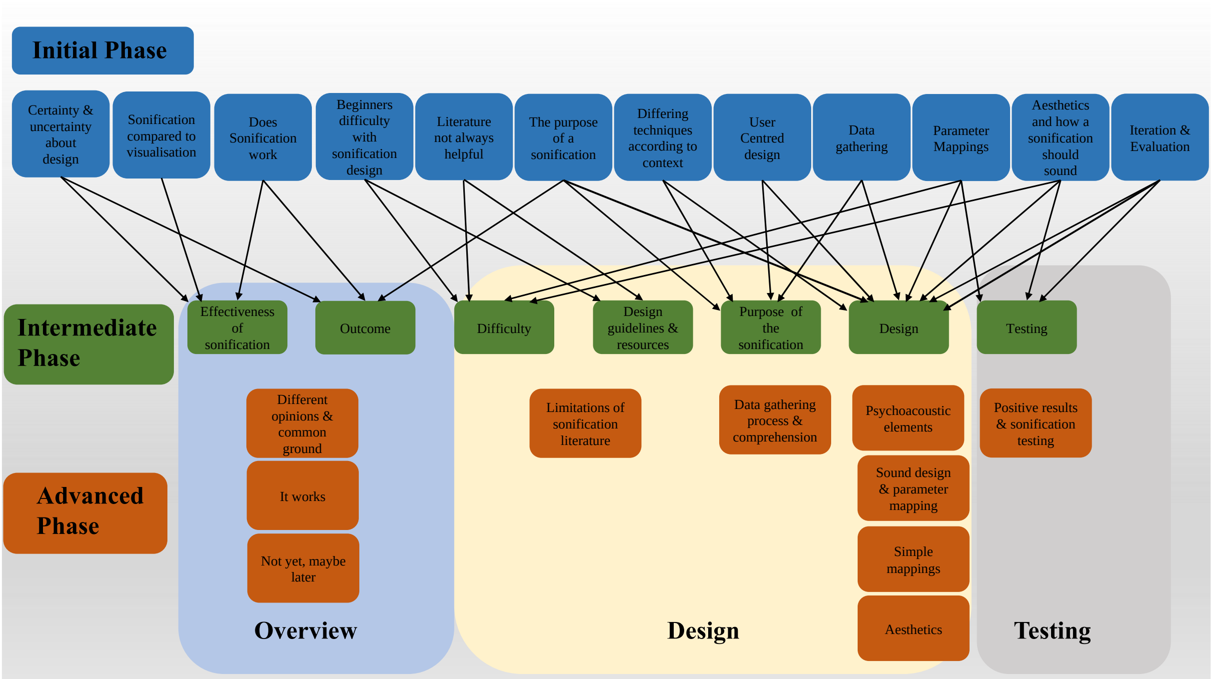

Figure 3.1: The three-pass analysis system based on grounded theory and the codes that emerged

Different Opinions & Common Ground

Paul Vickers (PV) made reference to the first ICAD conference: *"really you can trace it back to, in terms of where things really took off, was 1992 with the first ICAD."* Certain practitioners believe that sonification has been successful within this limited time frame. Bruce Walker (BW) clearly states that: *"I know absolutely, it is being used more and more."* Whereas Steven Barrass (SB) argues that the use of sonification is *"Pretty low or Zero really"*. When asked about effective sonification design Keith Nesbitt (KN) replied that: *"Some of the questions that you asked have been and are still being asked also about visualisation."* The common ground shared by the designers was that the sonification design process is challenging. Daniel Verona (DV) mentions how: *"It's not easy to do a direct correlation between the design criteria and the mapping"*. KN describes that even a well-prepared design could sometime falter: *"Trying to come up with understanding how to design these displays, your best laid plans can often go astray"*. These views are echoed by "Philart" Jeon (PJ): *"This is what we are doing including users and do participatory design, but still, it's not really perfect"*. In other disciplines of design such as HCI and Visualisation there are two key factors that are common practice. It is clear who the product is designed for, and users are involved in the design process. The second is that numerous iterations of the design are made. These practices have become more common in sonification design over the years, and all the participants spoke about these processes when describing data gathering and design exercises.

Data Gathering Process & Comprehension

All the practitioners discussed how they had consulted with people that they were designing for, or those that were related to the design process. In other instances, the designers had run mock tests with preliminary designs to improve their models. Jamie Ferguson (JF) described how there was a continuous back and forth interaction with the European Space Agency, ESA, in the design of his sonification of star maps: *"So they were pretty much on the ball with you. They would give you feedback on it and you would improve the model according to the feedback."* Robert Alexander (RA) also described this process by stating: *"I needed to first learn their approach and what's unique about their dataset. And then it became a back and forth dialogue."* RA's thorough investigation of the dataset he was sonifying led him to change his approach from using parameter mapping to audification: *"I had decided to go to the other route and actually, really use direct audification to try to find, really, again, you know, subtle and nuanced features."* It was this switch to audification that led to a ground-breaking discovery in the study of solar astronomy (RA): *"It was the audification work that led to the new scientific discoveries, which then led to the published papers"*. The discovery itself helped scientists to change their methods of research and it was through RA's sonifications that this became possible: *"I was listening to carbon 6 to 4 and what ended up happening was that no one had looked too deeply into the 6 to 4 ratio and then when we went back and plotted it, it was pretty easy to see that carbon is a much kind of smoother curve."* As PJ had pointed out: *"Sometimes sonification is very successful and sometimes just…nothing"*. BW explains that: *"Getting it right requires careful planning, information architecture, a lot of knowledge in the field, mastery of the tools"*. KN refers to the importance of iterative prototyping: *"The best approach these days is to try something and provide iterative prototyping"*. This means that numerous discussions are held between the users and the designers. Tests are conducted with different versions of the sonification and improvements are made according to the results.

PJ described the sonification design of emotional conveyance of dancer's movements. The team consists of dancers, musician and sound designers. The movements of the dancers are recorded whilst they danced to music that evoked certain emotions in them.

These movements were then given to the musicians and the sound designers and designed sound and music that convey the emotions reflected in the dancer's movements. A survey was then carried out with 20 participants to see which of the three final designs worked best. (PJ) *"We just finished a very basic survey type study with around 20 participants, non-dancers, they are just college students."* BW describes the complexity of designing any kind of interface and that inter-disciplinary knowledge is required for effective sonification design: *"It's hard work and requires inter-disciplinary teams and broad background to get it right."*.

Gionfrida (LG) described how: *"We proposed different tune structures, thinking they would sound better at the time, but they were more difficult for physicians to understand."* LG's final sonification reaped positive results: *"There was essentially an increase (improvement) between how they performed without sonification and how they performed with sonification"*. That is why the investigation and design process is essential for an effective sonification design, as clearly stated by SB: *"Design and design research is a real critical enabler in this field."*

Clearly identifying the scope of a sonification project is an important factor and DV emphasised this in his sonification design. DV was convinced that by using a Task Analysis approach a sonification could be much more effective. To explore this, he designed two sonifications using a Task analysis technique known as GOMS and two were data-based designed. DV describes how: *"My task based sonifications performed quite a bit better than my non-task or data based sonifications"*. This matched that claim that: *"Designing for a specific task can help listeners perform the task with the sonification"*.

One other essential part of the investigation process is reference to the literature. To obtain knowledge a designer has to learn about the subject by following currently existing models or prototypes that have been designed and tested. The interviews presented a number of arguments that reflected a weakness in this aspect of the sonification design process.

Limitations of Sonification Literature

There was shared concern about the lack of descriptions of sonification design processes in the literature of the field. DV described this by stating that: *"What I found so* *frustrating in sonification literature was, there was hardly ever any explanation of why a specific mapping or why a specific frequency range was chosen"*. SB also expresses certain limitations with the literature on the subject: *"A lot of their assumptions (the designers) are built into their decision making and they are the only ones that understand the rationale. And even when you read their papers with very little explanation about stuff, it's still assumptions that have never been tested"*. PV describes: *"If you look at the literature, a lot of it is still one off, bespoke, sonification systems with studies that are narrow in scope, so the results are not that generalizable"*. This point was further emphasized by BW *"It's either part of a class or a master's thesis and they pick it up over the course of a semester. They [students] are still obviously novices and even if they do very well, the chances are they haven't learned enough"*.

There was also the mention of a lack of vocabulary in sonification design. Mark Ballora (MB) clearly states that sonification: *"Just doesn't have the established vocabulary that visualisation does"*. He also refers to Carla Scaletti's comments in her ICAD 2017 keynote that also emphasizes this point: *"So she was talking about, that it doesn't have an established vocabulary (Sonification)."* Other fields of study such as Human Factors and Ergonomics design and Visualisation have an established vocabulary. DV argues: *"If there is a language of design that is familiar to people outside our community, then suddenly there is a less of a gap to cross between our work and their work (Human Factors and Ergonomics design)."*

Sound Design & Parameter Mapping

MB states that: *"Natural sounds, sounds that mimic nature, sounds that are completely abstract, it's all project specific"*. Sometimes the obvious association to a sound is required in the sound design. SB describes it as: - *"If people want to hear rainfall then they should hear rainfall. If the task is to hear the amount of rain then you should hear that as the amount of rain, not the pitch of a Cello."* MB also used mappings that mimicked the sound of the wind in a sonification that represented Meteorological storm data: *"Sometimes the storms get more intense but they don't get more symmetrical and she can't see that so readily from the videos but she could certainly hear it from the sonifications"*. The use of familiar sounds was also voiced by Dyer (JD): *"Real world objects make sounds in certain ways and those can be a good starting point for design"*. The familiarity of sound often acts as an anchor and this is taken into consideration when designing a sound and mapping it. Ferguson (JF) describes this anchoring as: *"try to tap into that, when people hear these things, they can begin to make analogies about it"*. PV also describes how easily people make the connection with more natural sounding designs: *"When you do the sound design you have to be aware that any sound you create can have an association with the real world, in fact, people are possibly going to reach for it."*

Simple Mappings

Simple sonification design is at times the necessary way to effectively map a dataset. The neural mappings described by LG were systematically organised to allow simple parameter mappings to effectively represent the data and achieve highly positive results: *"You can get lost with a lot of information. That information has to be very simple, straightforward"*. The simple sonic representation employed by LG still revolved around a multi-layered sound design, not complex, but consisting of more elements to enhance the semantic representation of the data. DV describes how his sonification consisted of simple sound design of more complex representations than simple one on one mapping: *"We can ascribe meaning to a sound, but we're not going to ascribe meaning to a sound based on one dimension of sound. Not just based on pitch, it's a big combination of all these different things"*. JD had also expressed the effectiveness of simple sonification mappings: *"It was informative just because of its ease of use"*.

Psychoacoustic Elements

The psychoacoustic elements of sound design play an integral part in parameter mapping. There are elements that could be more effective than others (BW): *"if you are using something like frequency then you have the built-in possibility of these logarithmic relationships"* and (BW): *"But amplitude is somewhat unreliable. People are quite poor at discerning levels of amplitude"*. Elements of Rhythmic representation are an easy association, and also have a temporal effect that are difficult to represent visually. JD describes how Rhythmical elements helped in coordinating movement of users in motion gesture sonification: *"Trajectories of movement when you're trying to time yourself quite precisely, tend to be more accurate if you go for this strategy, ballistic (Sound)"*.

Aesthetics

Aesthetics in Sound Design are a key element in the effectiveness of a sonification and MB clearly states that: *"I think the aesthetics are critical to it."* BW echoes this:

"Aesthetics absolutely plays a crucial role in any kind of technology. Sound is absolutely included in that. Something has to sound good, and also has to sound right". Sonifications can easily become unwanted sounds (KN): *"Things can sound like noise"*. It is this element of noise that has often led people to switch sonifications off (JF): *"What I've discussed with most people is that the problem with sonification is that most people turn them off"*. This doesn't necessarily mean that the sonifications sound unpleasant. Many of the researchers insisted that aesthetics does not mean that the sound designs have to necessarily sound pleasing. PV sees this as a problematic simplification *"a lot of sonification researchers view aesthetics simply though the lens of 'Does it sound nice?'"*. SB agrees with this: *"I don't think of aesthetics in terms of pleasantness or decoration. I'm much more vested in the idea of like I think that if it is efficient it will be aesthetic"*.

About Positive results of Sonification testing

The sonification designs discussed in these interviews were not all tested scientifically. Those that were reaped positive results. Those that weren't tested had some form of positive feedback. It can be agreed that sonification is most effective in representing temporal information. There are cases when sonification can outperform visualisation and this is usually when the user is unable to refer to a screen and needs some form of data feed in order to carry out a task. This is apparent with forms of motion guided systems. The literature reflects positive testing results but still seems to remain within the realm of isolated tests and this presents a false positive about the success rate of sonification and it's use beyond testing.

The discussion concerning Sonification testing and results concluded that many were done in isolation. Positive outcomes can give a false positive as to the success of sonification. MB criticises this approach and its limited perception of the bigger picture: *"A lot of the papers that you read it's like kind of bleep bloopy and they did a pilot test with 20 people and they got this out of it so by golly this is worthy of further research."* SB describes how the testing should be about evaluating current methods, as there is no proof that these mappings actually work, rather than constantly trying to prove that sonification works: *"the most common technique in sonification, it's still pitch mapping and it's hardly ever been evaluated"*. SB goes on to criticise current testing techniques: *"There's a big difference between hypothesis testing and knowledge building"*. PV describes a more daunting scenario: *"I don't think we've learnt very much about* *sonification design."* This could be due to a lack of understanding from the designer's part and PV goes on to say that: *"I think that we have a lot of sonifications that don't really do what they're doing with an understanding of the wider perceptual issues."*

It Works

There are those that have a more positive outlook towards where sonification is at the moment and where it is heading. BW strongly believes that sonification is being utilised:

> *"Scientific sonification is being used more. It's being used in oil and gas exploration and circumstances where there's a lot of data. It's being used in financial services, investment context, engineering and space exploration. Most of these situations where even the best visual displays are still not doing it. Multimodal, time varying complex patterns, all the kinds of situations where we point, to sonification and say that it's likely to succeed."*

One of the reasons why there is a lack of reporting of the more widespread use of sonification is that (BW): *"We don't hear about all of those contexts. Some of those things, especially the financial investing and oil discovery, the big companies are not going to advertise the fact that they are using these specialised tools."* Philart Jeon was reluctant to measure the success of sonification because it depends on the context. The use of sonification in industry is often overlooked and as an example PJ describes the incident where he purchased a washing machine and found that the sound design was the same one he had created 10 years earlier: *"When the washing machine cycled down the pitch generated a melody that I composed….ok seems successful. It's like 10 years later they still use that sound."*. PJ did go on to say that in academia, the success of sonification is different: *"But it is really hard to see that type of consistency in academic research."*. LG sees a strong potential in the use of sonification, especially in instances where the user cannot look at a visual display due to the task that they are carrying out. This is extremely prevalent in the medical realm: *"What I have always been thinking is that in the medical domain, they actually always rely on the visual information and they should actually rely more on the auditory feedback as well."*

Not yet, Maybe later

There are those that are not seeing any current progress but strongly believe it is a potential tool and that it will come into acceptance in the future. This more positive view towards the direction of sonification is based on the fact that most sonification designers believe that people in general are not really taught how to listen. KN, in describing how the visual component in humans is more dominant states the following: *"This is part of the problem in terms of making sonification more broadly used, is that there is just a stronger visual preference for many people and their hearing senses are under-utilised, under-trained."* PV also identifies this issue: - *"What we should be aspiring to is much greater skill in our listening."* MB strongly believes that the sophistication of the human hearing faculty automatically leans towards sonification becoming an accepted data analysis tool: *"That's the thing about sound. That's why I think it is inevitable that this becomes a part of our environment because the human animal is so responsive to sound."*

3.4 Discussion

The interviews give a clear picture of what sonification is, its potential when designed correctly and that despite these efficiencies, sonification has still not become a more accepted tool for scientific data representation and analysis procedures. There are those who have criticised sonification literature and have pointed to a lack of certain details that could help convey vital knowledge to any that would be interested in using the tool. Brazil (2010) had identified how daunting it could be for a person who is trying to learn about sonification design from the literature. Verona had expressed similar frustration in his interview comments and had also expressed a further vexation towards lack of clarity in most publications. His comments clearly stated that: *"Maybe because of that people just weren't designing for the task or maybe if they were, they weren't explaining how they did that in their papers"*. Frauenberger (2009) had also found these 'holes' in sonification literature where the descriptions of auditory display designs were lacking.

One of the main issues that have been highlighted is that a lot of sonification designs are contained projects, often dissertations or isolated studies. Many of these studies involve people who are new to the field, who have to learn as much as they can within a limited time frame and to create an effective sonification. This probably means that a lot of sonification designs lack the necessary knowledge, skillset or the lifespan to exist beyond the confines of that project. Walker had described how this was a common feature in all types of design scenarios: *"The vast majority of software, just in general, are built and go nowhere. I think that we also see the same kind of thing with sonifications."*

This lack of knowledge from the designer's angle could be one of the reasons why many sonifications are redundant. It is like the metaphor of '*the blind leading the blind*'. And it could also be the reason why the field has not yet established a common vocabulary. This is where sonification differs from Human Computer Interactive fields and Visualisation, which both have established vocabularies. Kramer et al. (1997) had outlined this problem and Barrass (1997) and had suggested that designers had to acquire a deeper understanding of the context of a sonification design in relation to users' behaviour. As Vickers commented: - *"I think our knowledge of sonification design and theory is still fairly primitive."* The emphasis for appropriate data gathering has been echoed in many publications (Hermann & Hunt, 2011; Frauenberger, 2009; Walker & Nees, 2011; Verona & Peres, 2017; Barrass, 1997; Anderson, 2005). Data gathering could differ from interviewing users. Gionfrida et al. (2016) had done a data gathering process based on literature findings and had designed an interface based on the knowledge acquired from this exercise.

3.5 Conclusion

The results give an indication of how each step of the design process is currently being practiced by sonification designers. There is definitely a general consensus with regards to the factors that contribute towards an effective sonification design. It is important to keep in mind that sonification design is a complex process that can be tackled from various angles. The main factors that a designer must take into consideration when designing a sonification are summarised in table 3.7.

Table 3.7: Design Guidelines Extracted from the Interviews

	Guidelines	**Comments**
1	Requirements Gathering	In-depth investigation of the dataset
2	Design suits the purpose & userbase	Sonification designed for specific purpose based on results from requirements gathering
3	Communication between designer & user	To learn each other's jargon and technical details
4	Iteration	Iterations are made based on feedback from user testing
5	Evaluation	User tests the model and provides feedback for changes to be made

The first guideline suggests that effective sonification design requires in-depth investigation of the dataset. A well-designed requirement gathering exercise should be conducted with the user to find out about the dataset, how the user actually perceives that data and how the sonification can be designed together with the user to suit the task that the sonification is likely to perform. This opens an initial channel of communication between the designer and the user that evolves along with the design process. More information could be needed after the initial requirements gathering to strengthen understanding of certain concepts.

The second guideline suggests that it is important that the designer does not allow their preconceived believes to interfere with the design of the sonification. The sonification is being designed to suit a specific purpose for a specific user base. It is not being designed to suit the purposes of the designer. The sonification design is usually determined from the results that have been obtained from the requirements gathering exercise which acts as the pediment for the design. At this stage it is important for the data analysis system to extract as much information as possible from the data gathered in the initial stage so that the foundations of the design can be properly developed.

The third guideline suggests that communication between the designer and the user is essential and should be kept open during the design stage. This allows both the designer and the user to learn each other's vocabulary which is then integrated into the design stage. It is often the case that the designer and user do not understand each other's technical language, and this hinders the users' understanding of the interface or certain aspects of its workings. In the case of sonification design it is often the case that these interfaces are created for people who are not professed in any form of sound or music studies and do not understand jargon such as pitch, timbre or amplitude. This is why the designer must be clear in communicating these concepts and how they relate to the mappings and convey the data.

The fourth guideline suggests that an iterative process should be practised so that the designer and the user can fine tune the model to better represent the data in a comprehensible manner to the user and also allow the model to take into consideration sustainability for future use. A number of iterations can help to determine the choice of sonification technique, parameter mapping and sound design. Iterations help both the user and the designer to obtain a clearer understanding of the interface design and its purpose. Each iteration fine tunes the model and irons out any defects that hinder the user experience.

The fifth guideline suggests that evaluation is a necessary part of the design process. The evaluation will determine the validity of the sonification and whether it can accurately represent the data in a way that is comprehensible to the user. The testing of the sonification has to be well prepared and should reflect the overall scope of the sonification design. One-time testing is ineffective and gives false positives. The testing process should be considered as further iteration of the design procedure. The evaluation will determine whether the sonification can successfully perform the task that it was intendedly designed for. It determines any further changes that need to be made to make the sonification as rigorous as possible and giving it the necessary sustainability making it future proof.

There seems to be a commonly practiced design criteria that has been highlighted in these interviews which could possibly contribute towards an effective sonification design. As stated by various practitioners, even by following these steps, there is no guarantee that the sonification will effectively represent the data and fulfil its designated task. To rate how successful sonification is in general, there is a divided outlook with regards to this, but there is an overall consensus that much more work has to be done to improve sonification design and implementation. Even though opinions are divided about the current status of sonification's present implementation in scientific research, there is a positive outlook and common belief that sonification will become an accepted and widely used means of data representation. The following chapter will put these design criteria into practice in one of three sonification design studies.

Chapter 4: Sonification of an Exoplanetary Atmosphere

This study investigated the design and evaluation of a sonification of atmospheric data from an exoplanet situated in a habitable zone. The process used for capturing atmospheric data from Exoplanets was described in Section 2.1 on page 17. The interface was designed for an astronomer who investigates these phenomena. User centred design methods were applied to create a meaningful sonification that could accurately represent the data and divulge unnoticed particulars when using visual means for data analysis. There were three distinct stages of development: A requirements gathering exercise inquiring about the work of the astronomer and the dataset. A design and development stage based on the findings of the requirements gathering. A system based on Grounded theory was used to develop premises that are grounded in the data and synthesised through qualitative coding. The third stage was to evaluate the sonification. The sonification design allowed the astronomer to instantaneously notice an important water feature, overlooked on a visual graph, where the noise signal was overlapping the source signal. The results suggest that multiple parameter mappings provide richer auditory stimuli that are more semantical to the user. The use of spatial mapping and movement allows for easier detection of sudden changes in the dataset and enables clearer distinctions between multiple sound sources.

4.1 Rationale

This study investigated effective methods of sonifying Exosolar Planetary data and tested design principles discovered from the literature review and the previous study conducted in chapter 3. The dataset represents water vapour in the atmosphere of an Exoplanet situated in the habitable zone of an Exosolar system. It consists of a source signal, water vapour and a noise signal which contains unwanted artefacts from dust particles, light from other stars and gases that distort the signal. The astronomer who participated in this study was interested in finding out whether sonification would enable him to hear water features that were probably masked in the visualised version of the dataset. The use of sonification could be effective when listening to a dataset that consists of two signal channels. When a person listens to the sound of the surrounding environment it is often multifarious. Humans have a great ability to localise one particular sound of interest amidst the rich, surrounding sound field (Oxenham, 2018). The ability to deconstruct complex acoustic waves to identify specific perceptual objects is known as Auditory Scene Analysis (Bregman, 1993; Alain, 2007). This is especially noticeable in speech, where a listener is able to switch between two different streams of dialogue that are separated one to the left channel and one to the right channel of a pair of headphones (Cherry, 1953). Such abilities could allow a listener to hear distinct details in multiple channels of data and to hear separation. This is extremely advantageous in being able to hear details that were lost in a two-dimensional visualisation where overlaps in multi channels have masked particular aspects of the data.

A listener can perceive various quantities and qualities such as sense of time, space and distinct subject-object relationships (Blauert, 1997). Through hearing humans are extremely capable of identifying events that carry semantic information about mass, material, interaction and force (Gaver, 1993). The quantifiable properties of the water vapour could give a sense of measurement, dimensionality and present a clearer understanding to the listener. An individual sound carries strong, associative ties (Hergarty, 2012) which convey mental images to the listener (Migham & Forrest, 1995), and though these are subjective there are also common archetypal associations that convey similar meaning to the many that listen to it (Chion, 1994).

This study aimed to find out whether more direct representations of the data could accelerate the user's association and understanding of its context. In the interviews conducted in chapter 3 of this research, Barrass had commented that immediate associations to a sound would greatly enhance the users' ability to discern datasets. He had stated that if the data is about rain then make it sound like rain and not like a Cello. Users have criticised the sound designs of sonifications stating that they find it hard to associate the sound with the data. Leplaitre and McGregor (2004) had studied the function and aesthetic characteristics of an auditory interface and found that these 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 his or her performance in analysing the data and this could even make the sonification redundant.

Scalletti (1994) emphasised a direct correlation between a dataset and how its meaning must be accurately represented in sonic terms. The sonification has to facilitate interpretation of the data in a communicable manner that is understood by the user (Barrass and Kramer et al. 1999). This means that a useable sonification is designed upon a dualistic underpinning. One component is the source, which is the data. The second element is the target, the listeners or users. This suggests that sonification design is built from the ground up in accordance with the task that it is meant to perform (Verona & Peres, 2017). An effective sonification design easily allows the user to retrieve the necessary information perceptually, physiologically, cognitively and by memory (Worrall 2019).

The sonification design of the exoplanetary atmosphere was based on a user centred approach. Many of the practitioners that were interviewed in chapter 3 all described that they had a continuous back and forth communication between themselves and the users. Barrass (1997) defines sonification as a mapping of information into acoustic, perceptual relations for information processing. This suggests that the designer works closely with the user to obtain a clear understanding of the necessary requirements and needs (Dix et al. 2009). Users and Designers have different perspectives and interests, and it is relevant to obtain both viewpoints to make the design more acceptable for the end-user (Foster and Franz, 1999). In the interview conducted with Barrass, as detailed in chapter 3, he had commented that many designers put their own assumptions into the decision making and that makes them the only ones to understand the rationale of the design.

One of the guidelines that came out of chapter 3 emphasised the importance of a thorough requirements gathering exercise. Good requirements gathering collects information about functionality, goals, constraints and sustainable design practices that influence its future (Silhavy et al. 2011). Systems like Grounded theory could be effective for data analysis since the emphasis is on the data and developing a design theory upon it and this helps to overcome any designer bias (Tie et al. 2019).

Referring back to Benyon's (2019) description from Chapter 2 of the user centred design approach the steps that need to be taken is to start by understanding the people that the product is being designed for. This is achieved by working with the user. The next step is about knowing the pros and cons of the technology. This is followed by the ideation stage where the designer has to find solutions for the technology based on the requirements of the users. Prototypes of the design are created, evaluated and new iterations are made based on user feedback. This is done until all issues with the product have been resolved.

The sonification was developed by using a Co-Design Iterative Prototype approach with the astronomer. Three iterations of the prototypes were sent to him as downloadable links by email and revisions and adjustments were made as verbal and written feedback (Sanders and Stappers, 2014). Nielsen (1993) described how even the best usability experts are unable to design a perfect user interface on the first attempt. This was also stated by Nesbitt in Chapter 3. Designers develop a usability engineering life cycle where each iteration has to be evaluated by the user. Once the sonification design has been completed it will be evaluated by the astronomer. Evaluation identifies any shortcomings in the design and continuously improves upon it from the feedback from the user. The process confirms the users' requirements, assesses the suitability of the system in accordance with the users' needs and gives an indication of future use of the product (Stone et al. 2005).

This research studies the potential use of spatial mapping in its relation to other parameter mappings and to object and event representation. In the context of this study spatial separation between to the two signals could make distinction between them clearer. There are also quantifiable measurements in the source data related to size, where object dimensionality suggests the occupation of space by that object. Sound and auditory events occur at particular times, places and are composed of various attributes. This alludes to the spatial properties of hearing which cannot be non-spatial (Blauert, 1997). It has been noticed that spatial parameter mapping in sonification design is often not potentially utilised in ways to make a sound object or event more realistic to a user.

To summarise the objectives of this study, it is believed that sonification can help unmask unnoticed aspects of water vapour in the astronomers' dataset. In a 2D visualised version of the dataset the noise signal overlapped the source signal. In a similar study conducted by Song et al. (2007) spatial separation was used between two concurrent audio streams of auditory graphs. Twenty pairs of graphs were sonified but no information regarding the data in the graphs was specified, but the sonifications were direct translations of visual graphs. Pitch was used to distinguish between one graph and another where one was located within the range between 92 to 587 Hz and the other graph ranged from 830 to 1567 Hz. The results suggested that spatial separation between the two signals improved listeners' ability to distinguish between them.
This study aimed to make the sound of the two signals distinct from each other by using associations that the astronomer is familiar with in relation to each of them. It was

believed that this would help to form the sound of each signal in more quantifiable dimensions making them additionally tangible and accessible to the user. To achieve a clearer understanding of the astronomer's association to these elements of the data, user design principles were implemented. Requirements gathering and a coding system inspired by grounded theory were used to base the foundations of the design upon the data and the user's requirements. An iterative approach helped to fine tune the sonification and improve task fulfilment capabilities. Evaluation was used to assess the efficacy of the sonification and identify any changes that would need to be made to improve the model. The final testing determined whether the sonification was able to represent this aspect of Exosolar astronomy adequately and whether the design practices chosen for this study were appropriate.

4.2 Method – Requirements Gathering

The requirements gathering exercise was conducted as a semi-structured skype interview with an astronomer who will be referred to as WV throughout the rest of the report. The interview lasted about one hour. Its purpose was to learn about WV's work, the data he works with and how it could be sonified. It was also important to understand how sonification could help WV to identify aspects of the data that were not evident in current data analysis practice.

Participant

WV is a male in his forties who has been working as a professional astronomer for over 20 years. He was recruited to participate in this study after having replied to an email that was sent to 109 astronomers who work in the field of Exosolar Planetary research. This list was compiled by searching for astronomers who work in this field on Google, reading through their papers and contacting them personally by email. The initial correspondence gave a brief description of the PhD research and seeing if they would be interested in participating in a design study to create a sonification based on the data that they worked with. Out of all the astronomers who were contacted only 11 of them had shown an interest in discussing this research and finally there were just 3 astronomers who had agreed to participate in a sonification design study. WV was one of these 3 candidates.

WV's field of expertise is studying Exoplanetary Atmospheres and climates. He considers his hearing and eyesight for his age to be normal and has no experience working in professional audio or any musical training. Axon et al. (2019) found that participants with no musical training were still able to use a sonification without difficulty. 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 by separating the signal and the noise onto different outputs. The separation would unmask any properties that were not previously accessible due to the overlapping noise.

Materials

A semi-structured interview was conducted on Skype and recorded using a Zoom H2N portable audio recorder. It was based around 22 main questions that were formulated by referring to the data found on the NASA Exoplanet Archive (NASA, 2020b) and the Extrasolar Planet Encyclopaedia (Exoplanet.eu, 2020a). Other questions were asked when elaboration was required. A participant information sheet (see Appendix A) was presented to WV providing details about the project and his rights as a voluntary participant. An informed consent form was signed by WV to confirm that he agreed to the terms of participation.

Design

The interview was designed to cover three main areas of investigation. The first stage was designed to obtain a clear understanding of the dataset. The second stage investigated parameter mappings that could be implemented to represent the data accurately and comprehensibly. The third stage gathered information about the sound design and the necessary tools that would be needed for the sonification interface design. A system inspired by Grounded theory was used to analyse the data. The qualitative data extracted from this process is coded, based on the data collected and not on predetermined conceptualisations, thus creating a theoretical framework built upon these findings (De Sousa et al. 2019). Table 4.1 shows the type of questions that were asked during the interview.

Table 4.1: Summary of questions for requirements gathering

Areas of investigation	**Questions**
Data	What does the data represent?
	Temporal aspects
	Periodicity
	Spatial representation
	Measurements
	Relationship between different columns of dataset
	What more can be discovered with the sonification?
Parameter mappings	Scaling the data
	Sonic descriptors of that data
	Sonic associations to the data
	What parameter mappings to use?
Sound design	Sound design of the sonification
	Sound design of the source signal
	Sound design of the noise signal
Interface design	Design of the playback device
	Temporal control of playback
	Ability to loop the sonification playback
	Type of sound system used for playback

Procedure

The interview lasted approximately one hour, and the questions evolved to adapt to the information that was being provided by the astronomer. Since the dataset is not temporal but spectral then the questions changed accordingly to inquire about this aspect. The results were transcribed and coded in Nvivo. The transcription acted as an initial stage of familiarisation with the data collected during the requirements gathering exercise. It allowed the researcher to systemise the information for further analysis. A three-pass system of coding based on Grounded theory was used to extract information and code the responses. This was the same system that was used to analyse the data in the study conducted in Chapter 3 and described in detail in Section 3.3 ‘Results’. It was decided to use the same system of data analysis so that the design of the interface would be developed to suit the astronomer’s requirements. A copy of the questions can be found in Appendix (A).

4.3 Results – Requirements Gathering

The requirements gathering exercise provided information about the dataset, parameter mappings that could be used to represent the data, the sound design and the interface design. The following section will give a description of what was discussed in the requirements gathering exercise.

The Dataset

WV is an astronomer who studies exoplanetary atmospheres. The planets that are observed in this manner are situated within the habitable zone of an exosolar system. The habitable zone is a hypothetical region in an exosolar system where planets orbiting within this area could possibly host life similar to that of the Earth (NASA Exoplanet Exploration, n.d.). Astronomers study the atmospheres of these planets by taking a spectral snapshot of them as they transit their parent star. This means that the data is not temporal but spectral. The various gases in the planet's atmosphere reflect different colours of the perceivable light spectrum. Different gases vibrate at different speeds and in turn effect the speed of light, therefore effecting the colour of the light that is reflected off the planet's surface. This allows astronomers to determine the type and the quantities of gases that are present in the atmosphere of a planet and to compare these to the Earth's atmosphere. This comparison allows astronomers to establish whether life similar to that on Earth is possible on the planet in question.

The colours of the different gases vary in wavelength of light which is measured in microns. The wavelength represents granular detail of a specific colour bandwidth within the spectrum and the intensity of this colour in relation to the amount of light reflected. When the light is reflected off the planet's surface it forms a corona around the planet. The variances in landscape and clouds of varying height and size reflect back different amounts of light coming from the star. These measurements of light are called *Effective Transiting Radii*. These radii are measured in kilometres. Figure 4.1 shows how the effective transiting radii vary within a wavelength of 20 microns of water vapour with the radii on the Y axis and the wavelength on the X axis. This is a graphical representation of the source signal that was sonified for this study.

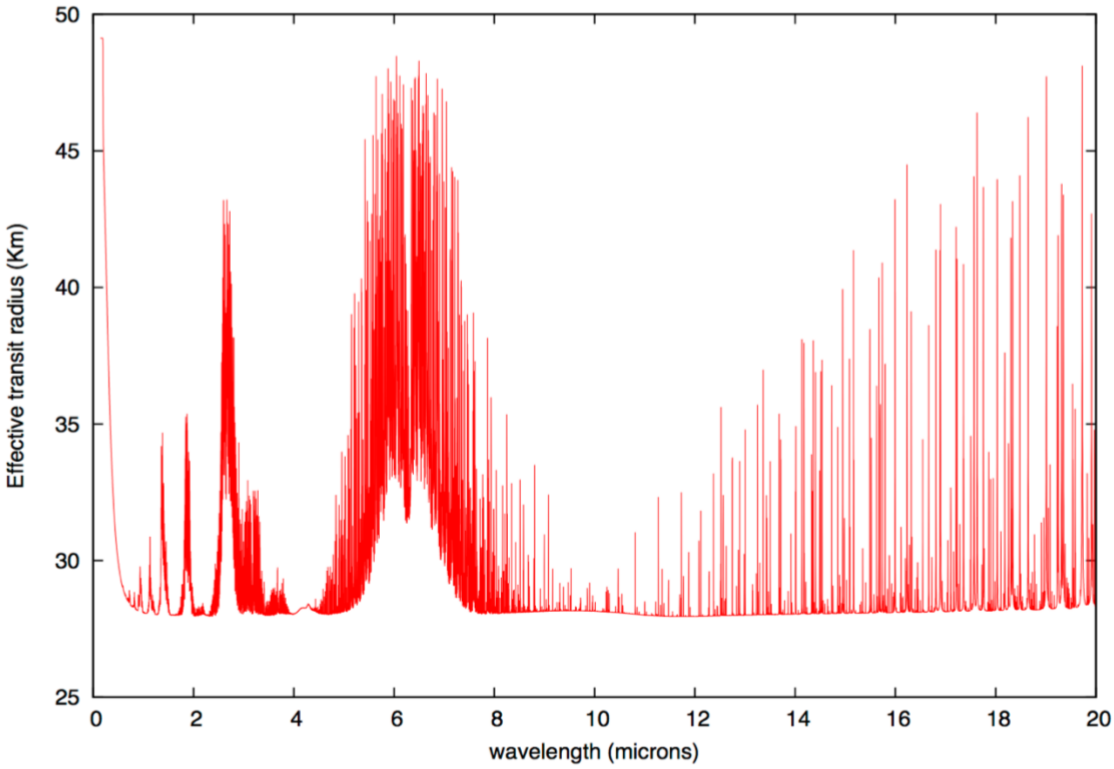

Figure 4.1: A graphical representation of the source (water vapour) signal

There are two signals, a source signal which is water vapour and a noise signal. A certain degree of noise is captured by the telescope. This noise comes from light from other stars or reflected off other celestial bodies, dust particles in space and gases. The noise is then separated from the source signal through a complex process of filtering and mathematical calculations refining the dataset.

WV wanted to sonify the effective transiting radii of both signals, to listen to them simultaneously and to see whether sonification could detect water properties that were not discerned in the visual representation due to overlaps between the source and noise signals. Emphasis had to be given to the peaks in effective transiting radii so that they could be easily distinguishable from the noise signal. These peaks represent the highest measurements of radii meaning that there could be the highest concentration of water vapour in clouds in the planet's atmosphere. Table 4.2 summarises what the dataset consists of.

Table 4.2: The Dataset

Information about the dataset	**Characteristics of the dataset**
Data type	Source signal - Water vapour data
Size of the dataset	19,855 lines of data
Measurement of the X axis	Wavelength - microns – frequency bandwidth blue – water vapour
Measurement of the Y axis	Effective transiting radii - measured in kilometres
Main features	Main interest - Peaks in effective transiting radii
Data type	Noise signal – Random noise
Temporal aspect of the model	No temporal aspect

The Sound Design of the Sonification

Pitch would be the main parameter mapping with lower radii being lower in pitch and higher radii higher in pitch. This is considered to be an effective mapping to easily be able to discern changes and is less likely to be masked by other sounds (Walker & Kramer, 2004). Walker had reemphasised this in the interviews conducted in Chapter 3 where he once again brought up the flexibility of using pitch and about how easily noticeable changes are in contrast to amplitude where changes are not so easily noticed. It is also considered to be effective at representing size, localisation and motion (Dubus & Bresin, 2013b). One other main mapping would be spatial separation between the two different signals. Since spatialisation is important to human survival, changes in physical aspects of a waveform and potential localisation are likely to engage the listener’s attention (Wightman & Kistler, 1997).

Both signals needed to be identifiable from one another. It was decided that the water vapour signal would have a water like sound that would strengthen WV’s association to it and make it distinguishable from the noise signal. The noise signal would be represented by white noise since the frequencies are equally mixed across the spectrum of human hearing (20Hz to 20KHz) (Farnell, 2010b). In the interviews conducted in Chapter 3 Ballora, Barrass, Ferguson and Dyer all spoke about the effectiveness of using sounds that are familiar to the user. Vickers had emphasised that any sound can have an association and that one has to use sounds carefully so that they clearly communicate the data to the user. The strength of familiarisation of sound is supported in literature by Cycowicz & Friedman (1998), Vickers (2013b) and Kirmse et al. (2009) who also pointed out that, if a sound is recognisable then a visual representation of the source is not needed.

The Interface Design

The interface design would have basic functions that would allow WV to explore the dataset with ease. It would need the ability to load two text files of source and noise that playback simultaneously. The user would be able to manipulate the playback speed and to select segments in the data to allow further scrutiny of particular points of interest in more detail. It would need the ability to repeat playback so that certain points can be heard in more detail. A graphical interface would be required allowing the user to visualise the dataset. This would be useful reference to compare the sonification to the visual graph and to keep track of the start and ending points of the playback when on loop. The interface would have to be designed to be used with headphones allowing WV to run it off his laptop. Numerical references of effective transiting radii and wavelength information would be useful as reference points and allowing the user to set a range for a specific segment of playback.

4.4 Sonification Design

Parameter mapping was the technique chosen to sonify the data since it is considered suitable for representing the multidimensional aspects of sound (Grond & Berger, 2011). This gave the necessary flexibility to create an informative sonification through the use of multiple psychoacoustic parameters that were required in order to create a water like sound for the source signal. Changes in pitch, timbre and amplitude would enhance the spatial movement of the source signal to sound more distinct (Blauert, 1969; Schneider, 2018b).

Table 4.3 provides details about the three-pass coding system that was inspired by Grounded Theory as described by Mills and Birks (2014). This system was used in Chapter 3 where the codes from that study were formulated using this technique. This three-pass system was found to be effective for recognising patterns and behaviours in the responses that could then be formulated into a theory (Charmaz, 2006; 2012). It was decided to use the same system in this study so that the design theory for the sonification would be 'grounded' on the data collected from the astronomer. The first initial pass extracted the general information that would be needed in order to design the sonification. The second, intermediate pass extracted further detail to form classifications and relationships between the data and the design process. The third, advanced pass provided the necessary design theory that would be used in the development of the sonification. This process also allowed recognition of further elaboration that would be required to fine tune the sonification design.

Table 4.3: Grounded Theory type codes formed from the requirements gathering

First Initial Pass	Second Intermediate Pass	Third Advanced pass
Atmosphere Chemicals Colour of light Water Vapour	Signal	Signal has to be distinct from the noise and sound like the data probably having water like features
Noise Masking	Noise	Noise has to sound like noise
Effective transiting radii Spectral not temporal Light reflected from planet's surface Kilometres Wavelength Microns Measurement	Data	Effective transiting radii mapped to pitch to allow more detailed distinction between them
Looking for hidden features masked by noise Distinction between radii Pitch Separation between signal & noise Spatial distinction	Purpose	Can sonification can unmask certain water vapour features hidden by the noise on a 2D graph?
Output Laptop	Technology	Accessible to astronomers to use on a laptop with no need for extra equipment
Data recognisable in the sonification Familiarity	Aesthetics	Water like features designed using multiple parameter mappings

The guidelines that had evolved from the interviews in chapter 3 suggest that communication with the user is one of the key factors to designing a sonification that can effectively portray the data. The idea of iteration was emphasised by most of the interviewees so that the sonification can develop and become more refined to suit the users' purposes. The sonification design for this model was built using an iterative design approach based on a method of prototyping where the sonification would develop in stages. The requirements gathering exercise provided the necessary basis for the sonification design and these were refined according to feedback that was given on each iteration. Versions of the sonification were sent to WV via email and he would reply by email, and if further clarification was needed then this was done via a Skype call. Table 4.4 shows how the iterative process worked in this design exercise.

Table 4.4: Three Stage Iterative Design Process

#	Feedback from WV	Changes made
1	Sounded brittle, scale too narrow, range not high enough and not representing peaks properly	Change the synthesiser or oscillators not as brittle sounding – Increase the range of the scale – Does not sound like water, more modulation needed in timbre and resonance
2	Peaks need to be more enhanced and Noise signal needs to indicate differences between low and high intensity. Graphical representation needs to indicate wavelength and microns in relation to sonification	Addition of SMARC effect on source signal peaks – Noise signal increase timbre and sharpness with higher noise intensity – Interface needed a graphical representation
3	Three different versions of the source signal dry, average and wet reverb – WV chose average reverb setting – cross panning between signal fine – more detail to indicate sonification movement on graphical interface	Average reverb setting version chosen. WV satisfied with sound design; Graphical interface needs an indicator for reference of sonification to microns

Method of Synthesis

The sound design of this sonification was built using subtractive synthesis techniques. This method of selective synthesis uses resonant filters to boost or cut unnecessary frequencies (Farnell, 2010c). Resonance is used to either excite or generate a raw signal or to vary acoustic properties of a broad spectra (Miranda, 2002).

Subtractive synthesis is effective for eliminating noise, keeping the source signal relatively clean and making it stand out against the white noise signal. This method of synthesis would allow a wide degree of flexibility to mould the sound design and at the same time avoid any noise or distortion that hinder the users’ perception of the data (Grond & Berger, 2011). Additive synthesis for example could have possibly created certain distortions that would have made distinction between the two signals harder, whereas subtractive synthesis allows better control of unwanted harmonics to the signal. This would ensure more differentiation between the source signal and the noise signal which was required for WV to be able to analyse the source signal effectively.

Subtractive synthesis depends on noise generation which creates large numbers of random particulars in a broad bandwidth. This noise can be eliminated with pulse width generation that creates 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, and this creates more energy for high frequency particulars (Miranda, 2002). This technique was considered to be most suitable to give more emphasis to the peaks in the dataset since it sharpens, resonates and emphasizes higher frequencies.

The first iteration was unpleasant to listen to according to WV. He found that the sound was brittle and thin. The oscillators were from Cycling 74 Max and it was decided to use an OB-XD VST synth plug (discodsp, 2021) that had more complex harmonic sounding oscillators that WV preferred the sound of. He felt that the sound was not so harsh, more rounded and broader in definition. More emphasis was also added to changes in the cut off frequency and resonance to make the peaks sharper and more defined. In the second iteration WV had just commented that he wanted to make the higher peaks sound more dramatic so that they could easily be distinguished from the lower peaks and would stand out more against the noise signal.

Scale

The effective transiting radii was mapped to pitch that would vary within the range of 50Hz to 9KHz. This range would allow consistency in reproduction between different datasets. Lower pitches would represent lower radii and higher pitches, higher radii. This would allow the peaks to be more distinct and to stand out against the noise signal. In the first iteration the scale was working between 100 and 600 Hz. This range was initially chosen since it was first expected that other chemicals apart from water vapour would be tested. The idea was to have various frequency ranges for the different chemicals, to make them distinct from one another. At a later stage WV had decided that it would be best to sonify and test the water vapour by itself and see whether the sonification provided any new insights about the dataset. The initial range that was chosen for the sonification sounded low in frequency and lacking in definition. It left little room for the peaks to properly be distinct from one another if they were similar in frequency. WV had specified that he needed to hear the differences in the higher peaks more clearly and be able to tell between the highest and the hi mid-range peaks. The scale was then adjusted to work between 50Hz to 9kHz to cover a broader spectrum to allow the peaks to be more distinct from one another. This range would also ensure that the user who was over 40 years of age would be able to hear the whole frequency spectrum in relation to the data, with the highest peaks not being too high that they cannot be heard.

This range was chosen since headphones are most effective between the range of 25Hz to 8kHz as indicated in figure 4.2. This would mean that radii peaks would be set to work to a rough maximum of 8kHz in order to be clearly distinguishable. Any changes in the higher mid tones, 3.5 to 8kHz (Sek and Moore, 1995), 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 and very high range where it is harder to hear pitch change (Moore, 2013c).

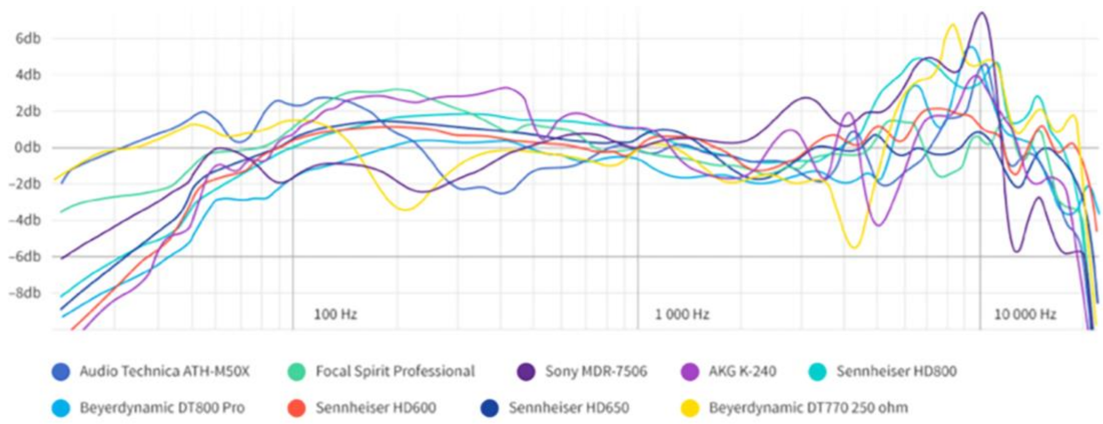

Figure 4.2: Frequency response curves for various models of headphones (Sonarworks, n.d.)

Parameter Mapping

Pitch was designated as the main mapping, but other mappings would be needed in order to replicate a water-like sound. A complex sound design would consist of multiple psychoacoustic attributes that work in relation to each other (Moore, 2012c). Considering WV's non-musical background, the source signal would mimic the sound of water droplets, a familiar sound with which he could make stronger associative ties. As Barrass had stated in the interviews conducted in Chapter 3, if the data represents rainfall and the task is to hear the amount of rain then the sonification should reflect the amount of rain and not the pitch of a cello. Ballora had also described the effectiveness of sonifying storms and mimicking the way they sound and how the user could immediately hear the asymmetry of the storm but couldn't see this so evidently when referring to the video. Familiar environmental sounds are consciously identifiable and bear significance without the need for visual reference (Kirmse et al. 2009). Ballas and Howard (1987) suggest that environmental sounds are comparable to speech and can be considered as a form of language. Speech and environmental sounds require bottom-up and top-down processing and use similar cognitive processes (Hendrickson et al. 2015). This suggests that familiar, environmental sounds could possibly communicate data more clearly to the user.

Environmental sounds are not repetitive, and their psychoacoustic properties continuously change. Pitch changes according to proximity and contact with various materials. Timbre gives an impression of proximity. Things that are closer are clearer in definition. Rhythm gives the idea of pattern and immediately alerts the listener if there is a sudden change. Sound works within a temporal-spatial domain and occurs in different positions across the spectrum between left and right ear. Movement within space is immediately detectable and there are also changes in pitch and timbre known as the doppler effect (Thoret et al. 2014) as an object moves towards or away from the listener (Gupta et al. 2012). The idea of using movement could relieve the strain of listeners fatigue due to the ever-changing position of things across the stereo field.

The first iteration was poor in representing water-like characteristics. The range of the changes in timbre to the source signal was not broad enough. The modulation that is characteristic of water droplets did not change so drastically. The higher peaks were not much brighter than the lower ones. This meant that the range had to be wider. In the second iteration the modulation was more defined and the changes in timbre were more articulated. The change in the pitch range also rectified this problem so that both pitch and timbre were clearer and more distinct as with the higher effective radii data. These changes sounded more natural due to the ever-modulating sound of the source signal. The only criticism that WV had at this stage was that he needed the higher peaks to sound more distinct than the peaks in the high mid-range.

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 (Pitteri et al.2015). It is suggested that the human cognitive system maps pitch onto a mental representation of space (Rusconi et al. 2004). The movement of the two signals counter to each other will allow clearer spatial representation and the ability to distinguish between them. This means that both signals would consist of multimappings of pitch, timbre and spatial panning changes to replicate the varying qualities of these parameters in nature in relation to sound object perception and movement. These changes would be determined by mapping them to the effective transiting radius measurements. The sonic representation of these radii would be mapped so that smaller radii would be less clear, lower in pitch and panned to the extreme of one ear. Larger radii would increase in clarity, pitch and move towards the opposite ear.

In sonification designs described in chapter 2, one of which was a navigation tool (Schito & Fabrikant, 2018) and the other was a tool for guiding blind people to avoid obstacles (Presti et al. 2019), panning was effective at guiding movement and prompting the attention of the users of these interfaces. It gave a stronger sense of orientation and the dimensionality of objects enhancing the users sense of spatial awareness. In both studies, pitch worked in unison with panning which helped to prompt the movement of the users effectively. Spatial orientation and object dimensionality was needed to give the effective transiting radii a more physical dimension allowing WV to sense the differences in size of the radii as projectiles bouncing of the planet's surface as tangible beams of light. Hence the panning movement combined with differences in pitch and timbre would help to create this illusion.

Design

The sound designs of the source signal used two mixed oscillators that consisted of both saw and pulse waves to generate rich harmonic quantity. Both oscillators were set to full amplitude. The effective transiting radius was mapped to the oscillator pitch controls of both oscillators, to the cut off frequency, the pulse width amount and the filter envelope depth. Table 4.5 shows the changes in these parameters in relation to the changes in effective transiting radii measurements. Pitch and Cut Off 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 the lower frequencies allowing them to be more discernible and resonant. The Filter Envelope Depth controls the Cut Off frequency. Lower settings have less control thus allowing the Cut Off to affect a wider bandwidth of frequencies. The higher settings control the output of the Cut Off limiting its output.

Table 4.5: Sonification design for source signal

Effective Transiting Radius Km	Pitch Hz	MIDI	Cut Off (Timbre) Hz	Pulse Width Amount Hz	Filter Envelope Depth Hz
27.9496187	50	0 – 0.1	0 - 443.77	2107.97- 3154.26	2107.97 - 3154.26
34.30688713	1276.38	0.1 – 0.3	443.77 - 1276.38	1276.37-2107.97	1276.37 - 2107.97
38.53834531	2107.97	0.3 – 0.5	1276.37 - 2107.97	443.77 - 1276.37	443.77 - 1276.37
49.1171684	4187	0.5 – 0.75	2107.97 - 3154.26	0 - 443.77	0 - 443.77

The noise signal uses a different synth engine and is generated by using a noise oscillator that increases in frequency with increases of noise measurements. The cut off frequency also increases with the noise allowing it to become more intense at larger measurements. This replicates the way that noise is more intense when the telescope captures it along with the signal. Higher noise settings increase in resonance making the signal sharper and more intense. The cut off allowed the user to choose the type of filter to use on the white noise (Low pass, High pass, Band pass, Band stop, Peak notch Low shelf, High shelf). The user could change the sound quality of the white noise signal in conjunction with the source signal that could allow clearer discernment of the source signal if more attention to detail of this article was 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. Table 4.6 gives an indication of the mappings used for the noise signal to represent changes in signal noise.

Table 4.6: Sonification design for noise signal

	Noise	White Noise Hz	Random Noise Hz	Cut Off Hz	Resonance Q
Minimum Range	0.000141	50	50	50	0
Maximum Range	29.39043	4000	4000	4000	25

Peak Enhancement

After the second iteration, WV suggested that the peaks in the data set needed to be more pronounced and that something was needed to make them more distinguishable from one another. In the study conducted by Kather et al. (2017) described in Chapter 2, the use of polyphony to sonify ECG data was effective at conveying 12 channels of the ECG signals and variances happening on each channel. Users could listen to all 12 channels simultaneously and pick out variances in any of the channels without this being overwhelming. This was probably achieved since the sonification as tuned to work within the scale of D minor where the notes work harmoniously with each other and any variances in one of the notes would be immediately detectible.

Source signal radii peaks would be enhanced by adding harmonics to the fundamental or base frequency (refer to Figure 4.3), making them more discernible against the noise signal. These harmonics would push the pitch of the source radii beyond 4187Hz up to 8000Hz. This means that the peaks would mostly be audible while varying between the range of 3500 to 8000Hz which is the span that is most discernible (Sek and Moore, 1995), (Moore, p 206, 2013).

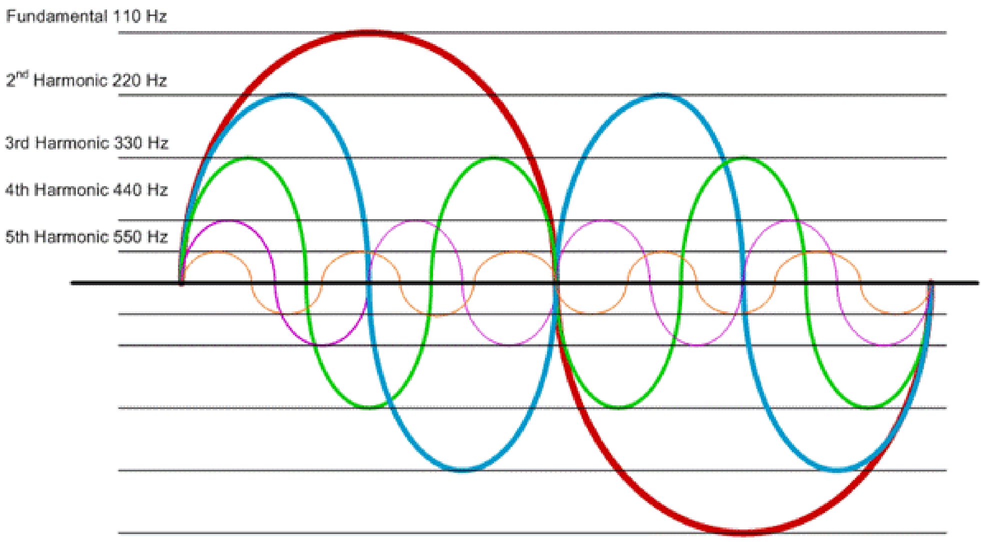

Figure 4.3: Harmonic Frequencies (Peters, 2010)

The sound design added 3rd, 5th, 7th and 8th harmonic intervals to the fundamental. Each harmonic would be introduced to the sonification at different radii measurements or pitch frequencies. Table 4.7 shows how each harmonic was introduced in accordance to the frequency rate of the fundamental. At 443.77Hz the 3rd harmonic would be added to the fundamental. At 1276.38Hz the 5th harmonic would be added to create a triad of tones, the fundamental, 3rd and 5th playing simultaneously. A total of four harmonics were added to the fundamental 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 in harmonious relationship to each other.

Table 4.7: 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

Figure 4.4 gives a visual representation of how the harmonics are introduced at the various stages according to the fundamental frequency. These are depicted in green for the 3rd, orange for the 5th, purple the 7th and light blue for the 8th. The differences in length of the radii are indicated in red displaying an increase in effective transiting radii, the equivalent frequency and added harmonic shifting from left to right ear.
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. In figure 4.4 the different ranges of panning between the two ears are indicated in black with the equivalent frequency range for each pan position.

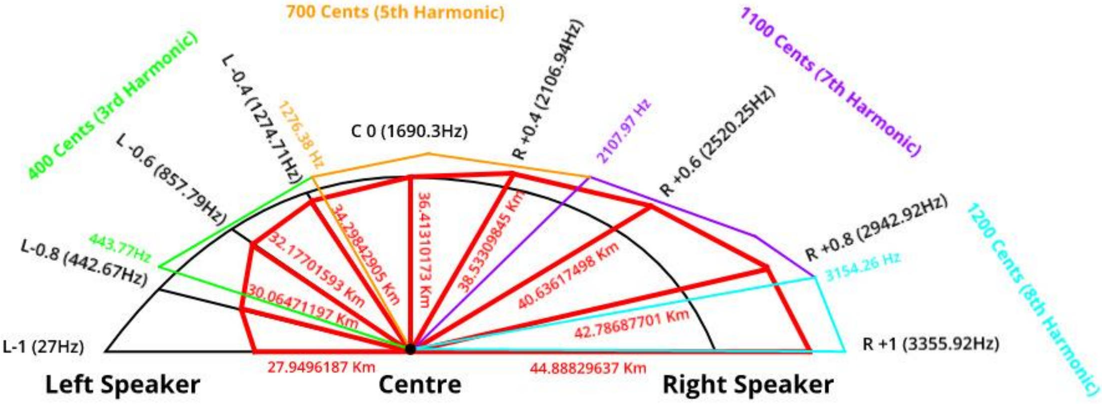

Figure 4.4: SMARC effect: Panning of source signal from left to right & added harmonics

The noise signal moved in the opposite direction from right to left ear as it became more intense. The listener would be able to hear both signals cross pan each other making them both more discernible. Table 4.8 gives an indication of this in relation to the differences in effective transiting radii. It shows the minimum and maximum frequency ranges of each shift in pan position from one ear to the other for both signals.

Table 4.8: Panning movement for Source & Noise signal Left (L), Centre (C), Right (R)

	Source Signal				Noise Signal		
Effective Transiting Radius Km	Minimum Frequency Hz	Maximum Frequency Hz	Pan Position	Noise	Minimum Frequency Hz	Maximum Frequency Hz	Pan Position
27.9496187	27	442.67	-1 (L)	0.000141	50	444.88	+1 (R)
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 (C)	11.754596	1629.78	2023.81	0 (C)
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 (R)	23.234784	3172.69	4000	-1 (L)

Static Function Settings and Reverberation

Other settings were used to determine the range of the sound modulations to work within set parameters which effected the timbre and amplitude of the signal. Table 4.9 lists these MIDI values which vary between the range of 0 to 1.

Table 4.9: Static function settings from the Synthesiser

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 cut off
Filter Envelope Decay	0.275	The break point for the filter to reduce cut off
Filter Envelope Sustain	0.27	The amount of sustained filtered signal
Filter Envelope Release	0.1	The 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	Length of time for note to go from inaudible to full audible perception
Amplitude Envelope Sustain	0.25	How long the note is heard after being triggered
Amplitude Envelope Release	0.25	How long the 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.

Reverberation

Once the sound design of both the source signal and the noise signal had been completed after the second iteration three versions of the prototype were presented to WV. One was the sonification without reverb, completely dry. The second version had an average level of reverb and the third had a full setting of reverb. WV was asked to choose the version that he preferred. He decided to choose the average reverb setting on the sonification since it smoothens the playback and didn't blur the sonification too much like the full setting of reverb had done. With the average setting he could still hear distinction between the different lines of data.

An average level of reverberation was added to the source signal as suggested by WV giving it more of a wet sound and not blurring the distinction between the separate tones of each line of wavelength data. The reverb was enough to smoothen the sound of the sonification which sounded dry, brittle and harsh to listen to. Two reverb units were used. One for each channel of output of the left and right ear. This would retain the reverb as a mono signal instead of a stereo 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. With two units connected in mono, the reverb would only be added to the signal when it is present within the field of influence of the effect and would only play on the one speaker where the signal was projecting from.

Interface Design

The interface consisted of basic functions that would allow the user to load both source and noise signal into the system and play them back simultaneously. Control of the speed of the playback and the ability to select segments of the data that could be played back on repeat function was needed. The playback speeds chosen ranged between 1 and 1000 milliseconds. The nine preset speeds were chosen in relation to the playback during. The faster speeds varied between 1, 3, 5 and 10 milliseconds, The mid speeds from 50, 100, 250, and the slow speeds from 500 to 1000. These speeds were chosen in relation to how duration of the sonification playback. This varied according to the speed at which the computer processor was able to cope with the task. The durations would vary but the higher speeds varied in playback from 2 seconds (at a speed of 1millisecond) to 3 minutes 20 seconds (At 10 milliseconds). The mid and slower speeds were to be used to slow the sonification down when selecting a particular section where the user had to listen to the playback in more detail and playback durations would be too long for a full listening. At 50 milliseconds playback could take as long as 16 minutes. A visual representation of the data was required so that WV would be able to look at the visual graph for reference.

It was during the third iteration that WV had asked for the visual interface to be improved. At first the only visual references on the interface were the small black boxes just below the control panel. WV wanted to be able to have an indicator that would scroll across this screen and demarcate the microns on the wavelength (X axis) as the sonification played back. The graphical interface was quite limited and not flexible, and these features could not be added. Instead, two screens were added below the interface were the sonification playback would be drawn out on these screens. One screen worked as a spectrograph which also had different colours to represent the various frequencies in the sonification. The second screen was an oscilloscope that would indicate the shape of the wave. The source and noise signal were represented on two sets of these two screens. These screens still did not allow the X and Y axis to be marked as wavelength and frequency and were not accurate at representing the wavelength. They took up the bottom half of the interface since they needed to be widened to be able to mark out the full length of the playback. Table 4.10 provides information about all the functions that were built into the interface. Figure 4.5 depicts the final version of the interface before the evaluation.

Table 4.10: The functionality of the sonification interface

Function	Reason for using these functions
Loading Function	Source and noise signals - separate load functions to upload the data text file into interface. Read button loads data text file into system. Open button opens text file so user can see data. Clear button clears text file from system so that another file can be uploaded.
Playback speed	Faster playback speeds allow comparing a number of datasets with each other and seeking patterns or differences between them. Slower playback speeds allow more detailed analysis. There are nine speed presets of 1, 3, 5, 10, 50, 100, 250, 500 and 1000 milliseconds and an additional box below these presets allows astronomer to input their own playback speed.
Data selection & loop function	Start and end point could be selected. Selection could be looped, and playback speed altered enabling listener to zoom in and listen to these segments in more detail. A reset button to start sonification playback again from beginning.
Mute Buttons & Volume Controls	Signal to noise ratio could be replicated to suit more realistic conditions by allowing user to alter volume levels between source and noise signal. Mute buttons included to switch off either of the signals to hear other one in isolation.
Filters and Oscillator in Noise Section	Noise section had a filter where astronomer chooses between 7 filter settings to alter sound of noise oscillator if needed to bring out source signal more clearly. Astronomer could add oscillator to noise to hear random patterns more clearly and choose the waveform of oscillator between 4 different waves
Visualisation of data	Graphic visualisation of dataset used as reference point to understand where playback had got to. Number boxes included indicating line number, wavelength and effective transiting radius. By knowing line number, the astronomer could input a start and end point in order to listen to a specific segment of dataset.

Sonification can be listened to at: https://soundcloud.com/michael-quinton_napier/sets/sonification-of-water-vapour

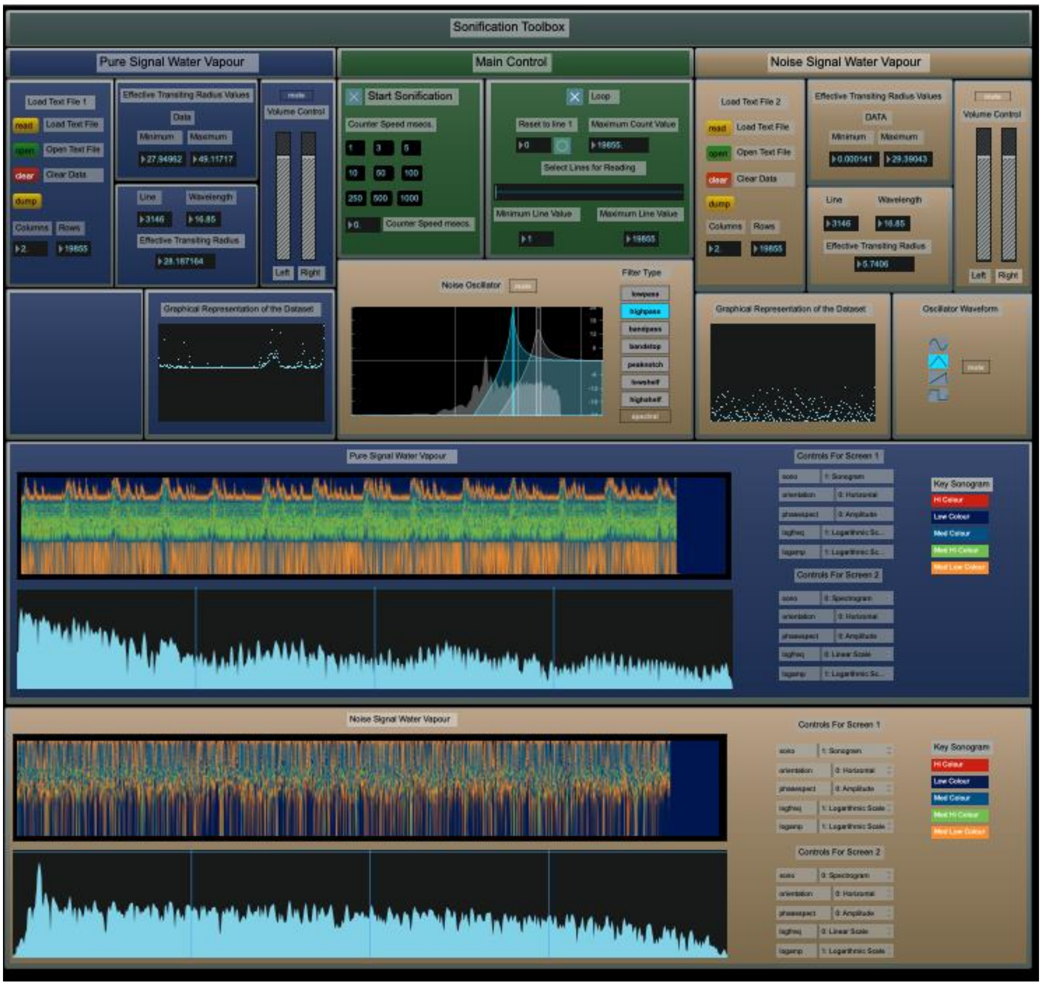

Figure 4.5: The sonification interface designed for WV showing all the functions & values of the data

4.5 Evaluation

The sonification design was completed and had to be evaluated. 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. It would also provide information about any changes that would be needed both in the case of the sound design and the usability of the interface.

Participants

The only person who would be testing the interface was WV. He was the only astronomer who participated in the design process and there were no other astronomers who were available to test the interface.

Materials

The sonification was tested on a Mac book. A QTX HA-40, four-channel headphone amplifier allowed the use of two headphone sets for simultaneous playback. Two Beyerdynamic DT770, 250 ohms, 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 (Moore, 2013g). Both interviews were recorded on a Zoom H2N portable audio recorder. Answer sheets (refer to Appendix C) and pens were provided. The interviews were conducted in WV's office, a quiet office environment with sound-proof windows. Figure 4.6 shows the setup. An informed consent form and participatory information sheet were provided describing the experiment and informing WV about voluntary participation. The interviews were recorded and transcribed.

Figure 4.6: Test material set up in WV's office

Design

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 adding to a total time of three hours. Both interviews were semi-structured allowing extra questions to be asked where necessary.

The first test consisted of two sections. The first consisted of 25 multiple choice questions based on a 5-point Likert scale running from negative scale 1 to positive scale

5. Likert scales allow more granular feedback than binary ‘yes’ and ‘no’ answers and are more effective at gauging the user’s expectations. These questions focused on acquiring feedback about the functionality of the interface, it’s effectiveness and the validity of each component. The second section of the first evaluation consisted of 12 questions about possible extra functions that could be added to the interface.

The second test inquired about the efficacy of the sound design. A total of forty four questions were asked about the comprehensibility of the sonification, it’s effectiveness in relaying the data and to see whether the sound design required any changes.

Procedure

The interview lasted roughly about 3 hours in length. The interface had been sent to WV before the testing along with instructions describing the interfaces functions. He did not have time to try the interface or read the instructions. A quick revision, or rather an explanation, about the interface and the sound design was given before starting. Since WV was familiar with the sonification design since he had been involved in the previous iterations, he could easily remember the parameter mappings once they had been explained to him. He had only heard the source and noise signal working in unison once when a recording had been sent to him of the two together but did not have the time to listen to the recording in detail.

WV signed the participatory consent form and was allowed to use the interface, explore its functionality and the sound design. During this period, he could ask questions about any of the functions if he didn’t understand them. He had asked about how to set the loop function if he needed to listen to a specific part of the data set. 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 had answered all the questions in both sessions and his responses were recorded on a portable audio recorder.

4.6 Results

The evaluation of the sonification was split into two parts, as described in the subsection entitled *Design* in section 4.5, with the first assessing the interfaces functionality and the second to appraise the sound design. This took an average of three hours. The following section describes the evaluation.

First Evaluation – The Interface

WV found the interface easy to use: *"Oh, it was easy!"* He could navigate through all the functions almost immediately: *"After the explanation, it was easy for me to follow"*. Table 4.11 shows the top ratings given by WV for the playback section marked in grey.

Table 4.11: Scores for loading and playback functions

Questions	Answer 1	Answer 2	Answer 3	Answer 4	Answer 5
Loading Function	Very poor	Poor	No opinion	Good	Very good
Playback	Difficult	Fairly difficult	Neutral	Fairly easy	Easy
Loop Function	Not useful at all	Slightly useful	Neutral	Useful	Very Useful
Playback speed ease of use	Difficult	Fairly difficult	Neutral	Fairly easy	Easy
Playback speed usefulness	Not useful at all	Slightly useful	Neutral	Useful	Very Useful
Mute buttons (Source, noise, oscillator noise)	Not useful at all	Slightly useful	Neutral	Useful	Very Useful

WV commented about the comprehensive layout of the interface and the usefulness of being able to change the playback speed:

> *"(What did you find most useful about changing the speed?) When I was hearing both noise and the source signal data together, I wanted to focus on one particular tone within the source and slowing down speed really helped me there."*

Noise signal section

The noise generation consisted of a white noise generator passing through a filter with seven different settings. These were low, high and band pass, band stop, peak notch, low and high shelf. This allowed the noise signal to be changed to allow more room for the source signal to transmit. The random noise generator consisted of a wave oscillator that allowed the user to choose between four wave settings of sine, triangle, saw and square. Both noise generators could be muted individually, and a general mute button was placed on the volume for this channel so that both could be switched off simultaneously. Figure 4.7 shows the noise signal section of the interface in yellow orange shade.

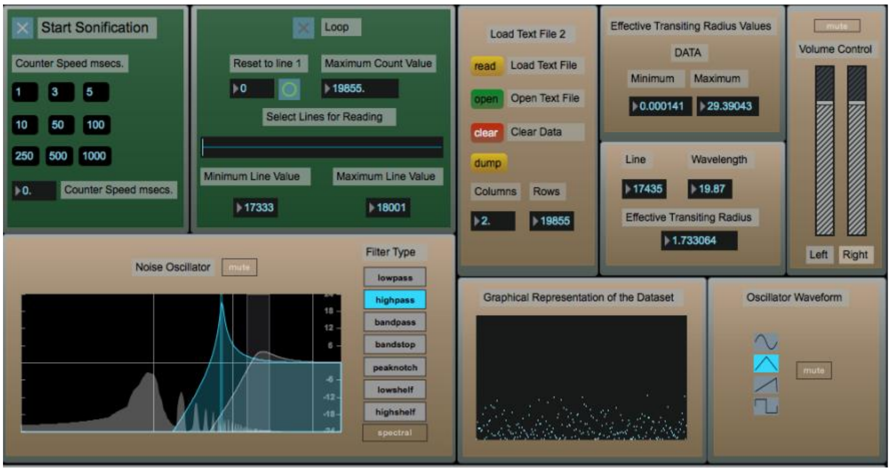

Figure 4.7: The noise signal section of the interface shown in yellow orange shade

The noise representation was deemed appropriate and highly informative, and the added random noise oscillator brought out the haphazard characteristics of noise. The white noise oscillator was the most effective especially due to the noticeable changes in timbre and loudness as the signal became more intense.

Functions that would need changing or improvement

There were a few things that would need to be changed or improved for the interface to be more effective. Table 4.11 lists these changes below. The visualisations 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 work using wavelength measurements instead of line numbers. Astronomers understand the data and are able to use the wavelength more effectively to home in on various segments in the data: *"Wavelength would be more useful for me than the line numbers because I don't know which line this feature occurs. I know which wavelength that feature occurs"*. As a final suggestion WV found that the marked 'X' for the play button was misleading and that it would be better to use the standard symbol indicated below in table 4.12.

Table 4.12: Functions that can be changed or improved

Function	Changes Suggested
Graphical interface	Display did not allow Wavelength or Effective transiting radii to be added to the X and Y axes which would have been more informative to the user. WV had suggested that a cursor that would move along the graph would be useful to pinpoint a specific artefact if it had occurred during playback.
Spectrograms and sonograms	These can be removed since they did not really serve any purpose
Cue Points	The use of Wavelength instead of line number
Play button	To use the standard play button found on other playback devices ▶

The second part of the first evaluation inquired about the need for any additional functions not currently found on the interface. Table 4.13 gives a summary of the functions that WV would be interested in adding to the interface. Most of the changes discussed were in relation to the sonification of other gases that are usually found in a planet's atmosphere which would be analysed simultaneously. Other additional functions that aided playback and gave more visual information were also suggested.

Table 4.13: Additional functions to be added to the interface after the evaluation

Function	Inclusion	Comments
VU Meter	Yes	LED type, range in decibels, ability to calculate the average (RMS) or peak of the signal
Equalisation	Yes	Noise only. To facilitate distinction between noise and source signal
Filter	Yes	Same reason as above. (Already has a filter on the noise signal)
Pan control/	Yes	Manual control over the panning of each signal
Added channels for more elements	Yes	Sonifying elements: methane, ozone, oxygen, nitrogen, carbon dioxide
Surround Sound capability	Yes	Only to be used once the other elements are added to the interface to make distinction between the multiple sources more evident
Pitch control on each signal	Yes	To make distinction between the multiple sources more evident
Record sonification as audio file	Yes	Allowing user to playback sonification in software audio players
Visualisation of the data	Yes	Wavelength (X axis) Effective transiting radii (Y axis). Cursor that moves through the dataset indicating the position of the playback
The addition of playback functions	Yes	Add rewind, fast forward, pause, a jog wheel and scrub function. Scrub function most favoured option. By placing the cursor on the visualisation and playing back from that specific point

Second Evaluation – The Sound Design

Before any of the evaluations had actually 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 WV had noticed a feature that he was not aware of: *"Ok, I found something interesting that I didn't notice before!"* Upon a second hearing WV announced that he was hearing a water artefact that he had not noticed before within the region of 2 to 3 microns of wavelength. WV reset the playback range and played the data once again and after 19 seconds of listening he confirmed that what he was hearing between 2 to 3 microns was indeed an important water feature:

> *"That's why I had to hear it a second time. I was under the impression, that this the main feature that I thought was going to be more, erm, higher signal to noise ratio. But it looks like this feature is the one that is giving quick readout."*

There was a broader peak in the region of 5 to 8 microns which at first seemed to be an important feature but this one was already evident in the visual graph shown in figure 4.8.

> *"And then I was honing on this feature (the broad peak between 5 to 8 microns) but then it looks like this feature (The smaller sharper peak between 2 to3 microns) is the one that's giving more signal. I would like to hear that again if you don't mind, because I just want to make sure that what I'm hearing is right."*

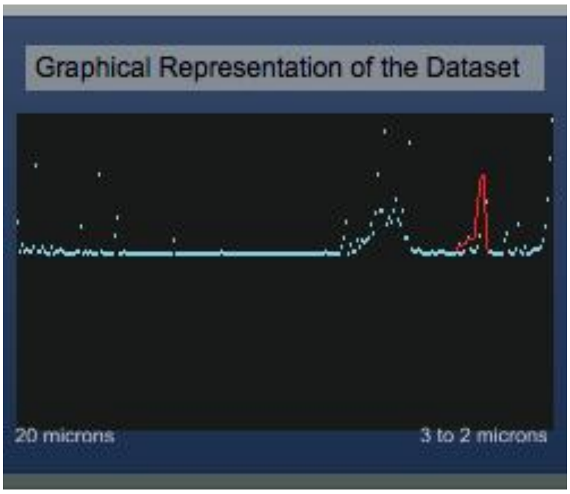

Figure 4.8: A graphical representation of the data. The broad peak between 5 to 8 microns is visible on the right-hand side of the display. The water feature between 2 to 3 microns is further to the right and marked in red.

The water feature between 2 to 3 microns was an unnoticed peak and consisted of an immediate signal that stood out clearly against the noise signal. (Refer to table 4.14) *"It's somewhere here. We are looking for this feature. At 3 (microns) starts now!"*

The range was from 2.666 to 2.672 microns. It was sharp, distinct and higher in signal to noise ratio than the broader peak at 5 to 8 microns. The fundamental frequency range of this peak was from 2090.77 to 3026.25 Hz as shown in Table 4.14.

Table 4.14 Water feature between 2 to 3 microns

Line	**Wavelength**	**Effective Transiting Radii**	**Frequency**	**Added Harmonics Hz**		
	Microns	Kilometres	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 4KHz emphasising a more distinct, sharp tone making it more noticeable above an increasing noise signal. *"Yeah, it was sharp but immediate."* On a visual display this peak was masked by the noise signal and was not noticed before:

> *"If it was the visual representation (A visual graph that WV was using before using the sonification), I probably wouldn't have thought about looking at it carefully but 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 sonification was effective, more so than originally thought. WV had discovered a new feature in the data that he had not noticed before in the visual graphs that he was using for data analysis: *"That feature was already there, and I was not paying much attention to it (on the 2D graph)."*

There was a lot of excitement both from WV and the designer, but this discovery would have to be confirmed by looking at the datasets once again in more detail. This was a task that WV was set to do after the evaluation: *"At least I heard something new here which I might have to follow up later on."*

All this had taken place before the first evaluation had started. It already answered many of the questions that were to be asked in the second evaluation which was about the sonification design and parameter mapping. In a later correspondence WV had described the particular water signal that had been discovered as being a standard water feature. This confirmed that the sonification had managed to make this feature identifiable.

First impressions of the sonification

The sonification left a positive impact on WV which he described as a *"Refreshing"* approach to analysing his dataset. He was most surprised by the impact that the sonification made and how by adding an extra sense he was immediately able to find new features in the data:

> *"I was not expecting that I would be able to distinguish between something that I can see and something that I can hear. I thought that I was expecting the same situation visually transferred to audio, in the sound form, because usually, you see this broad feature, you would hear the same thing, but then that, I was just mentioning to you, I found something new!"*

Listening to the data

The next set of questions enquired about WV's listening experience. The peaks were immediately noticeable due to the enhanced harmonics on the peak frequencies and the cross movement of the source and noise signal across the stereo spectrum as they increased in intensity. Even when the noise was increased in volume over the source it did not mask the source signal peaks which were noticeable without any difficulty:

> *"That particular feature, so the 2 to 3 micron feature, was the one that I was clearly able to distinguish between the noise and the source signal. Even when the noise was at a higher level compared to the source itself, but it was very brief."*

The playback speed of the sonification

The sonification interface had a total of 9 preset speeds 1, 3, 5, 10, 50, 100, 250, 500 and 1000 milliseconds. The user was also allowed to input their own speeds in a separate number box. WV's preferred playback speeds were described as follows:

> *"Ok, anything from 100 to 50 are good for me if I want to distinguish between the individual features of the source wave. And if I just want to hear how the*

> *signal and noise looks like or sounds like rather, then I would choose a faster one or something like a 10 or 5 milliseconds."*

By slowing the sonification down the user is able to hear anything that was not noticed at the faster speeds. The speeds of 1 and 3 milliseconds were too fast for WV to perceive anything. The slowest speed of 1000 milliseconds was so slow that WV could not tell the difference between the source and the noise signal:

> *"1,000 is pushing, 500 and 250 I can clearly see the signal, I mean hear the signal. It's too slow (1000ms) because you can't differentiate between the noise and the signal sound."*

The speeds of 50 to 250 allowed WV to be immersed in the data: *"Whereas, you know, if you go to slower speeds you are actually spending some time to absorb the data"*. The listening experience allowed the user to become more intimately engaged with the dataset leading to a deeper level of understanding.

Listening features

The next set of questions encouraged WV to give descriptions about the parameter mappings and to see if they were fully understood. He was able to see a direct comparison between the visual graph and the sonification:

> *"The patterns were repeatedly rising and going down, based on the features that I was able to visualise, because I know how it looks (due to the graphical representation in the interface). These are peaks rising and falling down but then some of them are quick, some of them are slow."*

Even though WV was familiar with the dataset he stated that he would be able to notice what was happening just by listening to it: *"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 different side of the headphones. The pure signal is coming from somewhere else. There was regularity in (the source) signal whereas with noise there isn't."*

It was clear that WV was able to perceive the multiple mappings of the source signal: *"I was able to hear the pitch change and amplitude change, frequencies, some underlying frequencies were there and also some not really strong signals."*

Aesthetic sound design of the sonification

The next set of questions enquired about the effectiveness of the aesthetic sound design of the sonification. The source signal was described as follows by WV: *"It sounded like water! I would say bubbling water, boiling, or you know. It's not a flow of water or something, it's like, it's motion of water."* When asked whether this aesthetic choice made discernment easier, WV stated the following: *"Yeah, definitely and because of the way you designed the water sound, I think I was able to pick it up much better than plain audio or something."* 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: *"Hahahaha (Laughter) Indeed! Noisy! I can tell you that! I just want to strangle noise! That's all I want to do!"* This helped WV to block out the noise and to concentrate on the source signal. Seeing how displeasing the noise was, WV was asked whether any alterations to the sound design were necessary to which he answered: *"There's nothing I would change here. I mean, I could ask, if you were God, to just remove the noise (Laughter!!!) But then, it can't be done! So that's the aesthetic I want."*

The familiarity of the sound design for both the source and the noise helped WV to become more engaged with the data:

> *"It's more receptive, that would make you listen more carefully to things that you might miss. More familiar, so that's good. That caught my attention and I really wanted to hear again and again because this is something different from my expectations and so I really wanted to focus 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, to which he answered: *"Yes, a resounding yes!"*

The use of sonification in daily astronomical work

The effectiveness of the sonification prompted WV to suggest that it could be used to analyse 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 analysed: *"They will refine the data properly and then they make it useable for the [astronomical] community to download..."*

4.7 Discussion

The previous section described how the sonification performed the task that it was intended to. WV immediately noticed a new water vapour feature that had been overlooked when previously using two-dimensional visualisation techniques to analyse the data. The sonification was able to communicate the dataset quite accurately to WV and reflects Scalletti's, (1994) views about the importance of precision in the translation of the data into sound. The sonification was also effective at directly conveying aspects of the data that were immediately recognisable to WV (Barrass and Kramer et al. 1999). In this study the user centred development was an effective method of sonification design. It is effective at obtaining a thorough understanding of the data and the needs of the user through the process of communication that develops through the iterative prototyping (Dix et al. 2009).

In chapter 3 many of the people that were interviewed had spoken about the effectiveness of having this dialogue with the users especially since they are the experts in their field and understand the data that they are working with and what they want to extract from it. Nesbitt had mentioned that the design of an interface needed to develop over various stages of iterations in order to develop its full potential. This was seen in the study with the first prototype that needed extra work to figure out the adequate scale, the source of the sound and the ranges for the modulations in the parameter mappings to more accurately represent the data. The iterative process also helps to iron out any discrepancies which are likely to occur. This streamlining allows the designer to improve upon the model and make it more user-friendly (Nielsen, 1993). Foster and Franz (1999) had also pointed out that while the designer was learning more about the users' requirements it was also important for the user to learn about the designers' process. Through the iterative process this was achieved whenever a prototype was presented, and the work was explained to WV. He became more familiar with the process and the mappings and could relate these concepts to the dataset more clearly the more he learned about them.

The data analysis process that was inspired by Grounded Theory was effective at drawing out what was needed from the user and also gave a deeper understanding of how WV related to the dataset. The descriptions that he gave about the data could be mapped out to correlations that could be reflected in sonic terms. His description of the effective transiting radii emphasised details about size, projection and transmission of light. These descriptions helped to organise the more complex mappings to reflect these characteristics such as timbre in relation to size and projection. Larger radii needed to be sharper. There was also the idea of movement of the light bouncing off the planetary surface and projecting out into space. Apart from the actual movement one could also imagine the pitch rising as the light projected further into space similar to a firework. It was possible to make these connections since the design theory was built upon the data where these rich descriptions were to be found (Tie et al. 2019). The use of more complex parameter mapping helped to give more shape and definition and creating a more tangible form of sound object. Humans are highly trained in subject object relationships (Blauert, 1997) and can easily extract semantic information concerning mass, material, interaction and force just by listening (Gaver, 1993).

One technique that was used in this study was to mimic natural sounds. This idea was inspired from the way that sound is used in film and in theatre and how powerfully a sound off camera or stage can portray strong associations. In the interviews conducted in Chapter 3 Vickers had spoken about the power of association of sound. He had described how a sound immediately forms and image in one’s mind and how designers had to be aware with this and more cautious with it so as not to convey the wrong associations. Barrass and Ballora had also spoken about this point and about the potential that a direct association has in the context of representing aspects of the dataset. Mingham and Forrest (1995) also described how the use of sound creates strong mental associations. Leplaitre and McGregor (2004) suggested the function and the aesthetics must be designed in relation to each other. The use of water-like sonification worked as a link creating a substantial familiarity and the listener is already well trained in understanding the dimensions portrayed by the sound. One other factor that was presented in works by Howard (1987) and Hendrickson et al. (2015) is that natural sounds act more like a language and that the same cognitive process is used to decipher environmental sounds.

WV was immediately able to perceive a new water feature, and this was mainly due separation between the source and noise signal. This was also found to be effective in the study conducted by Song et al. (2007) where spatial separation between two audio streams made them more distinct. This is especially beneficial where two audio streams share similar spectral characteristics (Best et al. 2005; Ebata, 2003) as was the case in this study where water like qualities are similar to white noise.

In the this study the spatial separation was taken a step further by moving the source and noise signals in cross pan to each other across the stereo spectrum. Movement has shown to be highly effective when having multiple sound sources where the listener can either focus on one sound (Oxenham, 2018) or multiple sounds in relation to each other. In chapter 3 Ballora had described how the panning movement of aspects of a storm effectively conveyed properties that were not immediately noticeable on a screen. When adding changes in timbral qualities in relation to the movement this gains more attention from the listener (Kronland-Martinet & Voinier, 2008). This was seen in this study when timbre was increased to enhance the peaks. The larger the peak the more it moved towards the right ear and increased in timbre prompting WV to follow that trajectory.

WV was able to distinguish the water vapour signal from the noise signal even when the noise was relatively high in amplitude when compared to the source signal. 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. The complexity involved in adding new source signals with different chemical qualities would need to be worked out 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.

The evaluation that was carried out for this study points towards improvements to the playback interface. The major change would have to be made to the visual display of the interface which lacked in the provision of the information that it was supposed to portray. Other additions to the playback interface are superficial changes like adding a few tools like 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 and tested. The sound design of the source and noise signal would not need any further adjustment. The design was able to perform the desired task and to provide additional information that was not perceivable when using the conventional means of visual display. 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.

It could be argued that WV was already familiar with the sonification since he had heard the different iterations and was aware of how the design had developed. There was however a long gap of about five months between the final version that was sent to WV and the Evaluation. The study's limitation was that it was only tested by one user suggesting a degree of bias with regards to the sonification successfully conveying the data and fulfilling the task that it was intended to. There is also another limitation that the interface was not developed with a team of astronomers who all study the same field. Due to limitations in finding candidates willing to participate the study was restricted to one person. The results would be more effective if the interface was developed with a larger team, was tested and presented similar results across the board. It could also be argued that the sonification design itself is made to suit the descriptions and codes that evolved in the interview with WV and maybe other astronomers would have used different language or jargon that would have altered the design of the model. The question remains whether this particular sonification design would still be as effective when tested by other people with different ideas about the data.

It is also worth considering that WV was familiar with the dataset and already had a strong conceptualisation of the data. The interface was not tested with other related datasets and it is not known how WV would have performed if he had listened to a dataset that he was not that familiar with. It could be that more time would be needed for WV to understand how the sonification was portraying the data and there is also the possibility that he would not be able to utilise the sonification as effectively.

In the case of designing water vapour 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 share in definite form as being gases which are subjected to similar sonic attributes. Gas like sounds would have to be distinguishable between each other and would have to be distinct from the white noise. Sonically gas and noise share sonic characteristics. The designer would have to see how the user could perceive these chemicals as gases and being able to immediately recognise one from the other. This is where 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.

Considering the limitations in the study there are various design criteria that have emerged and that can be used in other sonification designs. These criteria can be carried on to the next design exercise. They are summarised in Table 4.15

Table 4.15: Design Criteria that have emerged from this study

Criteria	**Comments**
Requirements Gathering	Conducting a detailed requirement gathering strategy to obtain a clear understanding of the data and users' perception of data.
Requirements Analysis	Using a data analysis system that aims to use data extracted from requirement gathering as basis for design theory
Iterative Prototyping	Creating a series of prototypes and testing them with user so that feedback from each evaluation can be used to fine tune model
Communication	Establishing a good communication channel with user where designer and user learn from each other's processes
Familiar sonic associations	Using familiar sonic associations for immediate recognition of sonification to dataset.
Multi Parameter mapping	Multi parameter mappings convey complex concepts and strengthen sound object conveyance, enhances spatial representation and movement
Spatial mapping	Spatial parameter mapping can convey the properties of a sound object effectively. Movement allows space for propagation without hinderance in multi-channel interfaces and directs listeners attention
Knowledge	Good knowledge of tools that are used to design sonification and good knowledge of psychoacoustics when using multiple mappings
Evaluation	Evaluate pros and cons of design and fine tune model according to feedback

The sonification guidelines that have emerged from this study reinforce the guidelines found in the literature in chapter 2 and the ones discussed in the interviews in chapter 3. The data gathering process has been an important stage in the development of the sonification. The requirements gathering and data analysis process are key steps in understanding the user's perception of the data and how they envision to use the sonification with it. The semi structured interviews allowed WV to talk and describe their data. In these descriptions, information about the dimensions of the data, the representation and imagery portrayed, conveyed rich representations of how WV imagines the data. These were the key points that were used to develop the sound design.

The iterative design process helped to confirm these representations allowing the designer to become more familiar with the user's image with each iteration. At the same time, it also allowed WV to become more familiar with the idea of sonifying the dataset. Sonification was an unfamiliar concept to him and through the iteration and the communication channel that had been established, there was an exchange of information teaching both parties about each other's work and then integrating that into the design.

To avoid having a sound design that would be intangible to WV it was decided to use a familiar sound design so that he could associate the sound and the data together. Using a real-life example, in this case a water-like sound for a representation of water vapour helped WV make an immediate association and somehow the data was more tangible to him since he felt that he was listening to water vapour. The sound does not necessarily need to be a direct association but could be symbolic. This can be learned from the requirements and iterative stage.

To create a more realistic sound effect multiple parameter mappings were needed to mimic the water, these other mappings still worked within the parameters of the data and were not extra components that added a coating to the sound design. All the modulations were determined by changes in the dataset. Timbre, amplitude and panning all moved in accordance to increases and decreases in the effective transiting radius data. This is a more complex way of creating the sound and to do so a deeper understanding of psychoacoustics and subtractive synthesis was needed. This reflects comments made by Bruce Walker in Chapter 3 who had emphasised the importance of knowing the tools of the trade properly.

In this sonification design spatial mapping helped to create a stronger distinction between the source and the noise signal, especially due to the movement of both signals. It also helped to give more definition and realistic dimensions to the sound object that was being designed, in this case effective transiting radii. Spatial mapping is probably an underestimated mapping especially in relation to movement. If movement mimics the nature of the object, then it is likely to make it seem more realistic. The use of the SMARC effect in this design created an illusion of vertical movement which is similar to the way that beams of light project off a planetary surface. Spatial mapping has the potential to strengthen these associations.

The evaluation stage acts as a communication platform since it allows the user to convey to the designer any changes that need to be made to an iteration. This stage acts as a learning stage for both the user and the designer. It is also an effective fail safe that highlights design flaws that can be remedied and then tested again for confirmation that the issue has been addressed. This is a powerful process since it also ensures a more sustainable model which also serves as a prototype for future revisions. Design is not easy, and evaluation helps to ease this process through creating a constant learning cycle.

The following chapter will be discussing a second sonification interface designed for a different aspect of Exosolar Planetary astronomy. The knowledge acquired in this chapter will help with the implementation of the second sonification design.

Chapter 5: Sonification of Accretion Discs in Exosolar Systems

The second sonification study investigates the design and evaluation of a sonification of accretion discs that are observed in twenty exosolar systems. The interface was designed for a professional astronomer who studies these phenomena. User centred design methods were applied to create a sonification of the data that could allow the astronomer to classify the accretion discs. The sonification was developed over three stages: a requirement's gathering exercise that inquired about the astronomer's work and the data, a design and development stage based on the findings of the requirements gathering, and an evaluation of the sonification design. Twenty datasets of accretion discs were sonified and analysed. The astronomer considered that the sonification effectively represented the accretion discs and allowed them to commence a preliminary, comparative classification of the various datasets. Multiple parameter mappings (pitch, spatial, timbre, amplitude) appeared to provide richer auditory stimuli that improved the level of interpretation to the user. The use of spatial mapping and movement allowed the user easier identification of fast changes and peaks in the data and allowed the user to understand the frequency and dimension of these changes.

5.1 Rationale

This study aimed to discover how successfully sonification can be applied to datasets that represent accretion discs that are found in young, developing Exosolar Systems. The astronomer was one of the three who accepted to participate in the overall research of this dissertation. He was interested to find out whether sonification could help him to classify various accretion discs. He wanted to see whether sonification could identify characteristics that were not evident when using graphical representations. Pattern recognition is described as being one of the main reasons for using sonification and its effectiveness can be tested in this study.

Accretions discs are dust clouds that surround a parent star like a ring. Certain principles like spatial mapping and the use of auditory affordances can be expanded upon from the previous study. The data consists of light curves which are captured light emissions from stars over periods of time. The accretions discs are noticeable due to dips in the parent star's light radiation that happen periodically and constantly.

The use of sonification could be effective at conveying dimensions and proportions of objects. Sonification could give clearer distinction of the size of an accretion disc and of dust clouds of various volumes since the disc varies in size along its circumference. Humans intuitively have an understanding of the proportions of a sound object and are able to recognise the origins of a sound source (Shinn-Cunningham, 2008). Chion (1994) had also described how sound conveys impressions of space, volume, significance, matter, expression and the organisation of time and space.

To make these sound objects more distinguishable the sonification aesthetics could take on familiar characteristics that are associated to the dataset. In the previous study in Chapter 4 the use of familiar, natural sound allowed WV to be able to distinguish between the source signal and noise. The more natural sounding water vapour was still distinguishable even when the noise was much louder than the source. Environmental sounds have a strong associative tie that could be recognised even with limited spectral information (Gyra, Kidd & Watson, 2003). Environmental sounds are like language, where words are meaningless unless the concept that they refer to has been learned. The association to a specific environmental sound object or event is not made unless we have previously experienced them and learned that association (Schirmer et al. 2011). In the previous study the use of water-like qualities helped WV to understand the parameter mappings. He had commented that the water-like qualities made the sonification more tangible and associable. Sound familiarity leads to identifiability (Cycowicz and Friedman, 1998).

An accretion disc is a ring of dust particles that form into clouds and orbit around the parent star of an Exosolar system. Considering the spatial properties of this disc, this study will explore the potential of spatial mapping in more detail. In the previous study spatial mapping was highly effective. Song et al. (2007) had identified the potential of using spatial separation of two audio streams which was a functional method allowing clear distinction between the two signals. In Chapter 4, spatial movement between source and noise signals was suitable for detecting important aspects of the source signal that were concealed by noise in the visualisation. The source and the noise signal shared similar spectro-temporal characteristics and spatial separation greatly reduced masking between them. Best et al. (2005) had found that spatial separation reduces masking between two different sound sources. In this study there is only one sound source which is an object that moves by rotating around the central star. The use of spatial separation and timbre could facilitate the comprehension of sonified attributes (Song & Beilharz, 2007). Other multiple parameter mappings including pitch, amplitude and tempo or rhythm could help the astronomer to more clearly identify the speed of the rotating disc and the size of the clouds contained within it. The changes in timbral qualities of a familiar moving object could enhance perceptual recognition (Kronland-Martinet & Voinier, 2008).

The implementation of user designed principles will be practised in this study. Seeing how effective these principles were in the previous study conducted in Chapter 4, these concepts can be tested again in a different context with different data and with a different user. Worrall (2019) speaks of the similarities of listening to a sonification and listening to linguistic speech. To be able to convey this level of communication through sonification design, the designer must attain knowledge of a person's interpretation of sonic properties (Pirhonen & Palomaki, 2008). The users' familiarity or preconceived perceptions of the data should be taken into consideration when designing a sonification (Ferguson and Brewster, 2017). In chapter 4 the requirements gathering was aimed at attaining information about the data, how the user worked with it, perceived and understood it, and the task that the user had in mind for the use of sonification in relation to the dataset. These four aspects were identified after the requirements gathering and the sonification design was based on manifesting these principles to suit these criteria. The results suggested that the design was considered effective and was able to fulfil its purpose.

The iterative process and the evaluation stage will also need to be utilised in this study allowing an open channel of communication between the designer and the user. This will allow the designer to get a clearer understanding of the user's requirements, clear conveyance of the data to the user and the ability to complete the given task effectively. These processes will allow the user to communicate whether any changes need to be made to the model to better perform the task (Hartson et al. 2001). Hermann (2008) suggests that a sonification must reflect the nature of the data in its sound design. Grond and Berger (2011) describe the process of parameter mapping as involving the association of information with auditory parameters and to ensure that the data is replicated in a comprehensible manner. These processes could help to achieve the effective mirroring of the data in sonic terms that are clear and relatable to the user.

To summarise the objectives of this study, it is believed that sonification can help the astronomer to classify similarities between a variety of accretion discs situated in various Exosolar systems. The astronomer believes that sonification could enhance pattern recognition facilitating the classification process. Requirements gathering and an analysis system based on grounded theory will be applied to ensure that the sonification is design is built upon the data and not on preconceived beliefs of the designer. To get a clearer understanding of the astronomers' association of the data, a similar user design practice to the one in the previous study will be implemented. This means that both iteration and evaluation will be used to test the effectiveness of the sonification in representing this aspect of Exosolar data.

5.2 Methods – Requirements Gathering

The requirements gathering exercise was conducted as a semi-structured interview with the astronomer who will be referred to henceforth as AD. The interview lasted about one hour. Its purpose was to learn about AD's work, the type of data that he works with and how this could be sonified.

Participant

AD is a male in his forties who has been working professionally in astronomy for about 14 years. He has been studying the development of exosolar systems by observing the accretion discs that are characteristic in younger star systems. The theory is that debris from these discs contribute to planet formation. By studying them astronomers hope to understand more about the formation of the Solar system. AD considers his hearing and eyesight for his age to be normal and has had previous experience working in live sound engineering, however, didn't have any musical training. AD was interested in applying the use of sonification to see whether it would be possible to classify diverse characteristics of a variety of accretion discs from various, young, exosolar systems. AD wanted to see whether sonification could offer a new dimension to the classification process of these discs.

Materials

A semi-structured interview was conducted in an office on a university campus and recorded using a portable audio recorder. It was based around 16 main questions (refer to Appendix A) and other questions were asked according to the feedback given by AD.

These questions differed from the previous study since AD had already suggested that the sonification would be based on Exosolar system data before the interview. In the previous study it was found that since the questions were based on the datasets found in the NASA Exoplanet Archive, they did not necessarily relate to the dataset of the astronomer. It was decided to ask more questions spontaneously in order to avoid this issue and to give freer rein to the astronomer to talk about his subject in order to obtain rich descriptions of the dataset. A participant information sheet (See Appendix A) was presented to AD explaining the details about the project and concerning his rights as a voluntary participant. An informed consent form was presented to AD who agreed to the terms of participation and signed the form.

Design

The interview aimed to cover three aspects of investigation: Inquiry about the dataset, identifying how the data can be mapped sonically and gathering information from AD about the sonification design. A similar analysis system to the one used in Chapter 4 and based on Grounded theory would be used since it proved effective for extracting rich descriptions which work as codes and indicators for the sonification design.

Procedure

The interview was conducted in an office on a university campus and lasted roughly about one hour. It was recorded on a Zoom H2N portable audio recorder. The interview, being qualitative, did not require a pilot study. This allowed questions to form in accordance to the responses. Questions inquired about the dataset, how it could be comprehensibly mapped sonically, sound design aesthetics and tools for the interface design. The recording of the interview was transcribed and coded.

5.3 Results – Requirements Gathering

The requirements gathering collected information about the data used by AD in his work, parameter mappings that could represent the data, sound and interface design. The following section gives a detailed description of what was discussed in the requirements gathering exercise.

The Dataset

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 that are influenced by this phenomenon are called dippers. The data is captured roughly over an 80 day observation period. AD says that: *"These are young stars and there is dust which is obscuring the star in ways that I wouldn't say we really understand but we have some ideas."* Figure 5.1 gives a graphical representation of a light curve dataset. Time is represented on the X axis, amplitude of light on the Y axis. The dips are seen as drops in the normalised flux on the Y axis or lessening in the amplitude of the light curve indicated in blue on the diagram.

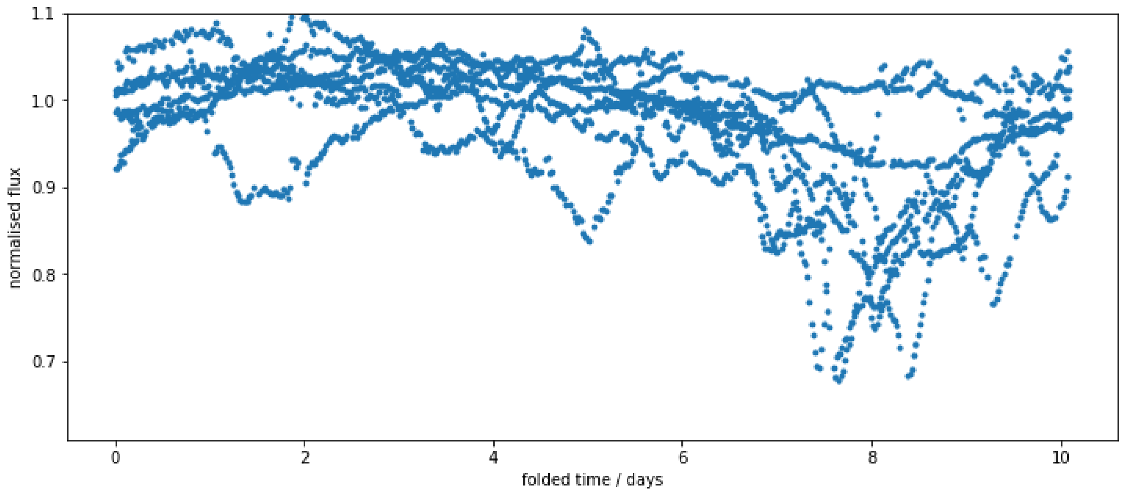

Figure 5.1: A graphical representation of various dips in the light curve

Astronomers study these young exosolar systems to try to understand how the Solar System could have formed and what conditions would be required for an Earth-like planet to emerge within one of these systems. The accretion of dust gyrating around the star is thought to approximately corotate with the star (Bodman et al. 2017). It is hypothesised that the differences in the disc's angle of orientation is determined by the stellar tilt axis (Ansdell et al. 2016). When light curve information of a dipper is captured, the image shows variances in intensity of stellar light and the dips caused by the accretion disc. The data consists of dips of various proportions and the movement of the disc circling around the star over a period of time. This means that the data is temporal-spatial. Table 5.1 summarises what the dataset consists of and what aspects would need to be mapped sonically.

Table 5.1: The Dataset

The dataset	Characteristics
Datatype	Light curve – measurements of light emitted from a star
Size of the dataset	The original dataset consisted of 3307 lines (Varies according to the dataset)
Measurement of the X Axis	Time – Days. This dataset consisted of 77 days (Varies according to the dataset)
Measurement of the Y Axis	Light flux – measured in lumens (lm)
Peaks in the dataset	Dips in light caused by dust clouds occulting the star

The Sound design of the Sonification

Pitch was chosen as the main mapping to represent the dips by rising in frequency due to its effectiveness at representing minute incremental changes (Walker & Kramer, 2004). When there are no dips the data portrays the actual light from the star which would be mapped to a lower frequency in pitch. The incremental changes in pitch would allow AD to distinguish between different dipper sizes which would come in useful when classifying the data. This is similar to the previous study in chapter 4 where pitch could allow WV to hear differences in the heights of peaks due to subtle differences in the pitch representation.

In imagining an accretion disc rotating around a star it was decided that the data could be represented in this way on a spatial surround system. The idea was to immerse the listener within the dataset to see whether this would help him to hear rhythmical patterns that occur whenever there are dips in the data. This means that the listener would be placed in a heliocentric position with the sonification revolving around his head. This could possibly aid AD to classify accretion discs when hearing similar patterns between different datasets. As seen in the previous study in chapter 4, spatial mapping was effective at conveying the dimensions of a sound object. The idea of defining the sound object more clearly means that it can be recognised without the need for visual representation (Blauert, 1997a; Gaver, 1993; Chion, 1994). In this particular case the image of a disc could possibly be made more tangible by creating a revolving disc. In chapter 3 various participants like Barrass, Ballora, Verona, Ferguson, Vickers and Dyer had referred to creating more realistic sound designs to achieve more direct associations with the data. In the study in Chapter 4 this seemed to assist WV in being able to focus on the source signal and understand how it worked in relation to the data due to its familiarity. To achieve a spatial surround component an extra element was added to the data by AD. Each measure of time was plotted onto a 360^{o} capacity that would allow the whole dataset to rotate several times around the listener. Figure 5.2 shows how the data was plotted.

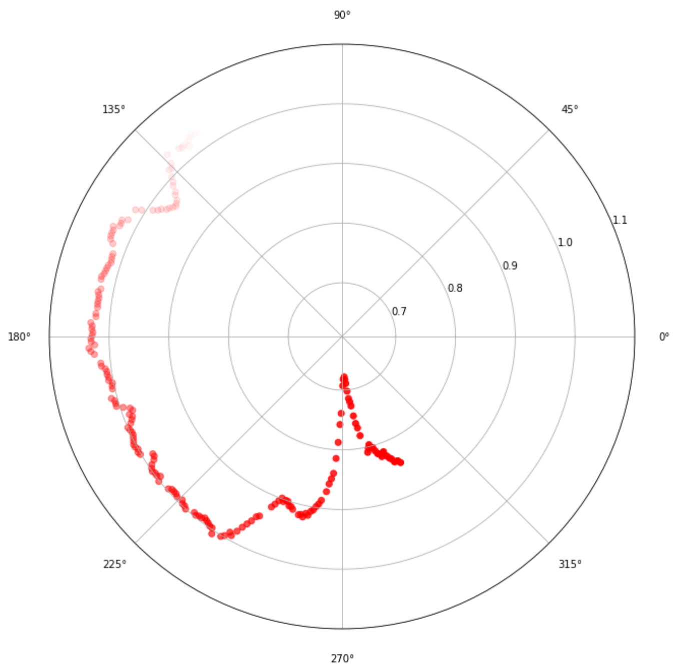

Figure 5.2: The plotting of the data on a 360º plane

Coordinates were provided as X and Y axis and also as Phase data. The phase data was more effective for rotating the sound since it belonged to one column of data and making it easier to map to a surround sound configuration than using the X and Y axis which required a more complex method to rotate the signal where both columns would have to combined into one data stream. Figure 5.3 shows an example of the dataset. The first column is time, the second, amplitude of light. The third and fourth columns are X and Y coordinates respectively and the fifth column is the phase data. Columns one, two and five were used for the sonification.

2061.305459	1.018121444	0.506507125	0.862235776	0.16546820
2061.325891	1.015658534	0.495502688	0.868606405	0.16749193
2061.346323	1.015462975	0.484418191	0.874836566	0.16951566
2061.366755	1.015905482	0.473255428	0.880925252	0.17153938
2061.387188	1.015193144	0.462016039	0.886871569	0.17356312
2061.40762	1.016513229	0.450702007	0.892674465	0.17558685
2061.428052	1.016159523	0.439315048	0.898333061	0.17761059
2061.489348	1.016670601	0.404735589	0.914433761	0.18368178
2061.50978	1.01857035	0.393075789	0.919506076	0.18570550
2061.530212	1.019127469	0.381352378	0.924429751	0.18772923
2061.550644	1.018891566	0.369567253	0.929203985	0.18975297
2061.571076	1.019423175	0.357722434	0.933827961	0.19177670
2061.591508	1.018413667	0.345819836	0.938300933	0.19380042
2061.61194	1.020604591	0.33386121	0.942622243	0.19582416
2061.632373	1.02059461	0.321848663	0.946791127	0.19784789
2061.652805	1.02055472	0.309784138	0.950806914	0.19987161
2061.673237	1.021005077	0.29766941	0.954669012	0.20189534
2061.693669	1.020605483	0.285506613	0.958376739	0.20391907

Figure 5.3: An example of the dataset

The Sonification

It was suggested that the Flux data would have a familiar sound that the astronomer could easily identify with. This would be similar to the approach taken in Chapter 4 which was also identified as a sonification design guideline. This would allow AD to associate with the dipper data more directly. It was decided that the sonification would sound like grains of sand particles being blown around in the wind based on a description that was given by AD, when he described the composition of an accretion disc consisting of grains of sand and fragments of rock. This would mean that the sonification would need more parameter mapping in order to replicate this kind of 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 at his desk instead of always having to connect to a surround system to analyse the data. This would also allow the user to test and compare both methods of spatial representation and to see which technique would be best suited for his work.

The interface design

The data would be provided in text format, so the system had to be able upload this format. One text file would be loaded at a time. The user would have control over the playback speed so that the sonification could be slowed down or sped up and have the ability to choose specific points of interest in the dataset for more detailed listening. The playback would need the ability to repeat itself meaning that a loop function would be required. The system would be designed to work both in Stereo and on a surround sound system. 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 would be able to record the sonifications and play them back at any time. Table 5.2 summarises all the components that were required of the interface.

Table 5.2: Results concerning the sonification interface design

Interface design functions	Results
Data format	Text file .TXT
Data to be sonified	Light amplitude to pitch and time to spatial coordinates
Playback	Variable playback speed control
Data manipulation	Ability to select certain segments of data for playback Ability to loop playback
Output device for sonification playback	To be used on stereo or surround sound
Recording device	Ability to record the sonifications as .WAV files

5.4 Sonification design

This section describes the different stages of the sonification design in detail. The requirements gathering exercise provided the following information that would be used for the sonification design. Table 5.3 gives descriptions of the codes that emerged when applying a system similar data analysis method to the one used in chapter 4 that was inspired by Grounded Theory.

Table 5.3: Grounded Theory type codes formed from the requirements gathering

First Initial Pass	Second Intermediate Pass	Third Advanced Pass
Accretion disc	Data	Distinction between dips in a system emphasised by pitch + surround sound to create a disc & enhance differences between different Accretion discs + Stereo to enhance distinctions in dipper sizes to possibly detect planets
Developing exosolar systems		
Dust & rock		
Surrounds star		
Dippers – dips in light (Flux)		
Size of dust, rock or planet		
Time = days		
Orbit (spatial coordinates)		
Distinction between dips (peaks) = Pitch	Purpose	Sonification used to classify accretion discs in different systems and possibly detect planets
Classification of dippers (Exosolar systems)		
Sonification sound	Aesthetics	Multiple parameter mappings to mimic a dust cloud
Familiarity		
Dust storm		
Output	Technology	To switch between surround & stereo & have a different perspective + Use on a laptop
Surround sound		
Stereo		

A similar method to that of chapter 4, of Iterative Co-design was applied in this study. In the previous study the system of iteration helped to improve the sonification design to suit the purposes of the user and to effectively convey new aspects of the data previously unnoticed. This method of iteration opened a channel of communication, that Benyon (2019), Dix et al. (2009) and Foster and Franz (1999) outlined as being important to the design process to obtain a more rigorous understanding of the dataset and the users' perception of it. Similar views were shared in Chapter 3 by Verona, Nesbitt, Walker, Philart Jeon, Alexander who had described their own design processes and how they had developed sonifications using iterative design methods. In this study the different iterations of the prototype were sent to AD via email and feedback was received either by email or discussed over Skype calls. Table 5.4 gives an indication of the iterative design process that evolved in this study.

Table 5.4: The Four stage iterative design process

#	Feedback from AD	Changes made
1	Pitch mappings are good. The scale seems fine (tested with one dataset). Peaks need more emphasis.	The peaks were enhanced by adding more resonance to the signal which at the same time amplified the peaks.
2	Stereo setting should give an impression of looking at disc from outside. Panning has to give that impression and distinguish between dipper sizes spatially	Stereo panning set that larger dips pan to the left ear and smaller dips remain on right ear
3	Remove volume control from interface. Recording function needed. Loading system too slow	Volume control removed to be controlled from user's computer. Recording function was added. Loading system revised and improved
4	Scale needs fixing (when tested with multiple datasets) for consistency in sonification between datasets. Scale not high enough in frequency range for sudden large peaks	Scale adapted to more widely set pitch range to represent differences in ranges between datasets

Method of Synthesis

The sound design of this sonification was built using both subtractive and additive methods of synthesis. It was initially assumed that additive synthesis would be sufficient since it consists of building up a sum of sine waves that constructively add harmonics increasing timbral and tonal features (Cipriani & Giri, 2010a). This would give dips more emphasis through a phenomenon called *Constructive Interference* which is when two sine waves of similar phase polarity sum up and add amplitude to the third wave (ibid). Additive synthesis gives the necessary sonic complexity similar to the way that sounds exists in nature. Real sounds are partly inharmonic and additive synthesis allows the use of non-harmonic partials that changes both the amplitude and the frequency of each partial (Farnell, 2010d).

When this method was applied the added harmonics were creating changes in the pitch that were altering the perception of the sonification and falsely representing the data. Added pitch characteristics distorted the original pitch mapping making it difficult to determine the dips properly. After numerous attempts it was decided to only use the additive synthesis to add more timbral features and to enhance grit and distortion in the signal whenever a dip occurred. This meant that the additive synthesis was no longer mapped to pitch change and its presence was reduced by setting it to a lower volume. It also helped to enhance the lower frequencies in the dataset where no light fluctuations occurred. This constant background drone of non-fluctuating light signified the presence of the star emitting relatively constant light.

Due to the inconsistencies that were occurring from the additive synthesis the first iteration took longer to complete. Seeing how subtractive synthesis was effectively used to represent pitch and timbre changes in the previous study in Chapter 4 it was decided to use this method of synthesis.

Subtractive synthesis was added as a second synthesiser to have more control over the pitch and timbre changes required for the sound design. Due to the reductive method used in subtractive synthesis it would be easier to control pitch and give the necessary precision required to properly represent the data. The sound sources in the subtractive method are rich in spectra and through Pulse width modulation and filtering certain particulars can be subtracted from the sound (Cipriani & Giri, 2010b). This synthesis was mapped directly to the Light curve flux controlling the pitch changes in the dataset.

Once the subtractive synthesis had been added and the appropriate mappings had been made the sonification was sent to AD. It was found that this method of synthesis could be adjusted and mapped more effectively without the additional harmonics that were affecting the pitch when additive synthesis was the main synth engine. AD found that the sound design was similar to sand grains and quite effective. He did suggest that the peaks needed more emphasis without being too harsh. Resonance was added to sharpen the peaks and adding amplification to the signal. A small amount of reverb was mapped to increase with a rise in the numbers of the light curve to smoothen the peaks. In the second iteration this adjustment was noticed by AD who felt that the peaks were now well defined and not too harsh.

Scale

The Light Flux would be mapped to pitch and varied from 65Hz to 9kHz. This would allow consistency in reproduction between different 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 as shown in figure 5.4 (Genelec, 2007). The lower range of light Flux would represent the solar light and lower dip measurements. The higher range of 9kHz would allow dips to reach a maximum range that would still be audible to the listener. The 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 (Sek &

Moore. 1995). 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 (Moore, 2012c).

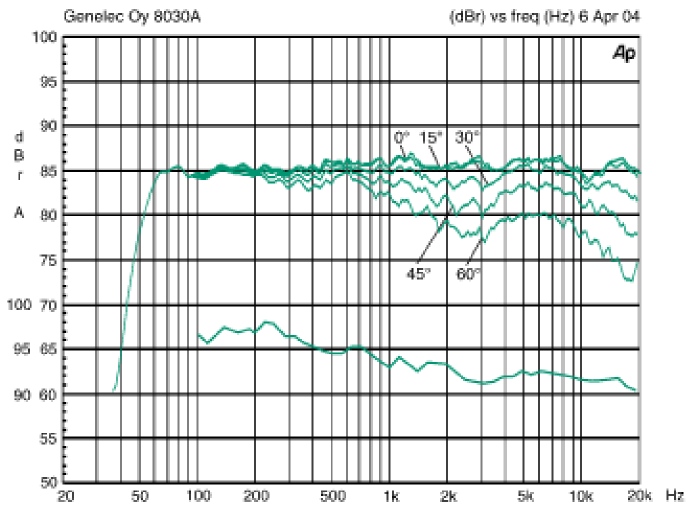

Figure 5.4: The upper curve group shows the horizontal directivity characteristics of the 8030A measured at 1m. The lower curve shows the systems power response (Source: Genelec, 2007)

In the first iteration the scale was set to a range of 55 to 4000 Hz which would be around an effective frequency range of hearing speech consonants which is between 2 and 4 kHz (DPA microphones, 2021). The reasoning for choosing this scale was to give the peaks more emphasis just as consonants are emphasised in this range. It was also influenced by the idea put forward by Worrall (2019) that sonification is listened too in the same way as language. Enhanced consonants would be equivalent to emphasised peaks. It worked when tested with one dataset where the peaks were not so high. A fourth iteration had to be included ever since AD had provided 100 datasets after the third iteration to be sonified. When different datasets with higher peaks were loaded into the sonification interface they clipped loudly and sharp, since the range was not wide enough for them to be represented. It was then decided to alter the range to 9 kHz which would still be within an audible range suitable for a user who is over 40 years of age and might have experience hearing loss in frequencies above 12 kHz. This range allowed the peaks in all the datasets tested to be properly represented without the harsh clipping sound.

Parameter Mapping

In chapter 3 Verona had spoken about the need for more complex mappings when conveying more elaborate datasets. In astronomical data there is often the representation of a body in motion at a moment in time or, as seen in the previous study, a spectral representation which consists of size and proportion like the measurements of the effective transiting radii. Audification is a common method used to sonify astronomical data like the extensive work of Gurnett (University of Iowa, 2020) or Alexander (2011), but in this study parameter mapping is more capable at replicating a sand-grain like sound and the movement and intensity of dust clouds. Various studies suggest that the mental processing of environmental sounds is quite similar to those used for spoken language (Dick et al. 2016). By using a familiar environmental sound, the user could develop a more acute understanding of the parameter mappings since the sounds are already familiar to him.

The spatialization for this model was designed to work on a surround sound system. In studies conducted by Quinton et al. (2016) and Tomilson et al. (2017) quadraphonic surround systems were used to represent planetary movements. Orbit speeds were more recognisable on the surround system as listeners could sense the differences in planetary orbit speeds due to them being represented spatially. Pattern recognition works on the basis of the timing of a sequence of events (Jone, 1978) and spectral analysis, which are timbral changes in the sound in relation to temporal and spatial cues (Espinoza-Varas & Watson 1989). Spatial perception is a pattern-recognition process where features of the environment are recognisable as patterns through time Lennox et al. (1999). By placing the listener heliocentric position, it could enable him to hear how the disc revolves around and in relation to the star, and possibly have a clearer understanding of the temporal-spatial dimensions of the discs orbit. Since the orbit of the disc is hypothesised to be in sync with the orbit of the star around its own axis then this configuration could give a clearer understanding of the star’s axial spin.

The spatialization was also configured to work on a stereo sound system. This would not only be advantageous for the astronomer to use when working on his laptop, but it will also give a clear indication of how the dust clouds pass in front of the star. The observations that are made of these accretion discs are done from a distance and all that is observed is the dulling of the light as an object passes in front of a star. This is change in perspective could give different insights than the surround sound configuration.

Design

The Sound design of the flux data was mapped through two synthesisers. The first synthesiser was an additive synth that was used to add more depth and definition to the lower frequencies. The sound was generated by using two oscillators that were set to full volume. One oscillator was a triangle and the other a square wave. The flux data was mapped to the Cutoff, the Hi Pass filter mix, the noise intensity and the output volume. The Cutoff, noise and output increase as the frequency of the flux increases. The Hi Pass Filter and the noise intensity decrease as the frequency becomes higher in order to give more emphasis to the lower frequencies and add more noise to the rumbling lower end. Table 5.5 shows the ranges within which the parameter mappings are changing in relation to the flux data. The full range of any MIDI parameters spans from 0 to 1.

Table 5.5: Sonification design additive synth 1 variable parameters mapped to the flux data

Parameters - Increase with Intensity			Parameters - Decrease with Intensity		
	Frequency Hz	MIDI		Frequency 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 was used to map pitch to the changes in flux data and to add timbral characteristics to give more definition to the dips. The pitch consisted of two oscillators a pulse and a sine wave. By adding overdriven harmonics to the sine wave this would change the nature of the wave making it richer in spectral content. The pulse wave gives both clarity and resonance to the sound. Other parameters were used to add sharpness and characteristic and to create the sand grain like sound. The added sharpness and distortion had to be balanced so as not to sound too harsh and brittle.

By adding various characteristics such as ring modulation and overdrive there were also significant increases in volume that had to be compensated for. These two parameters moved, increased and decreased conjointly with the pitch. As the dips became larger, they increased in pitch and became 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 wetter as the pitch increased to soften higher frequencies and take away the sharp brittle tones that were occurring at the high end of the frequency spectrum. Reductions in volume on both oscillators was necessary since the amplitude became much louder as the pitch rose. The sub oscillator also 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 due to certain resonances that were occurring making the sound softer. The amplitude decay increased with the rise in pitch making the tones longer, making the sound of the peaks more continuous allowing them to be heard as more of an object instead of disjointed, short bleeps. Table 5.6 shows the ranges of variance for all the parameters that were used to create the sound.

Table 5.6: Sonification design subtractive synth 2 variable parameters mapped to the flux data

Pitch		**Increase with pitch**			**Decrease with pitch**		
Parameter	Range Hz	Parameter	Frequency Hz	MIDI	Parameter	Frequency Hz	MIDI
Osc 1	65 - 9000	Reverb wet	65 - 9000	0.3 - 1	Osc 1 Volume	9000 - 65	0.3 – 0.8
Osc 2	65 - 9000	Ring Modulation	65 - 9000	0.3 – 0.5	Osc 2 Volume	9000 - 65	0.3 – 0.8
		Amp Env Decay	65 - 9000	0.2 - 0.8	Sub Osc Volume	9000 - 65	0.3 – 0.8
		Filter Overdrive	65 - 9000	0 - 2	Cutoff Frequency	9000 - 65	0.3 - 1
					Hi Pass Filter	9000 - 65	-1 - 1

Two modes of spatial mapping had to be created: One mode for surround sound, the other for stereo sound. The spatial surround system would be configured to work on a quadraphonic system. The sound would revolve around the listeners head in the same way that an accretion disc revolves around a star. The data consisted of two types of spatial coordinates. The first type consisted of X and Y coordinates that can be seen in columns three and four of figure 5.3. These two columns work in conjunction to each other. The X axis moves along the horizontal plane and the Y axis moves along the vertical plane. Figure 5.2 shows how the data moves between these two spatial planes. This series of data was left out of the model since it would require two fields of surround sound to work properly. These fields would consist of an outer and inner circle of speakers and the dips can be heard moving closer to the listeners the deeper they are. The data would move around and towards and away from the listener. Due to a limitation in the number of speakers available for testing and the complexity of moving the X and Y data as a combined signal it was decided to use the second set of coordinates.

The second set of coordinates was phase data that consisted of one column, the fifth column depicted in figure 5.3. The data would circulate anti-clockwise in the same way that an accretion disc follows the orbital spin of the star.

The surround system was designed to allow choice of the number of speakers from 2 to 12 to output the signal. The user would need to use an external soundcard connected to his laptop in order to be able to connect more than two speakers. The system allowed the user to choose their own soundcard, read by their computer's operating software and listed in a drop-down menu in the sonification interface. The surround sound had to shift from speaker to speaker by having a crossfader between each of the four channels across the quadraphonic field. Table 5.7 shows how the phase data crossfaded from one speaker to another in relation to the changes in time for two rotations. The darker boxes represent the peak volume in that channel as the amplitude starts to decrease and the signal starts to crossfade to the next speaker where the value has not been emphasised by a darker box. The volume range was set from 0 to 75 as a MIDI value. The range was capped to 75 and not 127 since distortion was occurring above the range of MIDI value 90. This kept the volume of each channel within a safe limit without peaking.

Table 5.7: Surround sound system: Crossfading between four channel output for two rotations

Time Range	Phase	Back Right	Front Right	Front Left	Back Left
2061.30546 – 2063.40996	0.1654	72.444436 – 0.000024	19.411448 - 75	0	0
2063.43039 – 2065.94353	0.3759	0	74.988578 – 0.000024	1.308954 - 75	0
2065.96396 – 2068.45666	0.6269	0	0	74.988578 – 0.000024	1.308954 - 75
2068.4771 – 2070.99022	0.8757	1.308954 – 75	0	0	74.988578 – 0.000024
2071.03109 – 2073.50334	0.1288	74.954313 – 0.000024	2.617485 - 75	0	0
2073.52378 – 2076.03689	0.3757	0	74.988578 – 0.000024	1.308954 - 75	0
2076.05733 – 2078.55001	0.6266	0	0	74.988578 – 0.000024	1.30894 - 75
2078.65216 – 2081.08355	0.88 – 0.1265	5.231758 - 75	0	0	74.817306 – 0.000024

The stereo panning would be configured to work by shifting from right (+1) to left speaker (-1) between the frequencies of 65 – 9000 Hz. The dips in flux would range from 0.678 to 1.316 magnitude of light loss. This would allow 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 signifying the size of the dip acting as an indicator rather than an exact quantifier. At slower playback speeds the movement is more discernible. Table 5.8 gives an indication of how the panning worked for the original dataset that was used as the basis for the development of the interface. Certain values of panning range would vary from one dataset to another.

Table 5.8: Stereo panning movement of changes in light flux

Panning	**Flux**	**Range Hz**								
Right 1	0									0
0.8	0									0
0.6	0.678									65
0.4	0.702								403.32	
0.2	0.761							1229.96		
Centre 0	0.801						1791.57			
-0.2	0.850					2477.89				
-0.4	0.900				3180.46					
-0.6	0.950			3880.23						
-0.8	1.000		4580.15							
Left -1	1.195 – 1.316	7317.16 - 9000								

Static function settings and reverberation

Other settings were used to determine the range of the sound modulations to work within set parameters which effected the timbre and amplitude of the signal. Table 5.8 lists these values for the additive synthesiser (synth 1) and Table 5.9 lists these values for the Subtractive Synthesiser (synth 2). These values are displayed as MIDI values that vary between the range of 0 to 1.

Table 5.9: Static function settings for synth 1 (Additive Synth)

Oscillator	Mixer	Filter	Misc (Routing)	Matrix	Env 1 VCA	Env 2	Master
Osc 1	Osc 1 Volume: 1	Filter Mod. 1: 0.192	Noise - Osc 1	Via XS-Mod Osc 1: ADSR 1	Attack: 0	Attack: 0	VCA routing: ADSR1
Osc 2	Osc 2 Volume: 1	Filter Mod. 2: 0.975	Ring Mod – Osc 2	Destination XS-Mod Osc 1: Osc 2 FM	Decay: 1	Decay: 1	Polyphony: 8 voices
Tune 2: 0.675	Sub Osc: Volume: 1	Filter Type: 36dB/Oct			Sustain: 1	Sustain: 1	Detune: 0.5
Fine Tune: 0.5	Noise Volume: 0.392	Keyboard Tracking: 1			Release: 0.46	Release: 0.48	Transposition: - 24
T-Mod 1: 0.192	Ring Mod. Volume: 0.628	Detune: 0.5			Velocity: 0	Velocity: 0	
T-Mod 2: 0.517	Feedback Volume: 1	Resonance : 1			Keyboard Tracking: 0.5	Keyboard Tracking: 1	
Source 1: ADSR 1					Break Point: 1	Break Point: 1	
Source 2: ADSR 1							
Vibrato: 0							
Pulse width 0							

Table 5.9 gives an indication of the static parameters that were set in the subtractive synthesiser, the second synthesiser. The MIDI parameters for these settings work within a range of 0 to 1 not from 0 to 127 like in usual MIDI standard.

Table 5.10: Static function setting for Synth 2 (Subtractive Synth)

Osc 1	**Osc 2**	**Master**	**Filter**	**Env Amp**	**Control**	**Reverb**
Pitch: 0.661	Pitch: 0.661	Volume: 1	Resonance: 0.33	Attack: 0.001	Osc crush bits: 1	Reverb size: 0.79
Osc:	Osc:	Portamento: -1	Keyboard tracking: +1	Decay:- 0.454		Hi Pass filter: 0.779
Fine Tune: 0	Fine Tune: 0	Master tune: 0	Filter Contour: 0.837	Sustain: 0		Low Pass filter: 0.519
Pulse Width 0.8	FM: 0.864	Transposition: 0.81	Filter LP: 24dB	Release: 0		
Phase: 0	Phase: -1	Voices: mono	Filter Env: Attack 0.286 Decay 0.454 Sustain: 0.881 Release: 0.449	Routing – Osc 1 Attack: 0 Destination amount: 0.813		

Reverberation

The reverb that was being added from Synth 2 was not enough and the sound of the dust clouds were still too harsh and metallic. By adding the reverb from another unit, the dust clouds became more grain like in sound and this made the sonification more pleasant to listen to. Two reverb units were used and were routed 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 muddy the signal and lose its sand grain effect the reverb size was set to a mere 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 design

The interface would consist of basic functions to load the dataset, control playback speed and the ability to select segments of the data that could be played back on repeat function. All these functions were the same as the ones on the previous interface. It was decided to keep these functions and to test them with AD to see if he wanted to change any of them. Even the playback speeds were kept the same to also find out how AD would manage them and what preferences he would choose once he had tested the interface. No volume control was added since there was only one signal and the user could control the volume from his laptop. This decision was taken after the third iteration. The original design had four volume faders allowing the user to control each speaker output channel. With the volume levels peaking at a MIDI output level of 75, it was decided to remove control of the volume to avoid any distortions that might contaminate the sonification with higher volume levels. It was after this third iteration that it was decided to include a recording device to the interface so that AD could record the sonifications of each of the accretion discs that he wanted to analyse. This would allow him to listen to the recordings in his own convenience on other media players of his choice. The recorder would allow AD to save the recording as a WAV, AIFF and FLAC audio file.

A small visual window was included to give an indication of the directionality and speed of the sonification as it revolved around the surround speaker system. People tend to consider visual references in addition to hearing to confirm localisation of sound sources (Ziemer, 2020). The visualisation consisted of a small yellow circle that rotates anti-clockwise which is the direction that an accretion disc normally spins at the speed of the playback of the sonification. Table 5.11 provides information about the functions that were built into the interface. Figure 5.5 displays the sonification interface with all its functions.

Table 5.11: Sonification interface functions

Function	**Reason for using these functions**
Playback speed	Changes in playback speed alter perception. Faster playback speeds allow comparing a number of datasets with each other and seeking patterns or differences between them. Slower playback speeds allow more detailed analysis.
Data selection & loop function	A start and end point could be selected. This selection could be looped, the playback speed altered, enabling AD to listen to these segments in more detail.
Recording Function	Record sonifications WAV, AIFF, FLAC formats to play on other devices
Visualisation data	A graphic visualisation of the dataset was used as a reference point. Number boxes included indicating line, time, flux and phase. By knowing the line number, AD could input a start and end point to listen to a specific segment of the data set.

Sonification can be listened to at: https://soundcloud.com/michael-quinton_napier/sets/asteroid-belt-in-an-exosolar

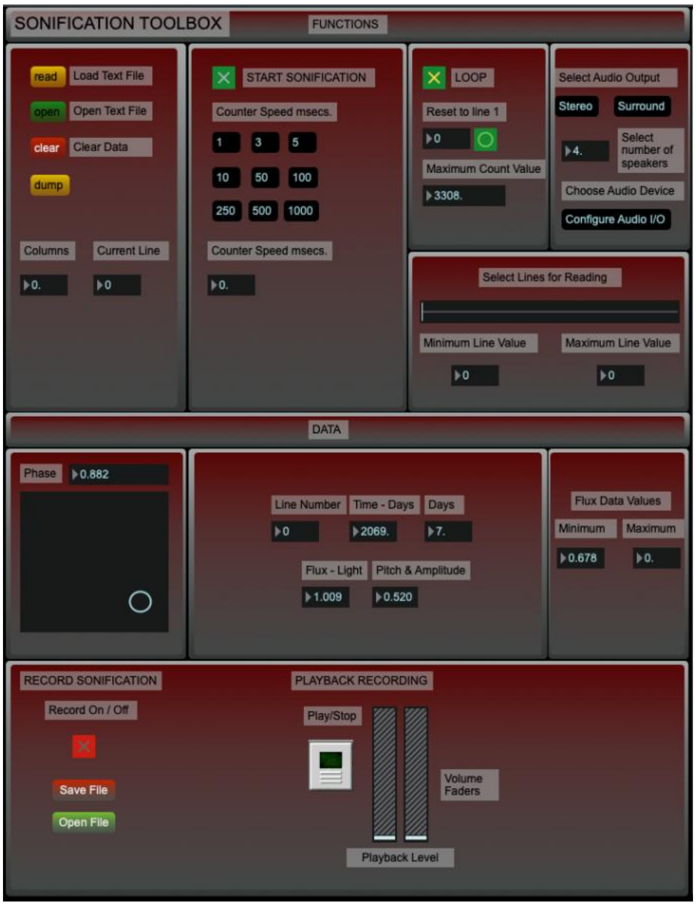

Figure 5.5: The sonification interface designed for AD showing all the functions & values of the data

5.5 Evaluation

The evaluation would determine whether any changes needed to be made to the parameter mapping and the functionality of the interface. It would also test whether the sonification offered any new insights to AD and whether it would serve its purpose in allowing him to classify the accretion discs.

Participants

AD was the only participant who tested the sonification. No other astronomers from AD's team who study this field of astronomy were available for the evaluation.

Materials

The sonification was tested on a Mac book with a firewire connection. An 8-output channel Digidesign 002 soundcard was connected to the computer so that four Genelec 8030A speakers could be connected to deliver the quadraphonic surround sound. Two speakers were placed in front of the listener, one left and one right. Two more were placed behind the listener one to the left and the other to 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 (Moore, 2012g).
A 24-inch HP, external display screen was used so that the user could use the interface on one screen and any other related software on the other one (Refer to figure 5.6).

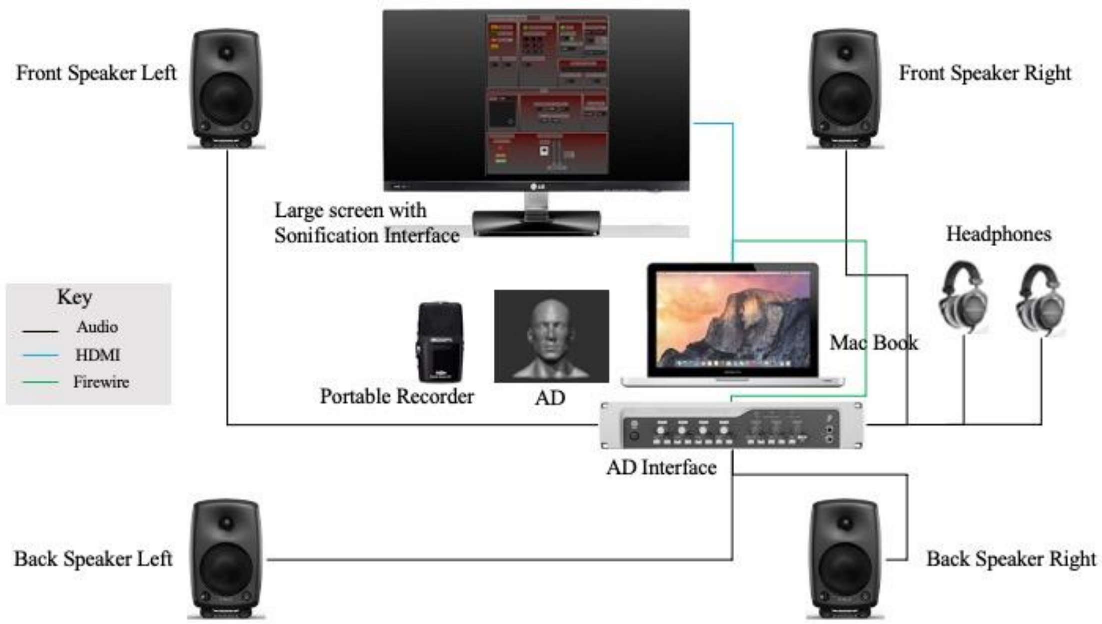

Figure 5.6: One of three set ups used for the first and second stages of the evaluation

A Native Instruments S2 mark 1 allowed the playback of four datasets that could be altered using the onboard EQ, by adding effects and to crossfade between the different channels in Native Instruments Traktor. Another two Genelec 8030A speakers were used to run the audio from the S2 controller. These speakers were also place to the front left and right of the listener and can be seen in Figures 5.7 and 5.9. This set up was used for the second part of the first stage of the evaluation so that added effects and other tools that could be added to the sonification interface could be demonstrated to AD .

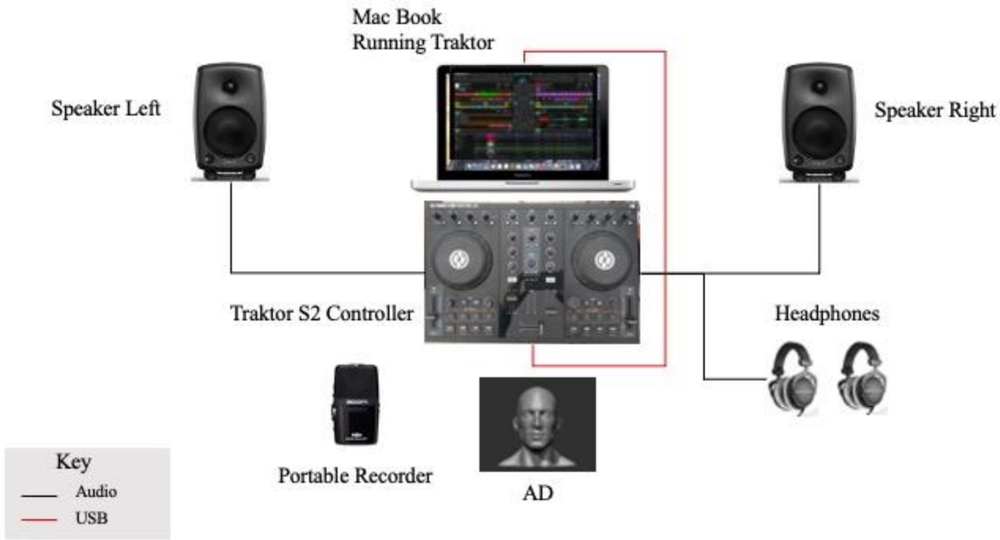

Figure 5.7: One of three set ups used for the second part of the first stage of the evaluation

An Akai MPC mark 2 allowed the use and control of 40 different datasets simultaneously in Ableton Live 9 and this set up was used for the third stage of the evaluation. This setup would allow AD to have all the different datasets laid out in Ableton and could be played by pressing one of the buttons on the Akai MIDI controller. This would allow flexibility for cross referencing accretion discs allowing easier access to switch between them for comparison. Figure 5.8 demonstrates the set up for stage three of the evaluation.

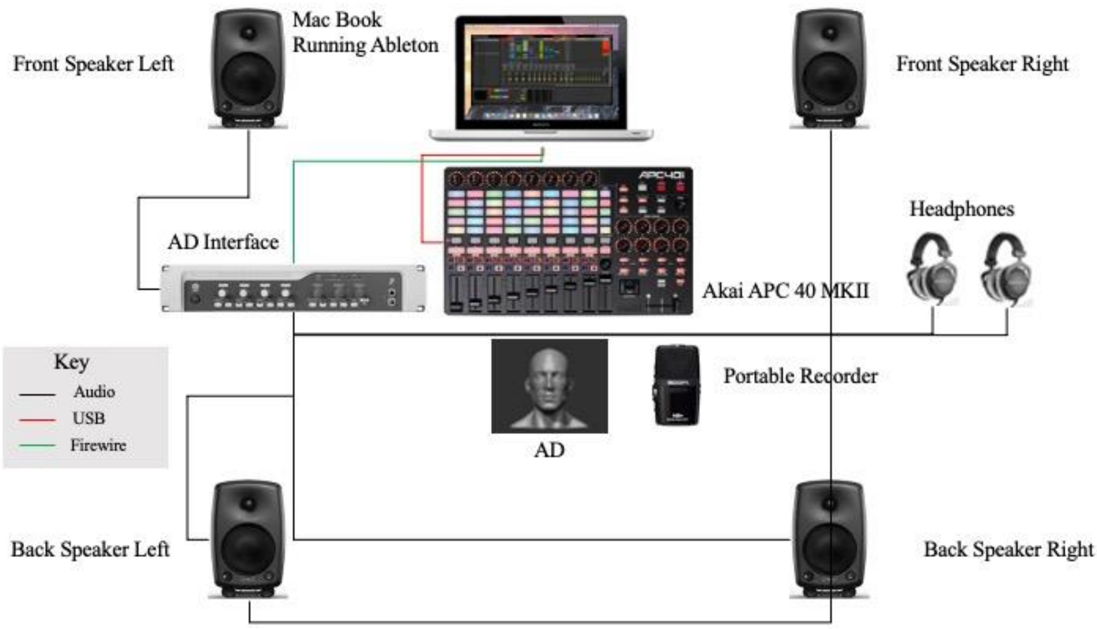

Figure 5.8: One of three set ups used for the third stage of the evaluation

Both interviews were recorded on a Zoom H2N portable audio recorder. Answer sheets (refer to Appendix C) and pens were provided. The interviews took place in a soundproofed auralisation suite at Edinburgh Napier University Merchiston Campus. This environment was quiet and did not suffer from any ill reflections that could taint the dataset. Figure 5.9 shows the setup in the auralisation suite. An informed consent form and participatory information sheet were provided describing the experiment and informing AD about voluntary participation (Refer to Appendix C). The interviews were recorded and transcribed.

Figure 5.9: Set up for the evaluation in an auralisation suite

Design

The evaluation consisted of three parts. The first 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. A copy of all the questions from the three parts can be found in Appendix C. The questions were adapted to suit the functionality of the sonification. Since the data was different to the data used in chapter 4 the questions had to be adapted accordingly. AD's dataset was time based whereas WV's data was spectral. The purpose of the sonification was also different since AD was using the sonification for classification of multiple systems whereas WV was testing to see if sonification could bring out masked characteristics of water vapour data amidst noise that is inherent in the dataset. Questions concerning the interface also differed in instances in relation to components that were not included in WV's interface like the use of surround sound, only one loading system for one dataset, no volume control and a recorded function, plus all the different number boxes that represented different astronomical measurements.

The first test consisted of two sections. The first part consisted of seven questions that were intended to capture AD's initial impressions of using the interface. The second section consisted of thirty two questions about possible extra functions that could be added to the interface.

The second test inquired about the efficacy of the sound design. A total of thirty four questions were asked about the sonification's effectiveness in relaying the data and to see whether the sound design required any changes.

The third test consisted of playing back twenty datasets that were chosen that were split into four sets of five. Each set consisted of accretions discs that had a variety of characteristics such as discs with not many dips, others with an average amount and others that were quite active. Each set consisted of discs with dips of various sizes. In some discs the dips were much bigger than others, while other discs had more homogeneous sized dips. Some datasets had more random changes and others were more constant. These are the common characteristics that were found when listening to 50 of the datasets and were used as the criteria for selection. Each dataset had been recorded at a playback speed of 1ms. AD would have to listen to each set of five 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 sonifications that he had listened to.

Procedure

The interview lasted roughly around four and a half hours long. At the beginning of the session AD was allowed to use the interface and to explore its functions. This gave him time familiarise himself with listening to the sonification and to switch between quadraphonic surround and stereo. He could also load and playback various datasets at different speeds. AD signed a participatory consent form before starting the evaluation. After spending a thorough hour of playback and familiarisation, AD proceeded to answer questions for the first evaluation which lasted about an hour and a half. A lunch break of about one hour was taken in between. The second test took about an hour and a half and AD answered questions about the sonification design. The third test proceeded immediately after the second test and lasted about an hour. Originally this test was supposed to compare forty datasets to each other, but this was cut down to twenty accretion discs, four sets of five datasets due to limitations in time. AD answered all the questions in all three sessions and his responses were recorded on a Zoom H2N portable audio recorder. All three interviews were transcribed and coded using the same system based on grounded theory that was used in the requirements gathering stage. This system seemed appropriate for extracting the information required to make adjustments to the interface based on the data collected from the evaluation.

5.6 Results

The evaluation of the sonification was split into three parts. The first assessed the usability and functionality of the interface. The second appraised the sound design and the third test was designed to see if AD could classify the datasets that he had listened to. AD had already used the interface during the iteration process. He had been sent a copy of the interface, a list of instructions and he had some time to explore the interface, with the original dataset and didn't try it with the other datasets. He could not test the surround sound function before the evaluation since he did not have a surround system to work with. Before starting the evaluation, AD was given a quick revision about the interface and how it works. Once this was completed, AD was given about an hour to explore the interface, test the sonification and to load various datasets into the system and listen to them both in stereo and surround sound. He was able to navigate through the different sonifications without difficulties and could already spot various characteristics, patterns and even differences between the different datasets.

First Evaluation – The Interface

This evaluation was split into two parts (Refer to Appendix C). The first part consisted of seven questions and aimed to capture AD's immediate impression of the usability of the interface. The questions dealt with ease of use and functionality. The second part consisted of thirty two questions about any further adjustments that could be added to the interface. The interview was semi-structured to allow further scrutiny about points mentioned by AD that aroused further interest in exploration. The questions were customised to allow AD to talk about the interface design and to extract rich descriptions that he could use to describe different functions. Then specific questions would be used to get more detailed information about a specific function. This is the reason why a UEQ (User Experience Questionnaire) was not used since the questions were too general and more specific answers were required concerning individual components of the interface, more detail on the aesthetics and other details which were specific to this sonification design. The UEQ could be more effective when used with a larger testing audience.

First Impressions

AD first impressions about the sonification were that the interface was comprehensive and easy to use. He had no prior expectations with regards to how the sonification might sound: *"Well I didn't have any expectation of what sort of sonification you would do but the one that you've done seems to work."* AD found that the sonifications created immediate associative impressions: *"I had some kind of association that makes sense, so that 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 quantitative as well, which is good"*, *"I like that!"* 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 quantifiable recognition of the sound object also gave a strong impression of the sense of time of the accretion disc's passage in front of the 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 that the various nuances of detail helped to make distinctions between different accretion discs more definite: *"There's a bunch of different things, bits of information which tell us a different story about each individual system."* As far as first impressions go AD felt that the sonification: *"I think it works pretty well."*

The interface – additional functionality or revision

The initial impressions of the sonification on AD were positive and he was able to identify quantifiable dimensions and movement that gave strong associative ties to the data. The second part of the interview consisted of questions concerning the use of the interface and any possible additions or revisions that could be made to improve the 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."* Even when using it for the first time AD found that the interfaces ease of use could be compared to a digital media player such as iTunes or other similar platforms.

With regards to changes AD found that the playback speeds could be limited to a range of 5 milliseconds to 100 milliseconds. Any speeds below 100 were too slow and any speeds faster than 5ms was too fast. 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 playback speed was 10ms which he found comfortable to listen to both on the stereo and on the surround sound configuration. This speed would allow him to hear details like short dips and at the same time not take too long to finish the playback.

AD found that the information boxes providing information about the minimum and maximum range of the light curve were not really necessary. The visualisation that indicated the direction and speed of the rotating sound was rather distracting and that it wasn’t really needed. The cue point selection for playback wasn’t something that he was particularly using since he was more interested in listening to the overall impression of the light curve. He didn’t say that it should be removed but that 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 that many that AD would want to add to the interface. He was particular impressed when the sonification was filtered using Equalisation (EQ) in Traktor that had strong 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. He found that this information could be useful to have: *“The EQ seems to be a powerful way of isolating something out maybe for comparing things.”* It would be especially useful when weighing up two datasets to each other so that the features of one light curve can stand out against the other and vice versa.

AD also felt that the addition of a metronome would be useful to have especially when listening to the light curves in surround sound. This would help the user to be able to hear any rhythmic patterns in a light curve coming from the dips. It would also make it easier to notice any lags in timing in the frequency of the dips occulting the sun. This could possibly mean that a heavier, denser body is crossing in front of the star. This could suggest the presence of a planet or a dense asteroid belt that could indicate that the exosolar system is starting to change and to host planets. The metronome would also help with localising sound on the surround system, hearing the timing and the metronomes click and also being aware of the spatial position of the signal. The metronome signal was suggested to be kept at a central point while the rest of the sound rotated around the surround field. That way it would be easier to determine the signal from the metronome.

The last additional function that AD would be interested in including is a function that tells you the length of the light curve in seconds before playback. This idea was inspired by the audio files that were loaded into Native Instrument’s Traktor and a length in minutes and seconds of the audio file would immediately appear when the loading was completed. To summarise the data gathered from the second part of the first evaluation, Table 5.12 will list all the additional functions and changes required by AD.

Table 5.12: Additional & revisional functions for the interface

Revisions		**Additions**	
Functions	**Changes**	**Functions**	**Suggestions**
Playback speed	Reduce range of Playback speed 5 to 100 ms	Equalisation/ Filters	Add filters low pass, Band Pass and Hi Pass to interface to filter out aspects of sonification so that listener can listen to specific aspects of the data in different frequency ranges.
Light Curve Range	To remove	Metronome	Addition of a metronome as an indication of temporal-spatial qualities of the data when using surround sound, kept in a central pan position
Visualisation	To remove	Function gives length of light curve	A function that gives the length of the light curve in minutes and seconds as soon as it is loaded into the interface.

Second Evaluation – The Sound Design

The second evaluation was designed to find out about AD's impressions of the sonification. It was to inquire whether the parameter mappings were clear for him to understand, whether the aesthetics suitably represented the data and to see what additional value the sonification added to the data analysis process. This evaluation consisted of 34 questions (refer to Appendix C) that asked about the sonification design, it was also semi-structured and allowed the interviewer to ask additional questions if required. The second evaluation lasted about an hour and a half.

The sonification was easily comprehensible to AD and he could comfortably understand how the parameter mapping correlated to the dataset. He could immediately discern the dips as they rose in pitch. He was quite surprised by the spatial representations both stereo and surround and how the perspective changed when switching between the two systems. He found that the pitch range of the sonification was comfortable to work with. It offered a broad enough range to give clear definition to the different dipper sizes. It had enough low end and had been calibrated to suit the speaker system, the high end did not go beyond his hearing capacity: *"I think the range must be pretty much right!"* AD found 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 other more subtle mappings of changes in timbre and reverberation helped more with associating the data to sand grains: *"There's the graininess, like the fact that you've not ever got pure tones, that's underlying everything."*

The spatial representation of the sound was deemed as being an important mapping for AD. Both the stereo and the surround sound options added stronger discernment of the data in different ways: *"That's the benefit of having both of them. They tell you similar but different things."* AD had found that by switching between the two spatial choices this allowed him to get a different impression of the dataset and this led to further insights about the nature of the accretion disc in relation to the star in terms of size and proximity: *"I think having both is actually pretty important because they give you different aspect of the light curve behaviour."* It also offered more information about the sizes of the dippers and their periodicity and frequency: *"What the surround gives mostly is being able to localise things in phase."* When a certain light curve went out of phase then it was immediately detectible. 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"*.

There was just one aspect with the surround sound that would need revising. During the playback the sound kept ducking (reducing drastically) in volume 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 more even. The problem continued to persist, and this was brought up by AD who found that the ducks in the signal were quite distracting:

> *"I think the main thing is having the surround panning be smoother because it feels like you're sitting in a circular room with four windows and something is running around the outside and you hear it when it goes past the window."*

This issue would have to be addressed and a solution found in order to have a continuous, non-interrupted signal rotating around the user's head.

The sonification was successful at allowing AD to extract the necessary information expected from the dataset. It also gave a more distinct definition of the temporal-spatial essence of the data. The sonification allowed AD to immediately hear differences between different datasets. He could hear regularity of dips between various systems, he could even discern from the speeds and frequency of the dips whether a system was closer to the star: *"There are different bits of information which tell us a different story about each individual system."* He could discern temporal and spatial dimensions clearly and could even hear size and dimensionality of an object or cloud. The sonification could present quick comparisons between different datasets. There was also more required listening to hear more subtle details. Seeing the amounts of data that were being portrayed by the sonifications, 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 by giving it sand-grain like features it not only made it easier to listen to, but he also found that it gave the data a certain physicality. The use of a more natural, familiar sound helped in terms of immersion and 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 further 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."* We often forget that most of the visualisations that we see of space phenomena are interpretations made out of scales of the numbers that are gathered by various technological apparatus. In a general aesthetic sense AD felt that: *"It feels like a good representation."*

AD was asked about the positive aspects of using sonification and about his likes and dislikes of using this medium. His overall experience was a positive one and he found nothing to dislike about using sonification. It was not tiring or irritating to listen to. He spent more than an hour listening to light curves and did not tire or feel that he needed 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 that the sonification had exceeded his expectations but also felt that dipper data was probably too simple a dataset to use with sonification. The sonification clearly and accurately represented the dataset but did not offer any 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 even 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 to his work AD 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."* This comment in particular echoed the way that sonification was used in the previous study in Chapter 4. AD had no knowledge at all about this study but somehow intuitively felt that sonification would be more effective when used in such a context.

One thing that AD did affirm is that sonification is an effective means of recognising patterns and that this was one way in which this particular sonification could offer advantages to his current work habit.

These conclusions were drawn before AD had attempted to try classifying the datasets and seeing if the sonification made the process of classification more robust and insightful. This process would be tested in the third and final evaluation concerning this sonification design. To summarise the Second evaluation Table 5.13 breaks down the feedback obtained.

Table 5.13: Summary of the second evaluation: Sonification design

Sonification Design	User Feedback
Accuracy	Dips were immediately discernible, and it was possible to tell differences in sizes of dips and of the actual accretion discs whenever they were present in a dataset
Parameter Mapping	Pitch allowed for quantifiable recognition of size and Spatial mapping enhanced these dimensions and gave clear indication of time-spatial relationships to the data and the parent star
Sound Object	Data was quantifiable and the dimensions of the objects were clearly discernible
Spatial Mapping	Spatial mapping was highly effective and gave broader definition to the sound objects from the dataset
Aesthetics	The use of natural, familiar sounds strengthened immersion, engagement and understanding of the accretion disc’s dimensions and of the dips
Use of sonification in work on dippers	Effective to use and accurate at representing the data but does not present new insights probably due to the simplistic nature of the dataset.

Third Evaluation – Classification Exercise

The third test was designed to use the sonification to classify a number of accretion discs according to their characteristics. Originally the test consisted of playing back forty datasets that were split into sets of five. Due to limitations in time available to AD only 20 accretion discs were tested. Each dataset had been recorded at a playback speed of 1ms and for section one AD would have to listen to four sets of five accretion discs and to classify each one. To structure the classification, AD was asked ten questions for each set concerning characteristics of the light curves (Appendix C). Section 2 required a more general assessment comparing all the light curves in all four sets. It consisted of eight questions that were designed to see whether certain patterns or trends emerged from the dataset. The third section inquired about the classification process and the sonifications that AD had listened to (refer to Appendix C for all the questions).

Classification test – Section 1 classification of twenty-four light curves

In the first test AD was asked to listen to four sets of five light curves and to classify them according to characteristics that he thought were relevant to his work. AD classified the light curves according to the depth of the dips. The Regularity of the light curve which indicated whether there were many changes in light flux. The Activity, or how active a light curve was in terms of the dips in flux. The change whether there were any changes in the rhythmical structure of the light curve and the frequency, the speed at which the light curve would spin. Each of these characteristics was graded with a number from 1 to 5 where 1 was the lowest number and 5 the highest. Table 5.14 shows the scores that AD gave to each characteristic of each light curve. There was one problem with some of the light curves. The baseline had not been set properly by AD for these datasets making them sound higher in pitch. He had not realised that he had made this mistake when he had presented these datasets to be tested. It was noticed by the researcher that these datasets sounded higher in pitch before the testing, but this was not considered to be an error due to lack of knowledge in this regard. When AD heard the differences in the pitch in these datasets, he immediately recognised that the baseline had not been set properly when he compiled the datasets. This limited the comparisons that could be made between the faulty sets and the ones that had been calibrated to the same baseline. These have been marked with an Asterix (*) in the table below.

Table 5.14: Classification of light curves

Set 1	Depth	Regularity	Activity	Change	Frequency	Comments
1	3	1	4	2	?	2 and 3 similar but not normalised. 1 & 4 sound similar. 5 sounds different: most active, deepest dips and deeper sounding
2*	4	2	3	2	?	
3*	4	2	3	4	?	
4	2	1	4	2	?	
5	5	2	5	3	3	
Set 2						
1*	3	3	3	2	4	1 not normalised 4 & 5 similar, very large dips. 2 & 3 similar, 4 lots of dips at first quiet towards the end and was different
2	3	1	4	3	2	
3	4	3	4	2	2	
4	5	2	2	5	3	
5	5	2	3	2	3	
Set 3						
1	5	2	5	2	3	1 biggest dipper, none of the light curves were similar. 5 not active, 2 low dips and 3 had large dips
2*	3	3	3	2	2	
3	5	5	4	2	1	
4	4	1	4	4	2	
5	4	2	1	4	?	
Set 4						
1	4	2	4	2	3	3 & 4 similar, 2 not normalised, 1 & 5 similar, 1 & 4 largest dips. All light curves active except light curve 2
2*	2	1	2	2	?	
3	3	2	4	2	2	
4	3	2	4	2	2	
5	4	3	4	3	1	

There were instances where AD found it hard to distinguish the frequency of the light curves especially in the first set. This happened since he had nothing to compare the first set of light curves to. His scores improved over time 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. He could hear differences in speed and could make out the different depths of various dips. He could tell which light curves were not so active and could even follow a light curves' activity and the depth of that activity. Probably if the sonifications were run at a slower playback speed then he could probably discern more detail. He had already mentioned that he found the playback speed at 1ms to be too fast and that he found it hard to follow the details at this speed.

Classification test – Section 2 Comparison of different datasets over all four sets

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 recognisable 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 much 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 spoke about the differences in rotation speed between the discs and described how the faster sounding dips were the ones that orbited closest to the parent star. He also suggested that the very deep dips probably consisted of large dust clouds that were blocking the star out significantly. Objects that are further away from the star rotate around it at slower speeds. We see similar laws of motion governing 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. This is what probably made them more distinguishable. These accretion discs also consisted of an interesting level of activity that made them more compelling to analyse in more detail.

Classification test – Section 3 General questions about the test

Section 3 was designed to inquire about AD's classification experience and to gauge whether he was able to successfully classify the accretion discs using sonification. When asked about how easy it was to discern details from the various sonifications AD found that he was easily able to do this. 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 difficulty. AD struggled to sense the regularity of the discs dip rate activity due to the speed of the playback where he felt that it 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 highly 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 mull over what he had heard and to listen to these sonifications again and probably at a lower playback speed. During the exercise itself AD felt that he didn't really learn anything new. However, he was impressed that the sonification compressed three months of data into 5 seconds and this immediate recall of events was advantageous when working on multiple datasets.

AD felt that the classification could be done quite easily especially when considering that he had never done it like this before. With more practice and the ability to listen to the datasets in more detail he could reap more information than he had currently extracted. This led to whether anything else would need to be added the sonification. AD felt that as it was, the sonification did not need any further additions. He did however refer to the addition of an EQ filter and to add the solar data as a separate feed and then make the comparisons between the stellar data and the accretion disc. This could possibly help in understanding whether the accretion disc truly did rotate in synchronicity with the star's rotational orbit. He did remark however that stellar mass data is just a rough approximation and that with these stars in particular were quite faint. The mass is usually calculated on the basis of the star's temperature. According to the heat detected from the star, astronomers can calculate whether it is of a small or large mass.

5.7 Discussion

The evaluation of the sonification design brought forward a number of aspects concerning its effectiveness. The sonification mirrored the data accurately, which is one of the points that Grond and Berger (2011) describe for effective sonification design. The sonification represented the changes in light flux to the point where AD could get an impression of the quantifiable dimensions regarding the size of the dippers and of the accretion discs. 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, then one could suggest that it did represent these dimensions in ways that a 2D visual graph cannot. The sonification worked effectively but AD felt that the sonification did not really present anything new. AD would still be able to do the same work using a visual graph or looking at the numbers. The sonification enhanced aspects of the data but it offered no new level of understanding of the phenomena that were being studied.

This sonification design follows up from the previous design in chapter 4 in the way that it was able to accurately represent the data. This suggests that the user centred design method that was employed was effective at achieving this level of accuracy. This also suggests consistency with sonification designs that were analysed in chapter 2 where we see examples from Alexander et al. (2011), Tomilson et al. (2017), Ballora (2014), Schaffer et al. (2012), Diaz Merced (2013), Verona (2017) which involved user centred design methods. The interviews in chapter 3 with Walker, Vickers, Barrass, Verona, Ballora, Philart Jeon, Nesbitt, Alexander who had also discussed user centred design and its relevance in finding out more about the user, the purpose of the design and what the data represents.

The sonification designed in chapter 5 reinforced the first four guidelines that were put forward in chapter 4: The importance of requirements gathering; The need for a data analysis system that allows for the data to be the basis of the sonification design; The use of iterative prototyping so that the designer can reap a deeper understanding of the purpose of the sonification and the data representation. These three points all add up to the fourth guideline, communication, an essential thread throughout the design process.

These were also four of the five guidelines that emerged from the interviews in chapter 3 which were also based on good requirement gathering, the design suiting the requirements of the userbase, the establishing of a good communication channel between the user and the designer, and the fourth guideline encouraged the use of an iterative design process.

In astronomy many of the concepts are complex and time is needed to get used what exactly is being represented by the datasets. This level of understanding is achieved both by speaking to the astronomers but also by involving them in the design process (Kirwan & Ainsworth, 1992). In both studies it was important for the designer to know about the astronomers' perception and interpretation of sound properties (Pirhonen & Palomaki, 2008).

In chapter 4 and in this chapter, the iterative design process reflects how the model evolved over time and how inaccuracies related to the data representation were identified by the astronomers in these stages of the sonifications' development. In chapter 4, WV was aware that the peaks needed to stand out against the noise signal due to knowing how overwhelming the noise would be. The first and second iterations were weak in representing this and the feedback from WV helped to arrange the peaks and represent them more rigorously to stand out against the noise.

In this chapter, the scale that was chosen to represent the data was only adapted to suit one dataset. Once other datasets were tested it became immediately evident that more headroom was needed to compensate for higher values that would be found in other datasets. It was AD who had understood why these sudden, sharp glitches were occurring, and once this was explained then the scale could be adjusted to work with other datasets. This suggests that the purpose of the sonification in both studies determined the design (Sebillotte, 1995).

In chapter 4 it could be seen how the use of familiar sounds or concepts in the sound design were considered to help WV to associate the sonification to the dataset. Using the same design principle in the sonification described in this chapter, AD also found that he could relate to the data and that the sonification made it sound realistic and tangible. In his own words, AD felt that the data was 'quantifiable'. The sonification could not help AD to hear actual, measurable quantities but he could get a clear idea of the differences in size in the dust clouds. This relates to the dimensions that sound is able to portray with regards to dimensionality as highlighted by Chion (1994). In both studies the sonifications were only tested with one astronomer per study, but there are now two studies, with different sound design principles where familiarity has helped both astronomers to get a more tangible and realistic understanding of the datasets that they work with. The use of familiarity reflects the suggestions that Barrass, Vickers, Ballora, Ferguson and Verona had mentioned in chapter 3 about using familiar sounds that the user can associate with. Cycowicz and Friedman (1998), Fencott & Bryan-Kinns (2009) and Smalley (1997) had also pointed out how listeners associate sounds to the related causes.

In order to sculpt the sonification design to sound more like a realistic or familiar object multiple parameter mapping are required. This was seen both in the previous study and in this study. The psychoacoustic properties work cohesively to mimic the sound object (Moore, 2012a). The understanding of how a sound is formed, is essential knowledge needed when designing sound that replicates the world around us (Bregman, 1994) and this reflects the eighth sonification guideline that was put forward in chapter 4 which is tied to the designers' knowledge of the tools being used. In chapter 5 the designer struggled to use additive synthesis for the sound design. Additive synthesis works in a closer relationship to nature where both in nature and in additive synthesis sound is made from inharmonic partials (Farnell, 2010d). It could be a more effective method of synthesis to use in order to represent natural, environmental sounds.

Spatial mapping has been used in both studies. In chapter 4 this was limited to work within the stereofield where it effectively separated the source from the noise signal. The movement of both signals allowed WV to perceive a water element that was currently overlooked when using visualisations of the data. In this chapter AD could choose between using stereo and surround sound and he found that both methods of sound representation could present different findings concerning the data. The stereo configuration helped AD to get a better sense of the sizes of the dust clouds since he could hear their relative dimension according to how much they panned from right to left ear. With the surround sound AD was able to get a better sense of the speed and proximity of the accretion disc and its relation to the parent star. In both studies the use of spatial mapping has been able to enhance sound object dimensions. This is reflected in work by Korland-Martinet & Voinier (2008) who also found that changes in timbre in relation to spatial movement strengthens perceptual recognition. This also reinforces the need for multiple parameter mapping since timbre plays an important role in sound object identification and movement (Song & Beilharz, 2007).

AD had stated that the sonification had superseded his expectations and that it could represent the data just as accurately as the visual graphs. This would be worth considering in the context of astronomers with impaired vision or blindness.

AD believes that sonification would be more beneficial when used with more complex datasets that contain multiple dimensions of data. He had felt that even though sonification accurately represented the dataset, since the data itself was quite flat and one dimensional then it didn't offer enough potential that sonification could possibly exploit. AD had also added that he had wanted more time to compare the different datasets and listen to them in more detail. The classification exercise that was conducted in test three worked within a limited time window of one hour. AD did not have time to familiarise himself with the different datasets and did not have time to develop the categorisation properly. It was also limited to a playback speed of 1ms which AD had complained that he found too fast for him to hear the details properly. Maybe with more time he could discover more artefacts related to the data and also develop a better system for categorising the data from the different accretion discs. This could be something that leads to a potential discovery through the use of sonification.

The final stage of evaluation was effective at finding out what further changes would need to be made to the sonification interface. The sonification design described in this chapter was similar to the one in chapter 4 where the actual sound design did not need any revisions, but it was the interface that would require certain additions and adjustments. In both studies the playback speed was suggested to be revised getting rid of the extremely fast and extremely slow speeds and working within the range of 5 to 100 milliseconds. Both astronomers had suggested using astronomical measurements instead of using line numbers.

Even though the sonification did not offer any new insights about the data but it did accurately represent the dataset effortlessly. The sonification was effective at compressing 80 days of data into milliseconds allowing the astronomer to perceive the accretion disc and its characteristics in a short amount of time. This was especially advantageous when comparing different datasets to each other, where the classification of accretion discs was achieved, but maybe more practice with the system could present more valuable insights to AD.

This study was also limited to only being tested with one astronomer who works in this field of astronomy and this presents limitations to the study. However, one must take into consideration that out of two sonifications designed for different aspects of astronomical data, both designs were clear representations of their respective datasets. This could suggest that the sonification design principles being practised in these studies could be effective for designing sonifications for astronomy, although further investigation would be required.

As a conclusion to this chapter, the sonification design guidelines suggested in chapter 4, which were based upon the guidelines suggested in chapter 3, have been effective at designing the sonification in chapter 5. At this point the guidelines do not need to be reviewed or refined but can be once again be tested in a third study, and to see whether they will still be applicable in the context of another aspect of astronomical study.

The Following chapter will describe the design of a third sonification design with another astronomer who works in a different field of Exosolar Planetary research. It will describe the design process, the testing and the evaluation and conclusions drawn about the project.

Chapter 6: Sonification of Planetary Orbits in Asteroid Belts

This study investigates the design and evaluation of a sonification designed to help astronomers detect any planets orbiting within an asteroid belt of an exosolar system. The interface was designed for an astronomer who studies this phenomenon. User centred design methods were applied to create an accurate sonification of the data that could allow the astronomer to perceive possible planetary movements within an asteroid belt. The sonification was developed over three stages: A requirements gathering exercise inquiring about the data that the astronomer uses in her work. A design and development stage based on the findings of the requirements gathering and the third stage, an evaluation of the sonification design. The sonification effectively allowed the astronomer to immediately detect a planet orbiting within an asteroid belt. Multiple parameter mappings provide richer auditory stimuli for the user. The use of more familiar, natural sounding sound design helped the astronomer to strongly associate the sonification with the dataset. The use of spatial mapping and movement allowed for immediate identification and understanding of the course of the planet through the asteroid belt.

6.1 Rationale

This study intends to see whether sonification can be successfully applied to a dataset that represents the movement of a planet in an asteroid belt. The movement is reflected through the collision of asteroids that occur in the planets trajectory as it orbits around the parent star of an Exosolar system. The previous studies in this thesis have been building upon certain sonification techniques that include the use of auditory affordances and spatial parameter mapping. Even though both astronomers had found that these methods were effective, but they have only been tested with two astronomers. To further develop these techniques, it is believed that they should be tested in a different context. The dataset represents the movement of a planet through an asteroid belt. The orbit does not change, and the nature of the planet does not vary over time, but its gravitational force has an effect on the asteroid belt within which it is situated. The colliding asteroids are pushed out of the way of the passing planet and this causes a ripple effect throughout the belt causing a wave in the belt. The angle of the belt is determined by the axial tilt of the central star around which it rotates. The data is a simulation of an Exosolar system designated as the Beta (β) Pictoris system. The astronomer who participated in this study wanted to see whether sonification could be used to immediately detect the presence of a planet within the system from the asteroid collision data. The sonification was designed according to the user's requirements and the practice of iteration was applied to ensure that the data had been represented accordingly. The final version of the interface was evaluated to see if the sonification enabled the astronomer to detect the planet, how effectively this was done and whether any new insights could be determined.

The dataset consists of temporal qualities indicating the various collisions that occur over time which are being affected by an external force (in this case, the planet). The collisions occur at coordinates both horizontal (X) and Vertical (Y) since the model is a 3D visualisation. The size of the collision is represented in a fourth column. This represents the magnitude of the collision. The collision itself indicates the meeting point of two bodies where the impact occurs. The dataset reflects a certain degree of complexity of spatial movement and localisation. Chowning (1971), states that source localisation when listening is a normal process, which suggests that when one listens to a sound one also expects to understand where the source is coming from and its context within the given space. This also suggests that spatial mapping is more likely to provide familiarity to the listener and a more accurate representation of a natural occurrence.

Sonification systems tend to be less effective when a complex data space is represented through a linear audio signal (Rosli et al. 2015). Spatiality provides required depth to an otherwise flat, sonic representation (McLeran et al. 2008). Sound is spatial by nature, meaning that it propagates and interacts with the given environment and through this interaction it provides directionality and exact source location (Nasir and Roberts, 2007). The use of surround sound extends beyond this limitation and gives a sound object more contextual and directional definition by transmitting more auditory data to the subject (Childs and Pulkki, 2003). Sound is explicitly related to the perception of time and evokes meaning within the listener (Liljedahl & Fagerlönn, 2010).

To convey these complex concepts clearly to the astronomer user centred design methods could help to create a successful sonification design (Lenzi et al. 2020). In the previous studies in chapter's 4 and 5 these design methods allowed both sonifications to mirror the data accurately. These methods can help the designer to attain the user's concepts in relation to the data and to understand the meaning and social significance that an object or event may convey (Hug, 2008). The sonifications created for both studies in chapter’s 4 and 5 applied the use of auditory affordances where natural, familiar sounds were applied. Various sonification designs have used familiarity in their work (Blanco et al. 2020; Wolf & Fiebrink, 2019; Mauney & Walker, 2004; Vickers et al. 2014; Nees & Walker, 2009). The sounds themselves are meant to work as a narrative that could convey recognisable concepts and quantities related to those objects. Sometimes the sound does not represent the object directly but articulates the related concept to the object or event. In film sound a principle known as *idea-associative comparison montage* is where sounds are chosen that are congruous to the event on screen. Apparently disassociated, yet conceptually related events are used to strengthen a basic notion (Zettl, 2013). In the study conducted in Chapter 4 Water Vapour was represented by a water-like sound that mimicked rainfall or flowing water. It was not the sound of water vapour itself. WV was able to relate to the sound design and immediately recognised that the water-like qualities represented water vapour.

In this study the idea of planet detection is based upon the result of the colliding asteroids that are being affected by a planet’s trajectory. There are various concepts that arise concerning the nature of the collisions, how an asteroid would sound when striking another one and how this would reflect the existence of a much bigger planet which is causing these collisions. Bødker and Klokmose (2016) describe how many designers who aim to produce more natural and intuitive user interfaces apply Fauconnier and Turner’s theory of *Conceptual Blends*. This theory is about creating a qualified match between two mental spaces and that selective components from these two inputs are blended together into a third mental space. The mental space is described as minute partial concepts formed from thought and dialogue for purposes of understanding and action (Fauconnier & Turner, 2003). MacDonald and Stockman (2018) used this method of blending to create auditory display design theory where user design methods were blended with film soundtrack composition and drew clear parallels between the different compositional processes. Requirements gathering was compared to Scene spotting, Conceptual design to Compositional arrangement, Detailed design to Musical scoring and finally, Evaluation in both cases.

Sonification design points towards the investigation into listening trends for a deeper understanding of user interface interactions. Listening is giving active attention to extract information from the sonic environment (Tuuri & Eerola, 2012). Oliveros (2005) takes listening to an expanded level of learning where she describes sound as carrying intelligence, ideas, feelings and memories. Ceraso (2014) states that listening should go beyond the perception of the ears, but also felt physically by the body.

In the previous two chapters the sonifications designs were modelled on a set of guidelines that were devised in chapter 4 and were developed in accordance to the criteria of that study. These guidelines had been influenced by findings in the literature review in chapter 2 where various sonifications were designed with the user like for example the various studies conducted by Schaffer et al. (2009; 2010; 201; 2012), Tomilson et al (2017), Verona and Peres (2017). The interviews in chapter 3 contributed to this after receiving first-hand information from various sonification designers and five guidelines were put together based on the methods described in these interviews. In these guidelines user centred design methods were highly encouraged. As seen on the previous two studies in chapter's 4 and 5 user centred design methods were effective for designing both sonifications that accurately mirrored both datasets in sonic form. This does not suggest that these methods offer a global remedy for sonification design but catalogues successful design criteria that have been tried and tested in two different studies related to exosolar astronomy. The design principles that had been put together in chapter 4 and also utilised in chapter 5 are being tested again in this study.

To summarise the objectives of this study, it was believed that sonification would help the astronomer to detect a planet in an asteroid belt situated in an Exosolar system. The guidelines that have been put together in chapter 4 were tested again to measure their consistency in designing sonifications for Exosolar Planetary astronomy. The final version was evaluated, and the results were presented in this chapter.

6.2 Method – Requirements Gathering

The requirements gathering exercise was conducted as a semi-structured interview with an astronomer henceforth referred to as AB. The interview lasted about one hour and was focused on learning about AB's work, the type of data that she works with and how this could be sonified.

Participant

AB is a female in her early thirties who has been working as a professional astrophysicist for about 8 years. Her work involved the development of a 3D visual simulation of an asteroid belt situated in an exosolar system. The simulation was called SMACK (*Super particle Model/ Algorithm for Collision in Kuiper belts*). She is also familiar with the concept of sonification and originally wanted to use it within her model to see if detecting a planet within the asteroid belt would be made faster and to grasp a deeper understanding of the planetary movement and related asteroid collisions. As a planet spins upon its own axis and orbits through a belt system it creates a disturbance causing multiple asteroids to collide. The movement of the planet creates an observable wave in the belt system. AB considers her hearing and eyesight for her age to be normal and has had musical training in learning to play the piano, but no experience in professional audio. Even though AB's 3D model could depict the movement of a planet within the belt, she felt that sonification could easily speed up the process of planet detection. It would be a much faster method than having to create a 3D model. She also felt that sonification would allow her to understand the movement of the planet more clearly.

Materials

A semi-structured interview was conducted on-line and recorded using a Zoom H2N portable audio recorder. It was based around 22 main questions (refer to Appendix A) and supplementary questions were asked in correlation to the feedback given by AB. A participant information sheet (See Appendix A) was presented explaining the details about the study and her rights as a voluntary participant. An informed consent form was presented to AB who agreed to the terms of participation and signed the form.

Design

The interview aimed to cover three aspects of investigation: The nature of the dataset, identifying parameter mapping of the data and gathering information from AB about the sonification design. The data gathered from this interview would be analysed using the same system based on Grounded theory that was used in the previous two studies since it had been effective, in both instances, for coding the data that is then used as the basis of the sonification design.

Procedure

The interview was conducted on-line and lasted roughly about one hour. It was recorded on a Zoom H2N portable audio recorder. The interview, being qualitative, did not require a pilot study, allowing questions to form correspondingly to the responses. Questions inquired about the dataset, the application of coherent parameter mapping, sound design aesthetics and tools for the interface design. The recording of the interview was transcribed and coded.

6.3 Results – Requirements Gathering

The requirements gathering exercise provided information about the nature of the dataset and how parameter mapping could be used to replicate the data sonically. It also provided information about sound design aesthetics and the user interface design. The following section will divulge the results of the requirements gathering exercise.

The dataset

AB is an astrophysicist who has been studying asteroid belts and Exoplanets. The gravitational perturbations of planets can create morphological characteristics in asteroid belts that are observable. Planets are detected by observing these revolving debris discs and the collisions of these particles across the discs plane. As the planet moves through the centre of the disc system it creates a spiral of planetesimals (Asteroids) that start colliding with each other (Figure 6.1). The spiral is a result of the planet's elliptical orbit. The disc is also warped due to the planets orbital tilt (Nesvold & Kuchner, 2015). By observing these collisions in a Kuiper belt system, it is possible to find planets that were previously undetected. AB has been studying the Beta (β) Pictoris system and had created a 3D visual model of it called SMACK. Figure 6.2 shows a horizontal render of the asteroid belt in the β Pictoris system. The data consists of four columns. The first column represents the time factor which measures over a million days. The second column represents the horizontal plane, or the X axis measured in astronomical units (AU). The third column represents the vertical plane, or Y axis measured in astronomical units (AU) and the fourth column represents the collision data of the asteroids colliding.

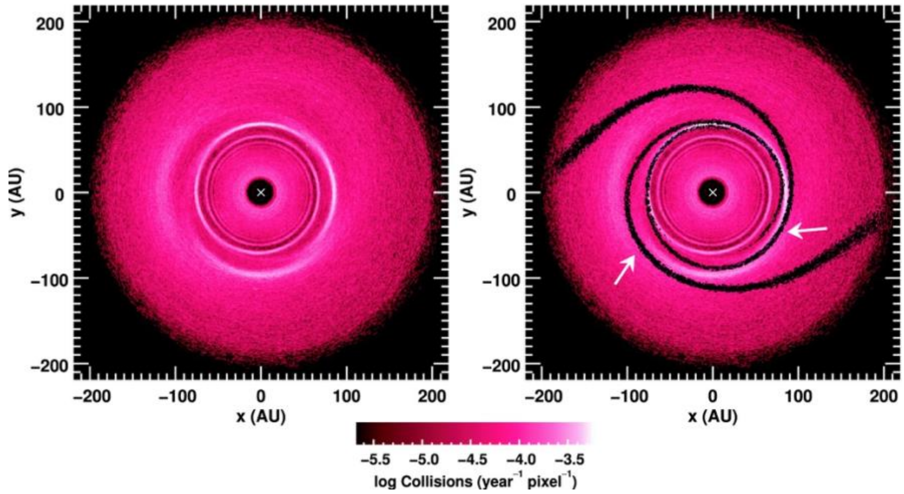

Figure 6.1: Left panel shows the collision rate map containing a broken spiral structure. Right panel is the same map indicating the planets orbital plane & how it effects the asteroid belt. (Nesvold & Kuchner, 2015)

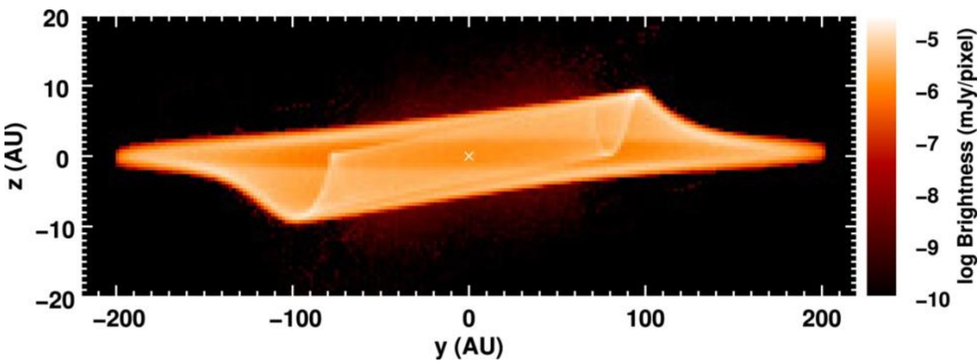

Figure 6.2: A 3D rendering of the β Pictoris asteroid belt. The star is marked as X. The resulting warp in the disc, measuring between -10 to +10 astronomical units (AU) on the Y axis & -100 to +100 on the X axis, indicates tilt of the planets orbit (Nesvold & Kuchner, 2015)

The asteroids are made out of rock and ice and vary in size. As the planet spins upon its own axis and orbits around the central star, its gravitational influence starts to throw asteroids about which begin to collide with each other, pushing them away from the central ring and creating a wave through the belt. The intensity of the collisions allows for the calculation of the mass of the planet. The speed of the orbit is calculated according to the frequency at which collisions occur within the spiral.

AB wanted to sonify the collision data to see whether the planet would be more easily detectible using sound and to achieve a deeper understanding of how the orbit of the planet was working within the Kuiper belt in the β Pictoris system. She hypothesised that through sonification she would immediately be able to find the planet and grasp the collision data in more detail. Table 6.1 summarises the details concerning the dataset.

Table 6.1: The Dataset

Information about the dataset	Characteristics of the dataset
Data type	Asteroid Collision
Size of the dataset	Over 1 million lines
Time	Measured in days
X Axis	Spatial horizontal plane Astronomical units (AU)
Y Axis	Spatial Vertical plane Astronomical units (AU)
Main features	Detailed sonification of asteroid collisions

The sound design of the Sonification

Pitch would be one of the main parameter mappings where lower pitches would represent larger sized asteroids and higher pitches smaller sized ones. This mapping has been quite effective at representing a wide range of changes in the data of the two previous studies. Incremental differences between different sized objects are immediately noticeable when using pitch. In the previous two studies WV and AD could hear distinct differences in the sizes of the peaks that they were analysing. In this study AB had suggested that this mapping would allow differences in the size of asteroid collisions to be more distinct.

The other main mapping would be spatial mapping that would be attributed to the X axis which indicated the spatial position of collisions occurring across the discs plane. This would be distributed on a Surround sound configuration where the listener would be placed in a heliocentric position with the disc orbiting around their heads. There would also be the choice to select a Stereo sound configuration where the listener would be placed facing the disc from a horizontal plane and would be able to hear the collisions occurring from left to right ear. This option would allow AB to use the sonification even when not having a surround system to work with. This method was also suggested after seeing the differences that were observed between surround and stereo listening in the study in chapter 5. AD had found that being able to switch between the two systems allowed him to hear relevant differences that informed him more about his dataset. AB agreed to try this out herself and to have both options in her model. AB’s dataset is similar to the ones used by AD in Chapter 5 which were younger star systems than the one observed by AB which was already a forming exosolar system inhabited by planets. Evolving accretion discs and their debris give a crucial indication of the phases of planet formation (Nilsson et al. 2010).

It was decided that the sonification should sound like ice breaking which is a familiar sound to AB that would probably help to speed up discernment and have a more immersive quality. In order to create this sound other parameter mapping would be needed such as timbre and amplitude that would indicate the intensity of the collisions and whether they were occurring in smaller or larger objects. Larger objects would have less clear timbre but louder due to their mass and smaller objects clearer in timbral qualities but lower in amplitude.

The interface design

The data would be provided in text format. AB would have control over the playback speed allowing the sonification to be slowed down or sped up. She would be able to choose specific points of interest from the dataset for more comprehensive listening. The playback would need a loop function for repeated listening of the data or of a segment. The system would be designed to work both in stereo and on a surround sound system. The interface would consist of number boxes indicating changing elements in the data. AB also requested a recording function so that she would be able to record the sonification and play it back at any time and on any supporting device platform. This function would also be convenient for playing back the sonification at conferences and other public engagement activities. Table 6.2 summarises the components that would be built into the interface.

Table 6.2: Results concerning the sonification interface design

Interface design functions	Results
Data format	Text file .TXT
Data to be sonified	Light amplitude to pitch and time to spatial coordinates
Playback	Variable playback speed control
Data manipulation	The ability to select certain segments of the data for playback The ability to loop the playback
Output device for sonification playback	To be used on stereo or surround sound
Recording device	The ability to record the sonifications as .WAV files

6.4 Sonification Design

The requirements gathering provided the basis for the sonification design. Table 6.3 summarises the findings and indicates all the factors that were required in order to design the sonification of colliding asteroids. In this study the coding was determined using the same system based on grounded theory that was used in chapters 4 and 5. These codes were extracted from descriptions that AB used to describe the dataset and the parameter mappings that she suggested for representing the sizes of the asteroid collisions. Since she was familiar with sonification she was aware of how certain psychoacoustic mappings could be used to represent aspects of the data. Table 6.3 shows how the data from the requirements gathering was analysed using three passes. The first pass looked for descriptions of the dataset, sonification design and mappings that were discussed in the interview. The intermediate pass looked for possible design processes that were discussed and how these linked to the descriptions coded in the first phase. The third advanced stage coded any descriptions that suggested more tangible design procedures such as functionality of the interface and the purpose of the sonification design.

Table 6.3: Grounded Theory type codes formed from the requirements gathering

<table>
<tr><th>First Initial Pass</th><th>Second Intermediate Pass</th><th>Third Advanced Pass</th></tr>
<tr><td>Asteroid Belt</td><td rowspan="9">Data</td><td rowspan="9">Asteroid collisions mapped to pitch for broader distinction + spatial mapping to represent coordinates of collisions</td></tr>
<tr><td>Colliding asteroids = Planet</td></tr>
<tr><td>Planet affects disc of belt (gravity)</td></tr>
<tr><td>Large collisions = Large influence</td></tr>
<tr><td>Time over days</td></tr>
<tr><td>Collision coordinates = Planet orbit</td></tr>
<tr><td>Collision magnitude = Planet</td></tr>
<tr><td>Movement (orbit = spatial)</td></tr>
<tr><td>Pitch = Collision size</td></tr>
<tr><td>Distinction between collisions</td><td rowspan="3">Purpose</td><td rowspan="3">To detect a possibly planet orbiting in the asteroid belt causing multiple asteroid collisions and affecting the disc of the belt</td></tr>
<tr><td>Planet detection</td></tr>
<tr><td>Impact</td></tr>
<tr><td>Rock</td><td rowspan="4">Aesthetics</td><td rowspan="4">Sonification to sound like ice breaking to mimic asteroid colliding. Multiple parameter mappings to create sound design</td></tr>
<tr><td>Large asteroid Bang</td></tr>
<tr><td>Ice breaking</td></tr>
<tr><td>Familiarity</td></tr>
<tr><td>Spatial Mapping</td><td rowspan="3">Technology</td><td rowspan="3">Surround sound to represent the disc + Stereo to represent the sizes of collisions + Laptop use</td></tr>
<tr><td>Surround</td></tr>
<tr><td>Stereo</td></tr>
</table>

The sonification for this study was developed using the guidelines that were suggested in chapter 4. Part of this design process was to use an iterative design approach. In the previous two chapters each design had benefitted from using this method of design since it allowed issues with the sonification to be addressed and arranged according to the feedback that was obtained. In the study conducted in chapter 5 the fourth iteration ensured that the scale that was initially chosen to represent the data had to represent a wider range of frequencies once other datasets were loaded into the system. Without that iterative stage there would have been an issue with the scale in representing the other datasets properly. In this study the various iterations were sent to AB and she gave feedback to suggest any changes that were required. Table 6.4 gives a summary of the iterative design practice conducted in this study.

Table 6.4: The three-stage iterative design process

#	Feedback from AD	Changes made
1	Pitch mappings need to be flipped - larger asteroids should be lower in pitch	Pitch was inverted, accidentally mapped the wrong way. AB asked for pitch to be flipped – larger collisions lower in pitch and smaller ones higher
2	Scale needs fixing to cater for all the changes in pitch To include a recording function	Scale needed to be made wider to cater for the diverse sizes of the collisions Recording function added to the interface
3	Loading system too slow	Loading system revised and improved

Method of Synthesis

The sonification was developed using subtractive synthesis. The synthesis that was used for this design was quite complex, but it allowed the flexibility necessary to compensate for all the changes in the data. The use of samples could have restricted the necessary changes that would be required and would probably have sounded less natural when altering the pitch of a sample. It was decided to use subtractive synthesis in order to have a clear signal that avoided unwanted harmonics. In chapter 5 when additive synthesis was used it was hard to keep a constant signal once certain harmonics began to affect the original wave. Subtractive synthesis would provide a clean, precise sound that could then be altered at a later stage using added effects. Two synth engines were used. The first subtractive synthesiser was used in order to add pitch to a clap sound. Two oscillators were used to add harmonics to the signal. Both oscillators were sawtooth waves and oscillator two was slightly detuned by 0.4 out of 1 MIDI value (0 to 1) giving the clap richer tonal properties. Sawtooth waves contain odd and even harmonics thus generating clear and harsh sounds (Swallow, 2012). The use of two waves would add more distortion to the signal making it sharper and dissonant which is closer to the sound of breaking ice and is also more impacting and explosive.

The second synthesiser was used to create the sound of a drum machine clap that would give the explosive impact of an asteroid collision and at the same time mimic the sound of breaking ice which would sound more like a clap. In order to have a clean, sharp signal it was thought that subtractive synthesis would be the most effective method to use. This technique allows a spectrally rich signal to be filtered to eliminate unwanted artefacts (Einbond, 2013). Changes in filter settings would determine the sharpness of smaller asteroids and the more booming larger asteroids.

Scale

The collision data would be mapped to pitch that varies between the range of 60Hz to 4kHz. The range would allow consistency in reproduction between datasets. Lower pitches represent the larger asteroid collisions and higher pitches the smaller asteroid collisions. Frequencies under 55Hz would not be audible on any speakers that would be used for the experiment. The lower frequency was set to 60Hz to allow enough range for low frequency explosions to manifest. In the higher frequency range, the limit was capped to 4kHz. Any frequencies propagating beyond that point would only result from added harmonics that would give quality to the timbre rather than contributing to the overall pitch. Short durational tones produce energy at frequencies other than the nominal frequency. The shorter the pulse the broader the bandwidth (Moore, 2012h). The nominal higher frequency bandwidth was kept to 4kHz so that any added harmonics could go above the threshold and still be audible to the listener. Short duration pitch distinction would be more accurate up until a 5kHz cap (Moore, 2012i).

In the third iteration it was noticed that the scale of the pitch range had to widened to slightly in the lower end. The original frequency had been set to 250 Hz since it was thought that this range would allow the lower end frequencies to be heard clearly. This however left the midrange to be more cluttered and there was less room for the larger collisions to be felt making a strong impact. Once the scale of the pitch was set to allow lower frequencies to be heard down to 60Hz then the larger asteroid collisions came through with more impact and there was more distinction between the collisions in the lower end of the midrange and the lower frequencies.

Parameter Mapping

The two main mappings were pitch and spatialization, but other mappings were used to help create the ice-breaking sound and distinction in impact between colliding asteroids of various sizes. In the previous studies familiar sounding sonification designs helped strengthen associative conceptualisation related to the material that the sound is representing (Vickers, 2013b).

Spatialization would work on a surround sound system so that colliding asteroids would occur in accordance to the spatial coordinates in column two of the dataset. This would mimic the trajectory of the planet's orbit that is signified through the spatial position of the colliding asteroids. This means that the listener would be in a heliocentric position listening to the asteroid belt spinning around her. This configuration will help the astronomer understand whether there is a planet orbiting with the belt, at what speed, mass and intensity.

Spatialization would also be configured to work on a stereo sound system allowing the astronomer to use the sonification on her laptop and will also give an outside perspective of how asteroids are colliding within the belt how the planet is affecting the belt from a horizontal perspective. The stereo sound will be configured so that the lower pitches will work on the left ear and higher pitches on the right allowing the astronomer to hear differences in the intensity and sizes of the collisions more clearly.

After the first iteration AB had noticed that the pitch had not been set properly and that that larger collisions were set to sound high pitched and the smaller ones to low pitch. This was a mistake that was made when mapping the pitch and it was switched around for the larger asteroids to be lower in pitch. AB had originally stated in the requirements gathering that she did want the larger asteroids to be lower in pitch since larger objects usually do sound lower in pitch in nature and this would be a more natural mapping for her.

Design

The first synthesiser was used for the changes in pitch. It consisted of two Oscillators that used sawtooth waveforms the second of which was detuned by 0.4 MIDI value in a range from 0 to 1 and not 0 to 127 as is usually the case with MIDI. Both Oscillators were set to full volume. Cutoff was set to vary with frequency. Higher pitched signal had higher Cutoff settings which gave smaller collisions more clarity. Table 6.5 show the ranges of the changes in these variables in accordance to the collision data and unchanging fixed synth parameters.

Table 6.5: Sonification design Subtractive Synthesiser 1

Parameters	Fixed/ Variable	MIDI (range 0 to 1)	Frequency Hz
OSC 1 Pitch	Variable	0 to 1	60Hz to 4000Hz
OSC 2 Pitch	Variable	0 to 1	60Hz to 4000Hz
Cutoff	Variable	0.3 to 1	60Hz to 4000Hz
Resonance	Fixed	0	
Brightness	Fixed	1	
Osc 2 Detune	Fixed	0.4	1600Hz
Osc 1 Volume	Fixed	1	
Osc 2 Volume	Fixed	1	

The second synthesiser was used to create a drum machine clap sound. The oscillator used for this was white noise set to full (1). The cut off filter varied according to the size of the asteroids with smaller collisions having higher Cutoff settings and larger collisions lower Cutoff settings. Table 6.6 shows the variable and fixed parameters in the second synthesiser.

Table 6.6: Sonification design Subtractive Synthesiser 2

Parameters	Fixed/ Variable	MIDI (range 0 to 1)	Frequency Hz
Cutoff	Variable	0.3 to 1	60Hz to 4000Hz
Noise volume	Fixed	1	
Filter amount	Fixed	0.7	2800Hz
Filter type 24dB	Fixed	-	-
Vibrato type	Fixed	0.6	2400Hz
Brightness	Fixed	1	
Resonance	Fixed	0	

Spatialization would be used to give temporal-spatial dimensions to the model and would consist of two modes of spatial mapping: One mode for surround sound, the other mode for stereo sound. The spatial surround system would be configured to work on a quadraphonic system (four speakers). The sound would have to revolve around the listeners head in the same way that a Kuiper Belt would revolve around a star. This idea was inspired by the way that the spatial sound was designed for chapter 5 where the same system was used. This was evaluated by AD who had found the surround sound allowed him to hear the dimensions of the accretion disc and the speed at which it orbited the parent star. This information was important for him to understand the proximity of the disc in relation to the star from the speed of the rotation. An asteroid belt is an also an accretion disc but consists of larger asteroids and possibly planets. By using a surround sound system, it would be possible to hear the speed of the planet rotating around the listener by following the path of asteroid collisions.

The data consisted of an X and Y axis. The X axis is horizontal, the Y axis vertical. The Y axis would not be used for the testing of this model since the surround sound would only work on a flat horizontal plane. The surround system allowed a choice of range between 2 to 12 speakers to output the signal. An external soundcard would be needed in order to be able to connect to more than two speakers. The system allowed the user to choose their own soundcard. The surround sound would be tested on a quadrophonic speaker system. The sound would move from speaker to speaker by having a crossfader between each channel transmitting from speaker one to four then back to speaker one again and following the same sequence repeatedly during playback. Table 6.7 shows how the data moved from one speaker to another in relation to the changes in time for two rotations. The darker boxes represent the peak volume in that channel. The volume range was set from 0 to 75 as a MIDI value. The range was capped to 75 and not 127 since distortion was occurring above the range of MIDI value 90. This kept the volume of each channel within a safe limit without peaking.

Table 6.7: Surround sound system: Crossfading between four channel output for two rotations

Time (days)	Collisions	Hz	Channel 1 front left	Channel 2 front right	Channel 3 back right	Channel 4 back left
59900000	0.0000000000000000001380000	3015	1.308954	74.988578	0	0
59900000	0.0000000000000000007620000	3015	74.988578	0	0	1.308954
59900000	0.0000000000000004080000000	60	0	0	1.308954	74.988578
59900000	0.0000000000000000173000000	2814.06006	0	2.617485	74.954313	0
59900000	0.0000000000000000020200000	2991.36011	1.308954	74.988578	0	0
59900000	0.0000000000000000006770000	3015	74.988578	0	0	1.308954
59900000	0.0000000000000000773000000	2104.859863	0	0	5.231758	74.817306
59900000	0.0000000000000000057300000	2955.900146	0	1.308954	74.988578	0
59900000	0.0000000000000000017400000	3003.179932	1.308954	74.988578	0	0
59900000	0.0000000000000000031600000	2979.540039	74.988578	0	0	1.308954

The stereo panning would be configured to work by shifting from the left speaker to the right speaker in conjunction with the rise in pitch. This meant that sound would move from left (-1) to right speaker (+1) between the frequencies of 60 – 4000 Hz. This will allow the listener to hear the differences in intensity of the collisions with larger collisions inclining more towards the left ear and smaller ones more to the right ear. It will also give a more quantifiable impression of the differences in collision. Table 6.8 gives an indication of how the panning moves from Left to Right speaker according the pitch.

Table 6.8: Stereo panning movement of asteroid collisions

Panning	Range Hz										
Left -1	60										
-0.8		863.76									
-0.6			1241.9								
-0.4				1643.88							
-0.2					1833						
Centre 0						2033.94					
0.2							2424				
0.4								2825.88			
0.6									3268.8		
0.8										3500	
Right +1											3800 - 4000

Effects added to the synthesised sound

A number of effects were added to the synthesiser sound as separate units. These effects helped to mimic the sound of breaking ice. The synthesisers used in this sound design lacked the required amount of distortion that was needed to achieve this goal and sounded flat, lacking the dimension needed to make the cracks sound more realistic. Three effects units were used to achieve this type of sound. The first effect is known as a Glitch Effect, the one used for this study was the *Glitchmachines Fracture*. This effect mimics a form of distortion created by digital transmission error or a lag in signal which causes the signal to stutter and to time-stretch. The Glitch effect is also known as *Databending* (Andersen, 2014). This effect uses Cutoff filtering and Modulation but also uses a parameter which is called *Stuttering*. Stuttering creates the jittery type of sound that comes from digital signal corruption. When set at fast speeds the stutter sounds similar to a Ring Modulation effect which multiplies two waveforms, called carrier and modulator. The resulting signal contains the additions and subtractions of the two signals' frequencies, which are called the upper and lower sideband (Hoffmann-Burchardi, 2008). Table 6.9 shows the parameters that were used in this effect unit. All of these parameters were fixed values that did not vary according to playback.

Table 6.9: Parameter settings for glitch effect

Parameter	**Amount**
Stutter Size	80%
Stutter Speed	96%
Stutter Mix	100%
Cutoff Floor Frequency	122Hz
Cutoff Modulation	100%
Resonance	70%
Cutoff Rate	20Hz
Modulation Rate	65Hz
Modulation Amount	32%
Dry/Wet	100%
Output	-0.10dB

The second effect, *Glitchmachines Hysteresis*, adds a number of different effects that add modulation and further data bending abilities. It also has certain synthesis aspects such as additional waves and a *Sample & Hold* function which can cause various types of audio signal degradation (Pichler and Skritek, 1980). Table 6.10 shows all the parameters that were affected using Hysteresis. All the parameters were fixed values not varying with playback. This effect added more distortion, and the added waveforms gave further tonal quality to the sound enhancing the timbre and sharpening the signal.

Table 6.10: Parameter settings for sound design effects unit

Parameter	Amount
Cutoff Modulation rate	0.142
Sample & Hold rate	0.357
Sine Wave 1 rate	0.132
Sine Wave 2 rate	0.162
Stutter Reverse	0.154
Modulation Amount	0.452
Stutter Proportion	0.79
Stutter Size	0.058
Filter	Notch
Dry/Wet	1 (full)
Output	0.874

The final effect to be added to the sound design was a reverb unit that added a sense of depth to each pulse and smoothened some of the harsh edges of the higher frequencies. The reverb, a *Max Reverb Object*, gave more impact and the idea of larger sized collisions in the lower pitches making the explosions sound deeper. Two reverb units were used and were routed in to work with both the surround and the stereo outputs of the sound. These reverb units were configured in the same way that it was in the model built in chapter 5 and since it worked successfully in distributing the reverb along the surround system then it was decided to use the same method. One reverb to spread across both the front and back left channels and the other reverb unit to spread across the back and front right channels. The tail of one reverb unit would mix into the attack of the second reverb unit due to a long reverb time of 11 milliseconds that was added to both units. The reverb size was set to about a fifth at 19.70 not to be too big and drown the distinction of the pulses but large enough to allow the lower pitches to sound larger as they exploded. The added tail gave more of an impression of larger asteroids colliding. The dry to wet ratio was set to 100% and this helped to give the impression of ice cracking where each break resonates slightly at a certain length of time.

When using the stereo system each reverb unit was connected to each channel of left and right preserving the signal's mono characteristics. The resulting outputted mono signal would pass through a mono reverb preventing the signal from projecting in stereo if the left and right channels were connected to the same stereo reverb unit.

The interface design

The interface was built to have the same basic functions as the previous models. It was most similar to one built in chapter 5 and consisted of a 'read' function to load the dataset. The user could access the actual text file using the 'open' button; A 'clear' button to remove the data from the system and a 'dump' button to ensure that the data has loaded into the system. The 'dump' function had a particular use with this dataset ensuring that the data was being loaded properly into the system. Cycling 74 Max can only read a total of 30,000 lines of text and the dataset consisted of 6 million lines. This means that only a portion of the data could be uploaded at one time. When discussing this issue with AB it was decided to test a portion of 30,000 lines of data that was taken from one of the earlier periods of data in the β Pictoris system to see whether the planet had already formed at that time. By loading 30,000 lines into the system which was the maximum limit there were times when loading alone did not upload the data fully into the system and the dump button would then be used to ensure that the data was loaded. Usually this would happen whenever the computer processor was affected by background processes that would occupy the CPU.

The user had the ability to control playback speed, which were the same speeds used in the previous models. There were also similar functions to select segments of the data and to playback on repeat. A volume control was not included allowing the user to control the volume from her laptop. This decision was based on the model built in chapter 5 where volume control for four surround channels could cause inconsistencies in the playback volume between speakers resulting in distorting the impression of the sonification.

A recording device was built into the interface so that AB could record the sonification and could listen to it or play it back in any regular media playback device. A similar one to the model in chapter 5 was included in this interface. This was decided after the second iteration where AB wanted to have the ability to record the sonification so that she could use the recordings in presentations. The recorder would allow AB to save the file as a WAV, AIFF and FLAC audio file. Figure 6.4 displays the sonification interface with all its functions. Table 6.11 provides information regarding all the functions that were built into the interface. Visual references on this interface were limited to the number boxes provided unlike the other two models where some form of moving visual indicator was included.

The sonification can be listened to at: https://soundcloud.com/michael-quinton_napier/sets/sonification-of-asteroid

Figure 6.3: The sonification interface designed for AB showing all the functions and the values of the data

Table 6.11: Sonification interface functions

Function	**Purpose of the functions**
Playback speed	Faster playback speeds overall impression dataset used for pattern recognition. Slower playback speeds for more detailed analysis.
Data selection and loop function	Data selection by choosing a start and end point. Selection can be looped, and playback speed altered.
Recording Function	To record the sonifications as WAV, AIFF and FLAC formats to play on other devices
Visualisation of the data	Number boxes included indicating line, time, X Coordinate and collision data.

6.5 Evaluation

The sonification design was evaluated to test its usability and the efficacy of the parameter mapping in conveying the data. The evaluation stage would determine whether any changes needed to be made. It would also test whether the sonification offered any new insights to AB and whether a planet could easily be detected by using sonification alone.

Participant

AB was the only participant that was involved in the testing. There was a possibility that a fellow astronomer who built the SMACK (Super particle Model Algorithm for Collision in Kuiper Belts) with AB was going to participate in the study, but this did not happen.

Materials

The sonification was supposed to be tested on a Mac book but on the day of the evaluation there was a technical problem that hindered the playback of the sonification. Many attempts were made to try and get the interface working but it kept crashing. Due to this set back the first test was conducted in person with AB in an office that had been booked for our appointment. The second test had to be conducted online about a month later after the technical issue had been resolved and a new copy of the interface could be sent to AB. The second test was done over a Skype interview. In both instances the two interviews were recorded on a Zoom H2N portable audio recorder.

When the test was conducted in person at the hired office space a QTX HA-40 four-channel headphone amplifier allowed the use of two Beyer Dynamic DT770 250 ohms headphone sets for simultaneous playback. 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 (Moore, 2012g). Answer sheets and pens were provided (refer to Appendix C). An informed consent form and participatory information sheet were provided describing the experiment and informing AB about voluntary participation (refer to Appendix C). The interviews were recorded and transcribed. Figure 6.5 shows the set up for the testing.

Figure 6.4: Set up for testing

Design

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. All the questions that were asked during the evaluation can be found in Appendix C. Each test would last about one and a half hours adding to a total time of three hours. Both interviews were semi-structured allowing extra questions to be asked where necessary. The interviews were modelled on the Evaluations that were designed in chapters 4 and 5 with the intention of asking specific questions about particular functions and broader questions to obtain rich descriptions from the astronomer.

The first test consisted of two sections. The first section consisted of 18 multiple choice questions based on a 5-point Likert scale running from negative scale 1 to positive scale 5. These questions focused on the functionality of the interface, it's effectiveness and the validity of each component. The second section consisted of 12 questions about extra functions that could be added to the interface.

The second test inquired about the efficacy of the sound design. A total of forty four questions were asked about the comprehensibility of the sonification, it's effectiveness in relaying the data and to see whether the sound design required any changes.

Procedure

The first interview lasted roughly about an hour and a half, twenty minutes of which were spent trying to fix a technical problem that had occurred which hindered the testing. The surround system was receiving too much information at one go when loading the data into the interface. This overload was jamming the system and stalling the playback. Several attempts were made to fix the issue, but none were successful. It was finally decided to run the interview based on an explanation given by the designer. Since the first test was all about the sonification playback interface it was possible to do this without having to use the interface itself. AB signed the participatory consent form and then proceeded to answer all the questions in the interview.

It was decided there and then that the second test would have to be done over Skype once the issue with the playback interface had been resolved. The interface would be sent to AB along with recordings at various playback speeds so that she could test the sonification before sitting for the second and final interview. Once the interface had been fixed, a Skype interview was arranged approximately and a month and a half after the first test. The second interview lasted about one hour. AB answered all the questions. Both interviews were recorded on a Zoom H2N portable audio recorder and were both transcribed and coded using the same system that was based on grounded theory used in both of the previous chapters.

6.6 Results

This would not be the first time that AB had used the interface. She had been sent a copy before and had commented about the loading function and how long it took to load data into the system. She had also suggested including a recording function to be added. AB didn't have time to try out the interface properly so the evaluation would be her first detailed test run. The results present the outcome of the evaluation.

First Evaluation – The Interface

AB found that the functionality of the interface was straightforward: *"The interface itself is great! It's a good layout!"* She found that the interface was self-explanatory and that it was easy to use. When asked about the rudimentary functions of the interface she gave the following ratings indicated in grey in table 6.12.

Table 6.12: Scores for loading and playback functions

Questions	Answer 1	Answer 2	Answer 3	Answer 4	Answer 5
Loading Function	Very poor	Poor	No opinion	Good	Very good
Playback	Difficult	Fairly difficult	Neutral	Fairly easy	Easy
Loop Function	Not useful at all	Slightly useful	Neutral	Useful	Very Useful
Playback speed ease of use	Difficult	Fairly difficult	Neutral	Fairly easy	Easy
Playback speed usefulness	Not useful at all	Slightly useful	Neutral	Useful	Very Useful
Number boxes	Not useful at all	Slightly useful	Neutral	Useful	Very Useful

The loading of the data was taking a while and crashing all the time. AB classified this as having no opinion about it but put down an extra note on her response sheet suggesting that this function was still bugged. She found the playback to be easy. When asked about the loop function, she had no opinion about this since she wouldn't be using this tool so often. It was easy to change the playback speed and she found it extremely useful that she could switch playback speeds during playback. With regards to the number boxes, she felt that they needed to be labelled according to their unit of measure: *"Yeah they definitely need units."*

When asked about the colour coding chosen for the different functions AB found that they were useful, but that they weren't colour blind friendly. The buttons that were encoded in red and green would be problematic for a colour-blind person to use: *"You have words, it's not like it wouldn't be useable, but if you are intentionally using green and red to represent different things, they're not colour blind friendly"*. AB did not find the information regarding the minimum and maximum collisions to be useful, but she did find that having number boxes related to column and rows of data would be good for debugging purposes.

The next question asked about the usefulness of having a tool that allows the user to select certain segments of the data. AB found this function to be extremely useful but stated that the tool would be more effective if it was labelled according to time instead of line number. She also suggested that if the selection bar had ticks and labels on it then the user would know how to select exact segments of time for playback.

When asked about the recording function AB found this to be especially useful. The fact that the sonification could be recorded and played back without the use of the interface offered flexibility: *"You can share with other people without having to go through this. Just put it in your talks and things. Yeah, that's very useful"*. She also found that the recording function was easy to use. AB also suggested that if the 3D model was integrated into the sonification interface then it should also be able to record the visualisation together with the sonification. When the recording would be played back the audience could see where and hear the activity in relation to that specific point in space and time.

First Evaluation – Functions that could be added to the interface

Part two of the first evaluation was aimed to find out whether AB would like to include additional functionality that was not currently found on the interface. Table 6.13 gives a summary of all the additional functions that AB would like to add to the interface.

Table 6.13: Additional functions to be added to interface after evaluation

Function	**Comments**
Equalisation	To facilitate distinction between small and large collisions
Added channels to load more datasets	More than one loading system to load different aspects of the data into the interface separately
Ambisonics representation of the Y axis/ vertical plane	The data is time-spatial and contains a vertical Y axis to show the effect of the wave in the Kuiper belt created by the planet
Visualisation of the data	To include the 3D visualisation in the interface and the ability to record this along with the audio
Playback functions	Add rewind, fast forward, pause, and a scrub function

Equalisation was chosen as an additional function since it could be used to filter out the small asteroid collision and allow AB to concentrate on the larger collisions which are lower in frequency. It was also suggested to have more than one loading system so that different aspects of the dataset could be loaded into the interface allowing AB to listen to the same space at different times and to be able to compare and find similarities or differences in the data. AB was interested in adding the Y axis to the surround sound aspect to have a vertical representation which would show the effect of the wave more clearly as it forms due to the planets' movement through the belt. This function would tie in with adding the 3D visualisation to the interface and having the sonification working in sync with the visualisation and that both can be recorded. AB also wanted more playback functions to allow faster scrolling through the dataset. This would include a rewind, fast forward, pause and a scrub function that would allow her to place the mouse anywhere on the timeline and to hear the audio in that specific space in time.

Second Evaluation – The Sound Design

The second evaluation was conducted about a month and half after the first evaluation due to technical difficulties that arose during the initial appointment between AB and the designer. Once these difficulties had been overcome AB was sent recorded copies of the playback ranging from 1 millisecond to 100 milliseconds playback. She was also sent a copy of the interface and the dataset itself so that she uses the interface and to discover the different functions. The second interview was conducted on Skype and lasted roughly about 1 hour. AB was unable to test the surround sound function of the interface and only got to listen to sonification in stereo.

When AB first listened to the sonification she immediately found herself looking for patterns. She described that the sonification was not harsh or tiring to listen to. She had expected it to sound like noise but was surprised when she found that the sonification had a structure and she found it pleasant to listen to. AB was immediately able to hear differences in pitch and could immediately tell that there were much less low-pitched sounds than higher pitched ones. She could also hear the directionality of the sound and feel the movement of the collisions taking place at different points in the stereo spectrum.

The next set of questions were related to the playback speed of the sonification. One peculiar aspect that arose with this sonification was that it was hard to tell whether the sonification playback speed had changed with the faster speeds. Up until 10 milliseconds the change was not that apparent. AB had noticed this and commented about it. By switching between the different playback speeds AB found that the faster ones gave a general impression of how the collisions were happening. The slower ones allowed her to hear things in a lot more detail. She found that at 100 milliseconds she could get a much broader impression of what was going on. AB felt that the faster speeds would be useful to listen to while doing some other task and just getting that overall impression. At the slower speeds AB was able to notice how the stereo spatial mapping was working and to really feel the differences in the collisions as they manifested around different parts of hearing between left and right ear:

> *"I would get a burst on one side of my head versus the other, which is really interesting because that implies to me that there are constant collisions happening, that are spatially dependent, which is what I would expect from knowing my data."*

AB noticed that there were much more smaller collisions from the higher frequencies and that the larger collisions were less frequent but happen in short bursts. These lower frequencies represented high energy collisions and AB had expected these to be less recurrent. She was also pleased that she could hear the differences in the low pitch collisions occurring at different places around her head. Through the sonification she could trace the trajectory of the planet through listening to the lower pitched collisions that indicated that a larger body was passing through the Kuiper belt. AB expected that if this was heard on a surround sound system then these spatial differences could be heard more clearly.

The next set of questions inquired about the sound design aesthetics. AB found that this was well done. She had previous experience in designing collisional sounds of the data herself and found that the design: *"It always just sounds very static to me because I'm picking sounds that are not that nice to listen to."* With the sonification design she found that: *"It does sound like ice breaking but it's also a bit more melodious than just static noise which I appreciated."* AB found that the pitch distinction was especially noticeable even though the sound design was similar to the sound of breaking ice. The sound design helped her to picture the collisions of asteroids in her mind and the context fit the dataset. She commented that if the sound design did not mimic the ice breaking sound then: *"If it had been some completely different sound, from a different context, it would have been just an extra step for brain to understand what I was listening to."* When asked to elaborate further on this comment she stated that the aesthetics of the sonification: *"It had a similar quality to rain falling on a roof."* This comment referred to the fact that the sonification worked in the same way as a natural sound with regards to the way that it was not a static sound and that it was continuously modulating. This is an attribute which is inherent in natural sounds that are forever changing in psychoacoustic qualities. These modulations: *"It did feel more natural rather than artificial. Even though obviously, I knew it was artificial, it didn't sound like anything that I had heard but there was a more natural quality to it."*

AB was asked to elaborate further on her comment regarding the relaxing sound of rain falling on the roof and whether any other images came to mind. She reinforced the fact that she could hear her model and the ice breaking as the asteroids collided. She also imagined the sounds of objects falling, rocks clattering down or rain fall. She felt: *"A real world parallel of various natural things striking each other in space and things falling to the ground."*

The next section queried about the size of the collisions and AB found that it was easy for her to hear the differences and distinctions between the various types of collisions. She could hear loose differences in asteroids that were roughly between 1 metre all the way to 1 kilometre. And she could also feel *"The real-world picture"* of small rocks hitting against each other.

The next question asked whether AB was able to obtain any new insights from the sonification. Since she had already conducted the study before with the 3D model that she built, she didn't learn anything new from the sonification. There was only one dataset of its kind and the evaluation could only be done with the dataset that was presented. This dataset was especially compiled to replicate the asteroid belt from the β Pictoris system. There was no similar model for other exosolar systems. Even though this could have affected the results of the evaluation, AB did state that if she used sonification when she had originally been analysing her data it would have given her the insight she required. She feels that sonification would have helped her to understand the system a lot better. Initially AB and her team had struggled a great deal to understand the data until they actually constructed the 3D model: *"And so I think having it (the sonification) as I was analysing it would have provided me with insights faster."* AB felt that this would have been the case especially if surround sound was applied.

This led to questions about the spatial representation of the data and how important this was as a parameter mapping. AB commented that this was the most important quality in her data since the nature of it was spatially dependent. She was especially impressed that even though she could only test the model on Stereo sound, she was still able to detect the planet in the Kuiper belt and fully understand the dataset clearly. AB wanted a good spatial representation from the beginning when the project was initialised between herself and the designer.

Even though the surround sound could not be tested the designer asked AB if she felt that it would have made a difference to the representation of the model. AB answered:

> *"Certainly! I think it would just provide another dimension, another spatial dimension to this. Like left versus right is interesting enough, but you know, adding another dimension spatially to that would, I think, provide even more information as we listen to it."*

The data also contained a Y axis which represented the vertical axis of the Kuiper belt. This was not included in the interface since it would require that more speakers would have been needed for the surround sound system in order to represent both the horizontal and vertical plane this would probably come to a total of about 8 speakers which was not a feasible option for testing. AB felt that by adding the vertical axis that would add another dimension of understanding to the dataset and would replicate the planetary movement in more detail. It would be able to show the ripple effect of the vertical peak of the wave of asteroids being tossed about as the planet pushed them away from its trajectory.

This led to the question of how surround sound would be used in AB's practical work. She felt that if she was working on similar, multiple projects she would: *"I would consider to have speakers outside my office in surround sound"*. This would only be applicable if she had an office to herself. Astronomers usually move every couple of years until they get a permanent job and often have to share an office with co-workers. There was also the disadvantage of having to carry a surround sound system to conferences and other public engagement exercises: *"And that would be unfortunate because I think that if I heard something that helped me understand the data better, I would want to be able to share it with people."* The designer then asked if it would be common practise for astronomers to use surround sound at conferences if they were using surround sound or VR related work where certain dedicated equipment would be needed. AB felt that if these practices were becoming more commonplace then conferences would be ready to set up dedicated rooms to playback surround sound sonifications.

AB described the spatial data in relation to the collision data. The higher pitched, smaller asteroid collisions were a continuous background sound and the lowest pitches started to come through in bursts varying from the right to the left of her. It was easier to discern the ones that were more towards either ear than the more central sounding collisions:

> *"I found myself trying to turn my head the way you do when you are trying to locate sound and of course it didn't help but that meant that my brain reacted as if it was a real sound difference."*

The next set of questions asked what AB liked about the sonification, whether there was anything she disliked and maybe if anything needed changing in the sound design. AB mostly enjoyed the spatial aspect: *"It made it feel for a moment like I was actually standing in the disc which was great."* AB did not feel that she disliked anything about the sonification and didn't feel that she had anything further to suggest to the sound design. She did want to test out the sonification with the 3D visualisation and to be able to control them synchronistical to each other. AB felt that if she was to do all this again, she would give the designer a smaller version of the dataset of a lower resolution. She felt that with the changes that were suggested to the interface design in the first part of the evaluation she could then use a slider to switch between different time scales and to watch and listen to what was happening at various moments in time. She also imagined having the visualisation to work logarithmically to match the logarithmic nature of sound. This would help to achieve a clearer understanding of the radical changes in the Kuiper belt causing a wave to propagate outwards: *"And so being able to jump to different times and see the different spatial effects would be interesting in this system."* The spatial characteristics of the dataset are an obvious mapping in this dataset:

> *"If you're standing at a certain radius within the disc and the wave, which you would hear as an increase in those low pitch collisions sweeps by you, that would be interesting if you would be able to hear it. You'd need a different dataset so that you could hear the time."*

The idea of being able to switch perspectives between the Stereo and Surround sound systems would enable the user to hear the wave and its movement from one side to another on the stereo system. The surround system would be used to hear that actual activity happening in different quadrants of the belt. Standing at the centre in a surround sound system would allow the user to hear the wave recede outwards away from the listener offering a new angle of perspective.

6.7 Discussion

Considering the drawbacks that occurred during the evaluation the sonification accurately represented the data allowing AB to immediately detect a planet charting through the Kuiper belt. She could clearly hear its path due to the explosive collisions data. AB could also hear rough, quantifiable differences in the sizes of the collisions and could get quite a good impression of the sizes of the different colliding bodies. Since the model was only tested in stereo due to the limitations of hardware it was surprising to find how immersive AB found the sonification to be. She could picture what was happening in her mind and felt a sense of being in the Kuiper belt and hearing all the activity as the planet passed her. Spatiality was able to provide a sense of depth as McLeran et al. (2008) had described. She had even mentioned that there were times when she wanted to turn her head to see where the collisions were happening. Nasir and Roberts (2007) describe the directionality and source location qualities that are evoked by sound. The sonification did not present anything new but AB told the designer that if she had used sonification in the initial development of her 3D model she would have been able to detect the planet and its trajectory a lot faster: *"And so I think having it (the sonification) as I was analysing it would have provided me with insights faster."*

It could be argued that since AB was already familiar with dataset then this is what led her to understand the sonification so quickly. One of the limitations of the study was that there was only one dataset of its kind so the sonification could not be tested with other Exosolar systems where planets were likely to exist within a Kuiper belt. It would be good to be able to test the sonification with similar data and with other astronomers to see if similar results could be achieved. There is however one interesting speculation, since the dataset was quite large and only a particular sample of it was taken, AB was still able to detect the planetary movement quite easily. Maybe one solution would have been to have taken a number of samples of the dataset and tested whether the results would be consistent, and that AB would still be able to trace the course of the planet moving through the Exosolar system.

The test itself differs from the other two tests that were conducted in chapters 4 and 5 where all the evaluation tests were conducted on the same day in the same environment. In the study conducted in this chapter the technical issues that had occurred forced the second part of the evaluation to be done much later and on Skype. This could have affected the results seeing that AB probably had more time to listen to the sonification and to familiarise herself with it much more than WV and AD had done. This could have resulted in AB forming a clearer picture of how the data is being represented by the sonification. This is where AB's familiarisation with the sonification is unclear since her time listening to it cannot really be measured like in the case of WV and AD who were constricted to carrying this all out during the designated testing periods. In the tests conducted with WV and AD all testing occurred on the same set of headphones or speakers. In the case of AB she would have completed the second evaluation using her own speakers or headphones. One of the criteria for the second evaluation would have been to obtain information about the model of speakers or headphones that AB had used to listen to the sonification. These details were not collected, and no particular information was gathered about her listening experience when using her own speakers or headphones. This information would have been important to compare consistency of the sonification when played back on various devices especially in relation to the replication of the larger asteroids and their lower frequency representation. It is not known whether any detail was lost due to the lower frequency range capacity of the media that AB has used for listening.

The sonification guidelines that were proposed in chapter 4 have been consistent in producing a third sonification representing a different aspect of exosolar planetary data. Even though the sonification was only tested with one person but there seems to be a consistency when all three models could accurately represent three different datasets and serve three diverse purposes. One of these consistencies is that user centred design methods seem to be effective to produce meaningful sonifications (Kramer et al. 1997; Lenzi et al. 2020). As was seen in all three models the iterative design process helped to iron out inconsistencies in the sonification design to ensure that the model mirrored the data more accurately. One can also see how the design process evolves from the earlier stages of data gathering up until the evaluation stage where a deeper understanding of the interface is reached by both parties. The consistency of the results in this study have probably emerged due to AB becoming more familiar with the sonification representing the data as it developed in relation to feedback that she had given with regards to changes.

This also occurred in the studies conducted in chapters 4 and 5. The whole design process creates a familiarisation that then saves time on training at a later stage. The user is already familiar with the interface and even though changes have been made since the previous iteration, but they are more or less familiar with the workings of the interface. One thing that can noted in the study conducted in chapter 6 was that the changes that were suggested by AB were related to functions on the interface and not the sonification design itself. This was also consistent in chapters 4 and 5 where WV and AD did not request any changes to the sonification design but suggested minor additions and improvements to the interface.

Another consistency is that using familiar, environmental sounds creates strong associative ties that make it easier for the user to understand what they are listening to (Blanco et al. 2020; Wolf & Fiebrink, 2019; Mauney & Walker, 2004; Vickers et al. 2014; Nees & Walker, 2009). AB had described the data as being: *"The real-world picture"* and *"A real world parallel of various natural things striking each other in space and things falling to the ground."*. One would expect the sound design to act as a realistic or conceptual impression of the asteroid collisions that were taking place within the belt (Zettle, 2013), especially if it was to complement the realistic visual 3D model that AB had developed. This also ties in with the need for multiple parameter mapping to create these realistic sound objects. This has been a consistent requirement in all three sonification models. The size of the object would be determined by the pitch and amplitude of the rock as it hits another asteroid. The lower pitch and louder amplitude would signify a larger body. As the rock strikes the other rock the impact sound would convey the energy and size of the collision through the timbre of the object. Higher pitched sounds would be more brittle and thinner when compared to a larger object that would sound less clear and more booming.

The third consistency is that spatial parameter mapping seems to be an effective mapping for astronomical data. This was also seen in the representations of solar systems made by Quinton et al. (2016) and Tomilson et al. (2017) where time, location and dimensionality are factors that seem to be enhanced when spatially mapping data consisting of moving phenomena. Sound depends on the surrounding within which it propagates. It is omni-directional and subjected to time (Liljedahl & Fagerlönn, 2010) and in this dataset the asteroids are moving so the spatial representation is essential: *"There are constant collisions happening, that are spatially dependent, which is what I would expect from knowing my data."* In all three studies spatial mapping was effective at conveying object dimensions and movement. In the case of the study conducted in chapter 4 the spatial movement was only used to convey the dimensions of the effective transiting radii and as a mapping it made size distinction between them clear and distinctly recognisable even when masked by noise. This means that spatial mapping should not only be considered for representing temporal phenomena effectively but could also be used in a greater context to represent sound objects more distinctly.

The temporal aspects of sonification have allowed a dataset of 30, 000 days to be compressed into an average of about two minutes of playback. AB was able to quickly run through the data and hear it more globally before slowing it down to listen to finer detail. This is the where the temporal aspects of sound seem to offer advantages that are missing in other senses. The ability to change the speed of the playback whilst the sonification is playing is also an ability that AB deemed as important. This allows the user to slow the sonification down if a sudden detail had caught their attention and needed further scrutiny. This would probably be quite a useful tool when using the sonification in conjunction with the visualisation.

AB spoke a lot about public engagement and how she would be interested in sharing a multisensorial representation of her data in audio-visual format. There are however several limitations that she did point out with regards to the use of surround sound and this where this study would have to look into further research regarding this matter. AB mentioned two limitations. Most astronomers share an office with other astronomers and would not be able to use surround sound and to disturb their co-workers. Astronomy offices are not equipped with surround sound. When wanting to share the data at conferences or in public engagement exercises it is not practical to lug a surround sound system around every time and there might be limitations in the presentation space that do not allow such a configuration to be set up.

This calls to question how future technologies will shape office or lab environments and the further development of multisensorial technologies might probably reshape the way that astronomers and other scientists from alternative disciplines carry out their work. This brings about the question whether the effectiveness of a medium, in this case the use of surround sound on both the X and Y axial planes, should be compromised to suit current limitations in hardware accessibility.

Due to the technical issues that cropped up, the system was only tested in stereo configuration and was effective enough to convey the data accurately. If spatial sound representation is just as effective in other sonification designs, then users of this technology might want to consider changing their working environment and allowing for spaces or rooms that host these technologies. This whole aspect might even push things on a much broader level where speaker and headset design technology might need to be revised to suit the new forms of audio replicating use-platforms.

These are all questions that might be taken into consideration when creating sonification designs for the future. It seems that as multisensorial data platforms become more integrated then sonification will have to suit the purpose. In a data portrayal environment where the user can see, hear and feel the data then one could compare this to a video game and maybe this platform of sound design points the way forward for sonification designers to dive into and to even be able to form universal design criteria that can be applied across the board.

One of the conclusions that can be drawn is that the sonification guidelines that have been suggested in chapter 4 have provided consistency as a design method in three separate studies pertaining to astronomical data of diverse fields of study. The testing of all three models was based around the astronomers that were originally recruited and involved in co-designing the sonification. The results suggest that these guidelines are effective for producing accurate sonic representations of the respective datasets when working closely with the user. The question does arise however whether other astronomers in each of the respective fields would be able to perceive the data so accurately if they were not involved in the design process.

The following chapter concludes this study with a general discussion about all the work that has been conducted in this dissertation. It aims to show how the research questions have been answered and the aims and objectives achieved. It also compares how this study stands against examples found in the literature review in Chapter 2 and feedback given on effective sonification design in Chapter 3.

Chapter 7: Discussion

This chapter critiques the research conducted in this thesis. It discusses the findings from the literature review and the four studies. It brings together an overall analysis and suggests improvements to the study that would be required in order to appeal to a much wider application of sonification in astronomy and possibly even in other fields of scientific research.

7.1 Research Questions

The research conducted in this thesis was based around three questions aimed at investigating the design and effective application of sonification in the field of Exosolar planetary research. The questions were as follows:

1. To what extent can sonification be an effective tool that might be used by astronomers and astrophysicists for exosolar planetary research?
2. What parameters would astronomers be interested in sonifying in relation to exoplanetary data?
3. What would be the most effective methods of sonifying exosolar planetary data for astronomers?

The motivation for these research questions was based on the hypothesis that sound, being a temporal-spatial phenomenon (Neuhoff, 2011), would be an effective means of representing astronomical data which is most often temporal-spatial or spectral. Most astronomical data are a collection of movements over time or the representations of celestial entities, which are embodiments of behavioural complexities. It is often the case that astronomical data records the relationship between these diverse bodies that interact with one another. It was believed that sound could add missing dimensions such as time and spatiality that visualisations are not so effective at representing (Diaz Merced et al. 2011).

To create meaningful sonifications is not a process that can be copied from a form of standard practice (Ibrahim et al. 2011). Sonification design is an open ended, creative process and one that would have to be investigated in order to suit the purposes of the task that it is meant to perform (Barras, 1997; Verona & Peres, 2017). Different datasets would require diverse criteria to suit the nature of the data (Kirwan & Ainsworth, 1992).

This could vary from the required method of auditory display such as Audification, Auditory icons, Earcons, Model-based sonification etc. to the various parameter mappings that could be utilised. The main goal is to shape the data to be comprehensible and accessible to the user and to ensure that the sonification is actually used and not switched off or put aside by a user (Sorkin, 1988). The process of designing a sonification for a particular user and to fit a distinct process requires certain elements that relate to the clear and comprehensive communication between the designer and the user and of the delineation of the data (Sebillotte, 1995). This research asks the fundamental question of how to communicate the properties of a dataset and to offer deeper insight. It is an exploration of discovering the hidden narrative of the various stars, planets and other cosmic phenomena and turning it into a communicable language (Worrall, 2019).

7.2 Sonification guidelines for exosolar planetary data

Three design studies were conducted and each sonification accurately represented the data and were comprehensible to the users. Each astronomer was able to understand the way that the sonification represented their data almost immediately. This allowed them to grasp a deeper understanding of the data especially in terms of temporal-spatial quantities. A series of guidelines had emerged in chapter 4 that were based on the interviews conducted in chapter 3 with various sonification designers, but also included elements of the design study conducted with WV. These guidelines were then utilised in both studies in chapters 5 and 6 to see whether they would still apply to different aspects of Exosolar Planetary data. In both studies these guidelines were still effective, and no additional criteria were suggested. These guidelines are recapitulated in Table 7.1 and will be critiqued in more detail.

Table 7.1: Guidelines for the sonification of Exosolar Planetary data

Processes	**Guidelines**
Requirements gathering/analysis	Requirements Gathering
	Requirements Analysis
User Centred Design Techniques	Iterative Prototyping
	Evaluation
	Communication
	Knowledge
Sonification Design	Aesthetics - Familiar sonic associations
	Multi Parameter mapping + Spatial to create a Sound Object

7.3 Requirements gathering/ analysis

The data gathering process consisted of two components. The requirements gathering exercise and the data analysis process. These two systems were used in all four studies including the interviews conducted in chapter 3. The scope was to try to pick out trends that emerged in an interview. Certain descriptions, associations, behaviours and other aspects that conveyed the users' attitude towards the field of study came out through their descriptions of certain things, especially in relation to sound descriptors.

Requirements Gathering

The requirements gathering was based on semi-structured interviews. This would allow enough flexibility for extra questions to be asked, and that the essential questions also got answered, especially with regards to necessary details that were required later. In chapter 3 most of the designers had based their requirements gathering by speaking to the users and finding out information from them about the datasets that were to be sonified. In the case of the interviewee Gionfrida, she took a different approach where her requirements gathering was based on literature findings related to the particular design method that she wanted to develop for her sonification design (Gionfrida, 2016). The end result was the same as interviewing users where she managed to find various design examples that she then utilised in her own model. The requirements gathering is not necessarily tied to user centred approach and can be done in different ways. The scope is to find out as much information as possible that can be used as a basis for the design (Silhavy et al. 2011).

In this thesis the requirements gathering conducted for the sonification designs were influenced by the datasets that were found in the NASA Exoplanetary archive and many of the questions were based upon that. During the first interview with WV, it was immediately realised that there are other datasets related to Exoplanetary research and that the Exoplanetary Archive does not cover all this ground. This is where the nature of certain questions had to be adapted to suit each interview. In all three studies it was felt that more was needed to get richer descriptors concerning the astronomers' attitudes towards sound and hearing. In the case of AB, she had attempted sound design before, but this was only found out in the second evaluation. It was known before that she had a musical background and knew what sonification was, but it was in the second evaluation that she discussed her attempts at sound design in more detail.

In the case of WV who was the less inclined towards music and sound there could have been more emphasis to find out about his listening attitudes. It is believed that stronger descriptors could have been obtained that were helpful to the sound design. This could have been achieved by having a form of questions that ask to describe certain sounds or grade them according to a list of descriptors. This could have been done with regards to psychoacoustic parameters as well, where the astronomer would be asked to grade these parameters in relation to everyday phenomena. This method would probably be more useful when interviewing a number of astronomers who work within that specific field of astronomy in order to look for trends in these descriptors that could be used in the sonification design.

Requirements analysis method

The requirements analysis method was based on Grounded Theory as described by Mills & Birks (2014) and this method was utilised in all the studies conducted from chapters 3 to 6. It was effective for extracting codes and paying attention to details in descriptions given by the sonification designers and astronomers, provided ideas and even the basis of the sonification guidelines and the designs (Tie et al. 2019). The method of three passes of coding of the data collected during the requirements gathering allows for picking up on further detail and understanding of the trends and behaviours that are layered in the responses.

The requirements analysis system used in this study was considered efficient. It was consistent in providing insights in all four chapters providing a deeper understanding of sonification design from chapter 3 and of the datasets that needed to be sonified in chapters 4 to 6. It was felt that the system was more effective in chapter 3 for recognising the trends in sonification design that began to emerge from the interviews. When interviewing 11 people this grounded theory-based analysis system was quite effective at finding specific, related ideas that were discussed in the different interviews. This means that such a system could be effective when producing sonifications for teams of astronomers.

It could be argued that the resultant codes are still subjected to a particular bias from the person using the system especially if they are looking for certain trends beforehand. Looking back over chapter 3 the codes do hint that there was a certain bias that emerged from the data that was spoken about from the interviews based upon impressions regarding sonification design. The same can also be felt in the design chapters where sometimes extra interviews were needed to clarify information about the data that was not understood clearly. It could be argued that since it was the first time that this system was used that there was also a lack of practise and even understanding of the coding procedure that did probably bias the results. It could be encouraged to use this system in other contexts and to see whether it is just as effective and to see whether it can be done with less bias, having learnt from the experiences gained in this research.

7.4 User centred design

Most of the people interviewed in chapter 3 had described applying user centred design methods for their sonifications. This method was used in the three sonification models described in chapters 4 to 6. The User Centred Design method helped to achieve a robust understanding of the how the data could be sonified to suit the needs of the user. It is a system that encourages communication as was described by Kirwan and Ainsworth (1992). In the three design studies it could be seen how this communication channel evolved throughout the process. The initial requirements gathering exercise helped to establish a good foundation and to acquire the basis for the sonification design, but this was only one step in the evolving design process.

The communication started to grow especially during the iterative design process. At first, when describing sonification to users like WV and AD, who had never experienced it before, it remained an abstract concept to them. It is only until the first prototype was presented that they were able to grasp how sound can represent their datasets more clearly. And this is when they could give feedback which helped to adapt the model to be better suited to represent the data. In the interviews conducted in chapter 3, Nesbitt had spoken about the importance of iteration and that the first design is often revised due to various shortcomings. Nielson (1993) and Hartson et al. (2001) had also discussed this and had emphasised on the importance of having iterations so that discrepancies can be ironed out.

In Chapter 3 many of the interviewees had spoken about needing to clarify further details about the data a number of times and this was also experienced in the design studies conducted in this thesis. There were also similar issues with parameter mappings and improving upon the sound. Initial designs sound unconvincing, usually there are data parameters that are not represented clearly and need arranging, often the user is consulted to clarify any misunderstandings. All these experiences were shared in the sonification designs in chapters 4 to 6. The interviews in chapter 3 also reflected the importance of allowing the users descriptions to influence the design of the sonification. Similar views were shared by Sebillotte (1995) and Benyon (2019). This is why a data analysis system based on grounded theory seemed to be the appropriate method to encourage this form of development.

The iterative design method also brought out the weaknesses of the requirements gathering exercises and showed where certain ground was not covered. This suggests that the iterative process helps as an extra measure to collect more data that was not acquired in the data gathering process. This continues even up until the final evaluation where feedback collected at that stage helps with any issues that are left in the design that need to be addressed. The iterative design process conducted with WV helped to improve the requirements gathering that was conducted with AD and AB. In chapter 6 it is noticeable that even though three iterations were still needed in the design process, but less work was needed at the second and third iterations when compared to the design processes in chapters 4 and 5. The iterative process also helped to gain experience and to think of work beyond the thesis if these sonification models had to be developed further on improving methods of requirements gathering, data analysis coding and iterative design methods, especially in conducting the evaluations.

One of the limitations of the method is that the interface that is being designed might be tailored to only suit a limited group of users who were involved in the co-design process but will not suit the requirements of users outside the design group. With the particular sonification designs in chapters 4 to 6, only built for one astronomer per dataset, it could be that the sonification is not as effective with other astronomers from these respective fields.

User centred design allows the users to learn the designers' jargon (Foster & Franz, 1999) and this is something that develops through the course of the iterative prototyping stage. It could be that this jargon is then not passed on efficiently to other potential users. This could be reflected in the instance of each of the three astronomers needing little training to understand the sonifications during the final evaluation. It would probably take more time for other users to understand the parameter mappings and how to use the interface. They might even need more time to listen to the sonifications and to utilise them effectively. Some might find that the familiar sound design does not represent the data the way that they would have imagined it to be represented sonically and might ask for a thorough revision of the sound design.

To overcome this, other methods of user centred design such as *Profiling,* could be employed after the second or third iteration to see if it is possible to identify a trend or habits in users' behaviour. *Role playing* could also be an effective method that could have been used. These two methods could have been utilised especially given that there was a lack of astronomers available to test the model. Whether or not these systems could realistically compensate for the lack of co-designers would have to be tested in future related work.

This is where the guideline related to *Knowledge* is encouraged to compensate for any weaknesses that can be overcome by using other methods as was mentioned in relation to the Profiling and Role playing. Even though these possibilities had been explored when conducting the literature review, they were not considered to be useful for the study. It is only after deeper reflection that the possibility of utilising them in future work came to mind. This guideline also relates to the knowledge of the tools being used to make the sonifications. This was an element that Walker, in Chapter 3, was insistent about. In the study conducted in chapter 5 the use of Additive synthesis had to be watered down due to the lack of understanding of how to overcome an issue in the added harmonics that was affecting the pitch. This was a result of not knowing this method of synthesis more rigorously.

7.5 Sonification design

One aspect that stands out in relation to sonification design for astronomy is that parameter mapping is usually used for public relations exercises and sound installations as can be seen in most of the examples that were described in chapter 2. One exception is the sonification interface called xSonify which was an initiative that Diaz Merced (2013) was developing with astronomers from NASA. Audification is used more widely as a scientific interface by astronomers. This could be happening since audification is something that can be done quite easily by an astronomer whereas parameter mapping sonification requires more work in order to develop such an interface. Parameter mapping also requires a more rigorous understanding of psychoacoustics and of the use of certain tools like synthesis, sampling and effects in order to create sound from the data. There is also the issue of producing the right scaling to suit the reproduction of the data and at the same time allowing enough of a frequency range to be able to reproduce other datasets from the same field of astronomy where larger numbers are present.

It could be suggested that parameter mapping is particularly undermined since they are designed by computer engineers who often use simple mappings for more complex concepts represented in the data. This runs the risk of the sonification not being aesthetically relevant to the data and the user finds it hard to relate the data to the sound. This is probably the situation, described by Nesbitt and Ferguson in chapter 3, when users switch sonifications off since they find the sound design to be irritating. Barrass and Vickers in the same chapter, had both commented that there is still a lack of knowledge when it comes to sonification design. Verona had mentioned that it is not just a matter of mapping pitch to a parameter when the data needs to be represented in more detail. Barrass brought up the issue that pitch has never properly been evaluated for its effectiveness. This is probably where sonification design needs more study to find out how these mappings work and in what context. It is these complexities that might push astronomers and other scientists to use a simpler method of sonification such as audification, just by speeding up or slowing down the wave to the spectrum of human hearing and achieving a sonic representation of the data.

The more complex approach of using parameter mapping means that astronomers would need sound designers to step in and design these systems for them. Many a time, astronomers do not have much time to sit down for interviews and evaluate iterations. In this study it was seen that how out of 109 astronomers who were contacted only three astronomers actually participated in these studies. It also suggests that the sound designers have to be skilled enough to be able to create an appropriate and effective parameter mapping. This once again emphasises the importance of *Knowledge* as a suggested guideline for sonification design and the statement suggested by Hug (2008) about the importance of knowing how sound works in nature.

In this particular study the sound design was more complex since it used familiar or more natural elements that were relative to the astronomer. The sonification designs took time to develop. The end result was quite satisfactory when seeing how the astronomers could work with the sonification, easily understanding the mappings and even being able to associate the data directly with the sound design. It would have to be seen whether these mappings are decipherable to other astronomers in these same fields.

Mimicking aspects of nature as a sound design aesthetic

Scaletti (1994) and Hermann (2008) attributed the relevance of a sonification to its ability to communicate the original information comprehensively. In the interviews conducted in chapter 3 designers such as Ballora, Barrass, Dyer, Ferguson and Vickers touched upon the subject of using natural sounds or sounds that mimic nature and to create strong real-world associations. The idea of using familiar sounds for sonification design was also backed by Blanco et al. (2020), Wolf & Fiebrink (2019), Mauney and Walker (2004) Vickers et al. (2014) and Nees and Walker (2009). These ideas inspired the creation of the sonification designs in this thesis along with the concept of *idea-associative comparison* approach taken from film sound, of using conceptual sounds which are not directly related to the event itself but assist the viewer or user to understand its association to the event (Zettle, 2013). All three astronomers in this study felt that having the sonification sounding like the actual objects or related concepts that were represented in the data helped them to reach a deeper understanding of the phenomena that they were studying.

As mentioned before, the study was limited in seeing whether this approach would work with astronomers from similar fields. It is believed that there are common descriptions or associations to the dataset that will emerge when involving more astronomers from the same field. Cycowicz and Friedman (1998), Kirmse et al. (2009) and Schirmer et al. (2011) had described how familiar sounds strengthen identifiability. This could suggest that using qualities such as water-like, sand-like and ice breaking associations could be interpreted similarly by other astronomers who were not involved in the design phase.

In the study conducted by Quinton et al. (2016) a sonification of the solar systems was co designed with a representative of a planetarium and a similar technique of using familiar association was used in the sound design. It was found that when the sonification of various planetary attributes were tested with a mock audience who were not involved in the sound design, many of the participants were able to decipher these qualities just by listening to the sonification. They gave similar descriptions of what they thought that a sound was representing.

The use of familiar sounds could be tested by devising a method of requirements gathering where a large number of astronomers are asked to give descriptions of their datasets to find out whether common associations arise. The results could suggest that there are archetypal patterns in their descriptions, and these could be used to represent their datasets sonically. Preferably this would have to be done on a large scale to gather as much information as possible to see if a common language arises. Interviews would probably have to be designed to not take up too much time but to effectively extract the information required.

The use of familiar sounds also suggests that a sonification is designed to take the form of a *sound object* (Gaver, 1993) which projects properties of spatial relationships, volume, significance, matter, expression and time (Chion, 1994a). Blauert (1997a) suggested that a sound object enables the listener to perceive it without the need for any visual reference. Shinn-Cunningham (2008) had spoken about the direct relationship between understanding the dimensions of an object in relation to the direction of the source. In astronomy time and spatial relationships are both properties that are common in datasets which could be considered to have more direct representation for clearer representation these properties.

Effective as a representation of time

Sonification is often suggested to be more accurate at representing time (Vickers & Holdrich, 2017). This is probably due to the highly acute temporal resolutions that are characteristic of human hearing (Goudarzi, 2018). Since astronomical data is mostly time based then this could suggest that sonification could be used in order to represent this data more accurately than visual representation, which could be less accurate at representing this factor (Johnson, 2004).

Time is compressed in a sonification and a dataset of 30,000 lines is brought down to 2 minutes of playback. This could allow the user to go through large amounts of data in less time by giving an immediate impression of the dataset, allowing the user to hear the events taking place. The sonification can be slowed down to hear events in more detail. The aspect of time also conveys information such as the speed of moving bodies which is an important aspect of astronomy.

In the studies conducted in chapters 5 and 6, accretion discs and asteroid belts work in relation to the parent star and their spin is tied to the orbit of the star on its own axis. Speed, in the study with AD, also conveyed the proximity of the accretion disc to the parent star, with higher speeds indicating more closeness and slower speeds more distance: *"The further the disc, the slower it goes. Discs rotating really fast, that probably means that it is very close to the star."* The time factor also helped AD to perceive the size of the dust clouds in relation to time: *"Some of the really small dips are shorter than a day but a lot of the time they last a few days."*

In the study with AB the time factor represented the changes that occurred within the asteroid belt as the planet orbited within its midst. The understanding of time in both models was reflected in the spatial representation of the data. In the study with AD the surround sound was able to convey the aspect of time of the model clearly and the occurrence of dust clouds masking the stars light could even be recognised in the form of a rhythmic pattern. Time changes in this pattern were immediately noticeable. In the study with AB the time factor gave a clearer indication of the planets trajectory through the asteroid belt making detection of the planet immediately noticeable. Even though a portion of the dataset was tested, the temporal-spatial relationship of the planet was clear to follow, and this gave a stronger association of the planets orbit through particular sectors of space over specific periods of time.

The time factor can be heard, but to get an indication of the measurement of time a visual representation of the time factor such as numbers of days, months or years is also needed to be able to measure where a certain occurrence took place within the dataset. This could suggest that an added sonic feature could be included to represent the differences in hours, days or any other temporal measurement by actually sonifying this data. This would be particularly useful for astronomers who are not at the screen or for astronomers who are visually impaired or blind. The actual sonification of time was only mapped spatially on the surround sound systems but this still didn't give a clear indication of the changes of the days in both models for AD and AB. In the study in chapter 5, AD had suggested having some form of metronome to be able to count the tempo of an accretion disc. It could be an option to set the metronome to work with the number of days to give an indication of how time passes in relation to the dips in star light.

Effective as a representation of spatial relationships

The use of spatial mapping in sonification design does suggest that multiple parameter mappings are utilised. Spatial mapping not only represents direction or orientation, but it also integrates time. Spatial mapping reflects the time that it takes for an object to move from point A to point B. Sound is spatial, as it propagates from a source, from a direction within an environment (Nasir & Roberts, 2007). As an object moves through space or interacts with its environment its sonic qualities change (Schafer, 1994). These changes are subjected to variations in the surrounding environment (Howard and Angus, 2017). It is these changes in the spectral components of reflections, from various surfaces encountered by the sound wave, that help determine a sense of place or spatial understanding for the listener (Blauert and Lindemann, 1986).

As an object moves through space its' timbral qualities are subjected to change and by adding this aspect to the spatial design it enhanced the perceptual recognition of the sound object (Korland-Martinet & Voinier, 2008). Spatial separation or movement combined with changes in timbre facilitate spatial object orientation (Song & Beilharz, 2007). Pitch is an element used in human cognition in relation to localisation in space (Rusconi et al. 2014). Changes in pitch are also related to spatial orientation as is experienced with the Doppler Effect (Thoret et al. 2014).

Spatial mapping seems to work as a cohesive agent that gels all the psychoacoustic qualities together to not only form a *sound object* but to also animate it with temporal spatial qualities. In the three sonification designs conducted in this thesis spatial mapping offered particular advantages in relation to time, size, orientation and the capability to enhance features previously masked and unnoticed on a flat 2D graph.

In astronomy spatial mapping has been effective at conveying the orbits of planets in studies conducted by Quinton et al. (2016) and Tomilson et al. (2017). It was also used effectively by Ballora (2014) to represent the spinning of Pulsars and the gyrations of Galaxies. In other fields of sonification Spatial mapping was effectively used in Geolocational mapping by Schito and Fabrikant (2018) and as methods for guiding blind people by Presti et al. (2019). In all of these studies spatial parameter mapping was used to convey or suggest movement and orientation.

In the sonification built for WV the dataset was spectral and had no temporal qualities. By creating movement between the source and the noise signal moving in counter direction to each other from ear to ear, this separation gave space for certain details in the source signal to be heard (Ebata, 2003; Best et al. 2005). There was enough physical space between each ear where the unnoticed water feature could jump out at the listener and catch his attention: *"Ok, I found something interesting that I didn't notice before!"* The movement of the signal could keep the attention of WV as he followed and traced these changes darting across from ear to ear. This spatial movement animated the source and noise signals and gave clearer distinction between them (Song et al. 2007). Movement of sound prompts users to try to localise the source. Even involuntary auditory attention often induced by moving sound, enhances early visual perceptual processing (McDonald et al. 2000).

In the case of using Spatial parameter mapping in surround sound there were limitations that became evident. In the studies conducted with AD and AB both astronomers, although eager to hear their accretions discs and asteroid belts in circular rotation on a surround system, both suggested having an option in stereo so that they could use the sonification on their laptops. Both astronomers do not have surround sound systems to work with. The set up used for surround sound in both studies required that the users would also need an audio interface that would have multiple outputs. Astronomers do not usually work with this kind of equipment. In the case of the study with AD the phase data was used for the rotation instead of using the X and Y data since X and Y would have to be presented on two sets of circular sound configurations, an inner and outer ring to represent depth of the dippers. In the study with AB the Y axis could not be included since it required more speakers to represent the vertical plane which was actually an important feature in the dataset that showed the size of the wave of asteroids that was created by the orbiting planet.

Surround sound could be emulated binaurally on a stereo configuration to mimic the surround movements of astronomical features. In the study with WV the vertical axis which represented the length of the effective transiting radii was created by using the SMARC effect to give the illusion of differences in height between radii. The larger radii located more towards the righthand side of the listeners' head. SMARC effect, (Spatial-Musical Association of Response Codes) creates the illusion of ascending when pitch and timbre are increased on the vertical axis of hearing in non-musicians (Pitteri et al. 2015). WV had no musical training and the SMARC effect was successful at conveying a sense of differences in height to the listener. It is interesting to hear WV's description of the dataset explained in terms of height: *"These are similar patterns rising and falling down. Some of the peaks are quick, some of them are slow rising and slow falling down representing the data itself."* Complex data sets call for complex representation and linear, flat, audio representations tend to be less effective as sonifications (Rosli et al. 2015; McLeran et al. 2008). AD found that he could understand the sizes of the actual dust clouds much better when using stereo sound. With the surround sound AD found that: *"I'm picturing how things are moving around. I'm localising things by their pitch whether the pitch was more or less, when it was in a particular location."*

This would suggest that further study would be needed to create more binaurally accurate representations of surround sound in stereo, also including Y axis orientation. There could still be two listening settings where the user can select between binaural and stereo, similar to the one used in the studies conducted with AD and AB to switch between circular representation around the listener and direct frontal observation when viewing the object at a distance.

Even though Spatial mapping has been suggested as one of the guidelines for sonifying Exosolar Planetary data, but it would have to be studied in more detail and tested with more people. One of the limitations in all three studies is that each of the sonifications were only tested with one astronomer per study. Other astronomers from each field would have to test the respective models and to give feedback of their experience of this mapping and its pros and cons. This guideline only stands in the context of having been effective in three studies related to three different aspects of Exosolar astronomy. There is however consistency between all three studies in relation to the use of spatial parameter mapping which should be taken into consideration when designing new sonification prototypes.

7.6 Summary

This chapter is a critique of the study conducted in this dissertation. It gives a reflective discussion about aspects of the study that were effective and also talks about weaknesses in the approach and how these can be improved upon for future work. The overall conclusion is that sonification could be used effectively to represent various aspects of Exosolar planetary astronomy, but it needs to be developed further and with a larger number of astronomers. A number of sonification guidelines have been suggested based upon interviews that were carried out with sonification designers and researchers and also developed through the sonification designs that were made for this thesis. These guidelines could assist a sonification designer to build effective sonifications in the field of Exosolar Planetary research. The following chapter will conclude this thesis by discussing the contribution to knowledge that this study has made and possible future work that can stem from it.

Chapter 8: Conclusion

The following chapter describes the contribution to knowledge that has stemmed from this research. Chapter 7 gave a critique of the study conducted in this thesis and described the pros and cons that arose. This chapter concludes this thesis by elaborating more on the relevance of this research in the field of sonification and its application in Exosolar astronomy. It also describes future work that be done to further develop sonification designs that are suited to represent Exosolar Planetary astronomy.

8.1 Contribution to knowledge

The sonification design methods used to create the sonic representations of the data have formulated a possible stratagem that can be implemented when designing sonifications for Exosolar Planetary data. The guidelines that have been formulated suggest methods of sonification design that could be applicable in designing other aspects of Exosolar Planetary data.

In this thesis three sonifications of different aspects of planetary data accurately represented the datasets of the three astronomers (Scaletti, 1994; Hermann, 2008). It is believed that this accuracy was a result of having an appropriate requirements gathering and requirements analysis strategy, user centred design practise focused on iterative prototyping, evaluation and the use of auditory affordances to create familiar sound concepts replicating objects or events in the data. When considering the level of consistency of providing accurate representations of the data in three different aspects of astronomy then this does prompt a need for further development of these methods.

This study produces a parameter mapping sonification that has been fashioned to be used as a scientific tool to assist astronomers in their data analysis. When comparing many of the parameter mappings described in chapter 2 that are related to astronomy it can be seen that there are few parameter mappings that are used for this kind of work. The most prominent of these is the work of Diaz Merced (2013) where the sonification interface xSonify can be used with various datasets in astronomy. This tool is probably more flexible than the sonification interfaces designed in this thesis. Information is easily sonified by using musical instruments that can be mapped to various aspects of data. The only limitation is that the sonifications have similar aesthetics between different fields of astronomy rather than actually sounding like the phenomena that the sonification should be representing.

xSonify also seems limited in its spatial representations which was quite effective when represented with more precision in the sonification interfaces built in this thesis. Spatial mapping was used to work as more accurate representation of the actual movements of the various astronomical aspects, and this allowed the astronomers to form a clearer picture of how certain changes were occurring in their datasets. In the case of AD, he was able to hear differences in the proximity of the accretion discs to the parent star from the speed of the surround sound playback. AB could get a more accurate impression of the planet moving through the asteroid belt from the spatial parameter mapping.

Astronomy in particular does tend to lend itself to have more precise spatial parameter mappings. When bodies move through space they can easily be followed through spatial representation and this could be especially useful when comparing the movement of different bodies in relation to each other. Spatial mapping had also helped to create more accurate representations of the cosmic objects and their dimensions making them more realistic to the user.

In making the dataset additionally realistic to the user, it is more likely that the mappings are easily decipherable since the user is already trained in listening to that specific object or event in real life. The user might not consciously understand how they know the changing nature of the sound of an object as it interacts with the environment but, as seen in the three sonifications tested, they can localise movement and understand proximity and other temporal-spatial attributes to the extent of actually looking towards that direction. It takes into account that, as mentioned by Vickers in Chapter 3 of this thesis: *"When you do the sound design you have to be aware that any sound you create can have an association with the real world, in fact, people are possibly going to reach for it."*

The use of auditory affordances could possibly tackle the issue with aesthetics that is a reoccurring conundrum in sonification design. Instead of using more synthesised sounds, which are often deemed displeasing by many users, synthesis can be used to replicate real-life occurrences. The generation of sound through oscillators, the VCA and VCF envelopes, the filters and Low Frequency oscillators are all tools that shape soundwaves and can mould them to sound like real-life objects of events. The mechanisms are there, it is just a matter of knowing how they could be used that has to be considered differently.

Sonification design could shift more to work within the paradigm of conventional sound design used in film, theatre and video game platforms. These mediums have a more developed body of work with regards to sound design and these principles could easily be implemented in sonification design. These sound platforms have more experience in understanding how certain sounds create reactions and convey events to an audience. These platforms probably have the vocabulary that sonification design is currently missing with regards to audiences listening attitudes and how certain sounds are used within a particular context. Ballora had spoken about the lacking vocabulary in sonification design in chapter 3 and this could be a way how to fill that gap.

8.2 Future work

The first suggestion for future work is that the sonification models designed in this study will be tested with other astronomers who work in the same fields as the ones that were sonified in chapters 4, 5 and 6. This will give further confirmation about the effectiveness of the use of auditory affordances in sonification design and will also determine whether the sonifications are still as effective as they were when tested with the people that were involved in the co-design process. The guidelines that have been suggested will need further endorsement from astronomers in these respective fields of astronomy. For now, they only work within the limitations of the studies conducted in this thesis.

One of the main restraints in the sonification designs used in this thesis is that three separate synthesis engines had to be designed to cater for the complexities of each sound design. This approach would not be practical since it limits the use of that sonification engine to one particular field of astronomical study. Since synthesis is the basis of the sound generation then a more generalised form of synthesiser engine has to be developed so that the sound design can be changed to suit different aspects of astronomical study. There is the option of using physical modelling in order to represent sound objects more realistically. This method of synthesis uses mathematical precision to mimic real life objects and their physical properties.

A hypothesis of how to create a synthesis engine that uses generative audio and physical modelling was one of the original aims and objectives of this study. This audio engine could even be used to compare different Exosolar systems to each other on both a micro and macrocosmic scale. Astronomy related sonifications would be able to work with data representation platforms like the openspaceproject.com (2020) which is a public platform used to educate people about the solar system. A lot of the 3D visual renders that are shared by this platform are often silent and being able to represent data parameters sonically could enhance the realism of these astronomical representations and add another sense for experiencing it with.

It would have to be seen whether such a system would be required by astronomers that can be used in their work. It could be possible to build a sonic model of all the Exosolar systems that have been discovered in our galaxy and this could be used for pattern recognition and other methods of data analysis. Interviews would have to take place to find out what type of model astronomers would be looking to build.

There is the need of a study that focuses on finding out how astronomers describe their data. This study would have to be conducted on a large scale to look for trends and patterns in astronomers' descriptions. Once the data has been collected it will have to be catalogued to represent these patterns. This study would also have to look at the more general attitude that astronomers have in listening to the real world. This could take the form of a listening test where astronomers will be asked to describe what they have listened to. Rather than suggested descriptions through the use of questionnaires or using grading scales, which could introduce bias in the results, written descriptions could be encouraged. This approach would have to be studied in more detail to ensure the most effective strategy.

The sonification design techniques that have been practised in this study will have to be tested in other contexts. As mentioned in chapter 4, when designing the sound for several gases of a planetary atmosphere then one would have to study how the design will make one gas distinguishable from another in a multi-faceted dataset. The idea of designing according to the user's conceptual idea of these gases could be a means of making this happen but this hypothesis would have to be tested. It would have to be seen whether it would be possible to overcome the difficulty of using more realistic representations of gas which are likely to sound almost the same to each other. The concept related to those gases might be a better basis for the sonification design, but this will have to be studied in detail.

Considering the successful representation of water vapour data in the study conducted with WV, it was mentioned in the evaluation that he was interested in further developing the model by sonifying the other chemical constituents that are found in the exoplanet's atmosphere:

> *"It's definitely needed. It is probably immediately applicable to the James Webb's space telescope that is going to be launched, hopefully, in the next two years. When we have a final dataset output, then maybe we would be able to use this as a medium to see how the data is represented through audio compared to a visual representation."*

The James Webb telescope will be used to observe the formation of galaxies, stars and planetary systems (James Webb Space Telescope, 2020). WV had commented that the sonification interface was already capable of being used with data that might be retrieved from the James Webb telescope related to the observation of Exoplanetary atmospheres. This would be a continuation of developing the current model.

Machine learning has become an important data analysis method used in astronomy. It is still not the preferred method since there are certain discrepancies that are likely to occur within the searching methods suggested by astronomers. It is quite likely that data is being filtered out especially between one process and another since multiple processes are run with the same data to clean out noise and purify the signal as much as possible. Up until now astronomers are using visualisations and number checking to double check the system and are still considered as the preferred systems of data analysis. As seen in this thesis, visualisations and numerical data analysis still have limitations that could possibly be covered by introducing sonification as a checking system. It could be quite effective especially when there are overlaps in the data as was seen in the study conducted in chapter 4. This method of sonification would need to be studied with the astronomers that work in these fields to create a system that can compensate for the various limitations in the current data analyses systems.

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Appendix A: Requirements Gathering Exercise – Ethics forms & Questions

Application for Cross-University Ethical Approval

Research Details

Name:	Michael Quinton
School or Professional service department:	School of computing
Email:	M.Quinton@napier.ac.uk
Contact number:	+44 (0) 131 455 2770
Project Title:	**The Sonification of Exoplanetary Solar Systems**
Start Date:	1st October 2015
Duration of Project:	3 years
Type of Research: Doctoral Student	

Screening Questions

Please answer the following questions to identify the level of risk in the proposed project:

If you answer 'No' to all questions, please complete Section 3a only.

If you have answered 'Yes' to any of the questions 5-14 please complete Section 3a and 3b.

If you have answered 'Yes to any of the questions 1-4, complete all of Section 3.□□□

	You Must Answer All Questions	**Yes**	**No**
1.	Is the research clinical in nature?□	☐	☐
2.	Is the research investigating socially or culturally 'controversial' topics (for example pornography, extremist politics, or illegal activities)?	☐	☐
3.	Will any covert research method be used?	☐	☐
4.	Will the research involve deliberately misleading participants (deception) in any way?	☐	☐
5.	Does the Research involve staff or students within the University?	☐	☐
6.	Does the Research involve vulnerable people? (For example people under 18 or over 70 years of age, disabled (either physically or mentally), those with learning difficulties, people in custody, migrants etc).	☐	☐
7.	Is the information gathered from participants of a sensitive or personal nature?	☐	☐
8.	Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?	☐	☐

9.	Have you identified any potential risks to the researcher in carrying out the research? (for example physical/emotional/social/economic risks?)	☐	☐
10.	Are there implications from a current or previous professional relationship i.e. staff/student/line manager/managerial position that would affect the voluntary nature of the participation?	☐	☐
11.	Will the research require the use of assumed consent rather than informed consent? (For example when it may be impossible to obtain informed consent due to the setting for the research – e.g. observational studies/videoing/photography within a public space)	☐	☐
12.	Is there any risk to respondents' anonymity in any report/thesis/publication from the research, even if real names are not used?	☐	☐
13.	Will any payment or reward be made to participants, beyond reimbursement or out-of-pocket expenses?	☐	☐
14.	Does the research require external ethics clearance? (For example from the NHS or another institution)	☐	☐
15.	Does the research involve the use of secondary data?	☐	☐

3A. Details of Project

In this section please provide details of your project and outline data collection methods, how participant consent will be given as well as details of storage and dissemination.

Please give a 300 word overview of the research project	
This study presents the possibility of using sonification as a scientific data analysis tool that can be used by astronomers and astrophysicists. The tool may either be used as a standalone tool or in conjunction with a visualisation aspect. The approach taken in order to create this tool is based on a 'User Centred Design' so that the tool can be custom made according to the needs of the scientists. In order to gather information for this study Michael Quinton will be interviewing a number of astronomers and astrophysicists about Extra-Solar Planetary Data sets and determining which of these parameters are relevant to their work. The interviews will be conducted using Skype and will last about an hour in length. These interviews will be recorded and transcribed and the information gathered would be used to describe how successful sonifications are made.	
Data Collection	
1.	**Who will be the participants in the research?**

	Professional Astronomers and Astrophysicists who have been working in these respective fields of study
2.	**How will you collect and analyse the research data? (please outline all methods e.g. questionnaires/focus groups/internet searches/literature searches/interviews/observation)**
	Data gathering will take place by conducting a series of Skype interviews from around the world.
3.	**Where will the data will be gathered (e.g. in the classroom/on the street/telephone/on-line)**
	The data will be gathered by conducting a series of Skype interviews
4.	**Please describe your selection criteria for inclusion of participants in the study**
	By choosing Astronomers that are working in the field of astronomy
5.	**If your research is based on secondary data, please outline the source, validity and reliability of the data set**
	N/A
Consent and Participant Information	
7.	**How will you invite research participants to take part in the study? (e.g. letter/email/asked in lecture)**
	By contacting potential candidates by email.
8.	**How will you explain the nature and purpose of the research to participants?**
	An explanation of the research will be given in the Informed Consent form and will also be explained in person on the day of the interview
9.	**How will you record obtaining informed consent from your participants?**
	Participants will be asked to complete an Informed Consent Form
Data storage and Dissemination	
10.	**How and in what format will data be stored? And what steps will be taken to ensure data is stored securely?**
	It will be stored in a safe place in a filling cabinet at work to which only Michael Quinton will have the key. The data will also be stored on a computer and will be saved

	on Michael Quinton's hard drive in a folder that can only be accessed by Michael Quinton
11.	**Who will have access to the data?**
	The raw data will only be accessible to the interviewer. The summarised data will be shared with the interviewers supervisory team and will subsequently appear in the interviewer's PhD dissertation and possible future publications
12.	**Will the data be anonymised so that files contain no information that could be linked to any participant?**
	The information obtained from these interviews will reflect the work of the individual, therefore anonymity will be required
13.	**How long will the data be kept?**
	The data will be kept for three years while the interviewer completes the PhD study in September 2018
14.	**What will be done with the data at the end of the project?**
	It will be disposed of securely by using the university services
15.	**How will the findings be disseminated?**
	The findings will be disseminated in a PhD thesis and in conference papers
16.	**Will any individual be identifiable in the findings?**
	N/A

3B. Identification and Mitigation of Potential risks

This section is designed to identify any realistic risks to the participants and how you propose to deal with it.

Does this research project involve working with potentially vulnerable individuals?

Group	**Yes**	**NO**	**Details (for example programme student enrolled on, or details of children's age/care situation, disability)**
Students at Napier	☐	☐	
Staff at ENU	☐	☐	
Children under 18	☐	☐	
Elderly (over 70)	☐	☐	

Disabled	☐	☐	
Migrant workers	☐	☐	
Prisoners / people in custody	☐	☐	
Learning difficulties	☐	☐	

If you are recruiting children (under 18 years) or people who are otherwise unable to give informed consent, please give full details of how you will obtain consent from parents, guardians, carers etc.

N/A

Please describe any identified risks to participants or the researcher as a result of this research being carried out

There are no risks to the participants or the researcher as a result of the research

Please describe what steps have been taken to reduce these identified risks? (for example providing contact details for appropriate support services (e.g. University Counselling, Samaritans), reminding participants of their right to withdraw and/or not answering questions, or providing a full debriefing to participants)

Participants have the right to withdraw and/or can refrain from answering questions, a full debriefing to participants has been explained in the informed consent form and will be explained again before starting the interview.

If you plan to use assumed consent rather than informed consent please outline why this is necessary

N/A

If payment or reward will be made to participants please justify that the amount and type are appropriate (for example the amount should not be so high that participants would be financially coerced into taking part, or that the type of reward is appropriate to the research topic).

N/A

3C. Justification of High Risk Projects

If you answered 'Yes' to the screening questions 1-4 this section asks for justification on the choice of research topic and methodology.

If you have answered yes to question 1 please give a full description of all medical procedures to be used within the research and provide evidence that the project has obtained NHS ethical approval.

N/A

If you have answered yes to questions 2 (research into a controversial topic) please provide a justification for your choice of research topic, and describe how you would deal with any potential issues arising from researching that topic.

N/A

If you have answered yes to questions 3 or 4 (use of deception or covert research methods) please provide a justification for your choice of methodology, and state how you will mitigate the risks associated with these approaches.

N/A

Declaration		
☐	I consider that this project has no significant ethical implications to be brought to the attention of Research Integrity Committee	
☐	I consider that this project may have significant ethical implications to be brought to the attention of the Research Integrity Committee	
Researcher Signature: [redacted]		**Date: 16th November 2016**
Director of Studies: [redacted]		**Date:15th of November 2016**

Checklist

All applications require the following to be submitted with the application form

Participant Information Sheet	☐
Informed Consent Form	☐
Interview/Survey Questions	☐

The Sonification of Exoplanetary Solar Systems Informed Consent Form

Edinburgh Napier University requires that all persons who participate in research studies give their written consent to do so. Please read the following and sign it if you agree with what it says.

1. I freely and voluntarily consent to be a participant in this research to be conducted by Michael Quinton, who is a postgraduate student in the Edinburgh Napier School of Computing.
2. I have been informed of the broad goal of this research study. I have been told what is expected of me and that the study should take no longer than one hour to complete.
3. I have been told that my responses will be anonymised. My name will not be linked with the research materials, and I will not be identified or identifiable in any report subsequently produced by the researcher. I have been told that these data are for may be submitted for publication.
4. I also understand that if at any time during the interview. If I feel unable or unwilling to continue, I am free to leave. That is, my participation in this study is completely voluntary, and I may withdraw from it at any time without negative consequences.
5. In addition, should I not wish to answer any particular question or questions, I am free to decline.
6. I have been given the opportunity to ask questions regarding the interview and my questions have been answered to my satisfaction.
7. I have read and understand the above and consent to participate in this study. My signature is not a waiver of any legal rights. Furthermore, I understand that I will be able to keep a copy of this consent form for my records.

______________________________ ____

Participant’s Signature Date

I have explained and defined in detail the research procedure in which the respondent has consented to participate. Furthermore, I will retain one copy of the informed consent form for my records.

______________________________ _______________________ Researcher’s Signature

Date

The Sonification of Exoplanetary Solar Systems – Participant Information

Before accepting to participate in this study please note that your participation is voluntary. This means that you can decide not to answer any questions, or you may stop the survey at any time if you feel that you are unable or unwilling to continue.
The purpose of this study is to create an effective sound design of the planets of Extra Solar Planetary systems, which can be used as a scientific data analysis tool by Astronomers and Astrophysicists. This will form part of my PhD research in Sound Design and this information will also be used in a future study that may be published in either a journal or for a conference paper.

Astronomers and Astrophysicists working in the field of Extra Solar Planetary discovery of both genders and aged from 18 years onwards are being asked to participate in this study. The interview will take about one hour.

For the interview you will be asked a number of questions regarding your familiarity with sonification and audification. You will also be asked about Extra-Solar planetary data and about which parameters you consider to be relevant to your work in this field. The interview will be recorded on video recording software and these recordings will be transcribed. The videos will be immediately destroyed once the transcriptions have been made. All responses will be anonymised. Your name will not be linked with the research materials and will not be identified or identifiable in any report subsequently produced by the researcher.

Thank you

Michael Quinton
M.Quinton@napier.ac.uk
Skype: - rusty.cowboy
Telephone: - +44 (0) 131 455 2770 School of Computing
Edinburgh Napier University

Requirements Gathering with WV

1. Can you please give me an overall view of what the data represents?
2. Can you please describe the timeline within which the data is functioning?
3. Can you please describe the first column?
4. How does the first column function in relation to time?
5. How does the first column function in relation to spatial representation?
6. How do you think the first column of data should be represented sonically?
7. Can you give any sonic descriptors in relation to how you imagine the sound for the first column?
8. Could you please describe the second column of data?
9. How does the second column function in relation to time?
10. How does the second column function in relation to spatial representation?
11. How do you think the second column of data should be represented sonically?
12. Can you give any sonic descriptors in relation to how you imagine the sound for the second column?
13. Can you please describe the third column?
14. How does the third column function in relation to time?
15. How does the third column function in relation to spatial representation?
16. How do you think the third column of data should be represented sonically?
17. Can you give any sonic descriptors in relation to how you imagine the sound for the third column?
18. Can you please describe the data related to the noise from the detector?
19. How does this data relate to the other data parameters in the data set?
20. How does the data of the noise detector function in relation to time?
21. How do you imagine the overall data to be represented spatially on a surround speaker configuration?
22. Would you like to have temporal control, would you want to speed up and slow down the data, and if so by how much?
23. Would you want to be able to change scales so that you could focus in on one aspect? This could be done increasing or decreasing factors so that only large differences are registered, or very small differences are audible.
24. Would you want the ability to loop small sections, so that you can explore chunks of data rather than a whole data set? And would this include being able to switch on and off rows or columns.
25. Do you have any further comments, suggestions or considerations to add?

Requirements Gathering with AD

1. Can you please give me an overview about the data and what aspects of it you are interested in sonifying?
2. Over what period of time were observations made in order to compile the data?
3. Can you please describe each column in the dataset in detail?
4. Which columns represent time, and could you describe how time is working in the dataset?
5. Which columns represent spatial representation and movement of the different celestial bodies?
6. Can you give any sonic descriptors in relation to how you imagine the sounds for each of the columns?
7. Are there any elements of the data related to noise from the detector and would this be represented in the model?
8. How do you imagine the overall data to be represented spatially or on a surround sound configuration?
9. Would you prefer to use speakers/ headphones or both when using the model?
10. Would the model need some form of temporal control, would you want to speed it up and slow it down, and if so by how much?
11. Would you want to be able to overlay more than one circumbinary system in order to make comparisons between systems and how do you envisage doing this?
12. If you would like to represent planetary resonances then how do you imagine doing this and what aspects of the data would be needed in order to be able to represent this phenomenon?
13. How would you like to sonically distinguish between stellar sounds and planetary sounds?
14. Would you want the ability to loop small sections, so that they can explore chunks of data rather than a whole data set? And would this include being able to switch on and off rows or columns?
15. Would you want to be able to change scales so that you could focus on one aspect? This could be done increasing or decreasing factors so that only large differences are registered, or very small differences are audible. (This is like a zoom in, zoom out function)
16. Do you have any further comments, suggestions or considerations to add?

Requirements Gathering with AB

1. Can you introduce yourself and about your profession?
2. Can you describe the data that you work with?
3. Can you describe how the X and Y axis are used in relation to the visualisation of the data?
4. Can you describe how a planet would be detected in an asteroid belt?
5. How do you confirm that what is being observed is a planet?
6. How does the asteroid belt rotate in relation to the star?
7. Are there any other elements that make up the dataset?
8. Do you compare the simulation to real life observations?
9. How successfully does the visualisation compare to the real life observations?
10. How do you think sonification can help as a tool for data analysis?
11. How would you describe the mass of the objects represented in the data?
12. What is the timescale of the dataset?
13. How would you sonically represent the differences in mass between the different bodies in the dataset?
14. Would you want the data to be represented spatially?
15. How does the data work spatially?
16. Is there any coordinate data that can be mapped spatially?
17. Is the star represented in the model?
18. How do you want to represent the temporal aspects in the dataset?
19. How do you want to represent differences in intensity in the dataset?
20. What are the main details of importance that you want emphasised from the dataset?
21. How do you imagine that the data would sound?
22. What tools would you need in order to playback the sonification?
23. How important is playback speed?
24. How will playback tools assist you in your work?
25. Would you like to listen to the data on both stereo and surround systems?
26. Are there any other ideas that you would like to include?

Appendix B: Consent forms & Questions for study investigating sonification techniques

The Sonification of Exoplanetary Solar Systems - Informed Consent Form

Edinburgh Napier University requires that all persons who participate in research studies give their written consent to do so. Please read the following and sign it if you agree with what it says.

1. I freely and voluntarily consent to be a participant in this research to be conducted by Michael Quinton, who is a PhD student in the Edinburgh Napier School of Computing.
2. I have been informed of the broad goal of this research study. I have been told what is expected of me and that the study should take no longer than one hour to complete.
3. I have been told that my responses will not be anonymised. My name will be linked with the research materials, and I will be identified or identifiable in any report subsequently produced by the researcher. I have been told what these data are for and may be submitted for publication.
4. I also understand that if at any time during the interview. If I feel unable or unwilling to continue, I am free to leave. That is, my participation in this study is completely voluntary, and I may withdraw from it at any time without negative consequences.
5. In addition, should I not wish to answer any particular question or questions, I am free to decline.
6. I have been given the opportunity to ask questions regarding the interview and my questions have been answered to my satisfaction.
7. I have read and understand the above and consent to participate in this study. My signature is not a waiver of any legal rights. Furthermore, I understand that I will be able to keep a copy of this consent form for my records.

______________________________ ____

Participant's Signature Date

I have explained and defined in detail the research procedure in which the respondent has consented to participate. Furthermore, I will retain one copy of the informed consent form for my records.

______________________________ ______________________

Researcher's Signature Date

The Sonification of Exoplanetary Solar Systems – Participant Information

Before accepting to participate in this study please note that your participation is voluntary. This means that you can decide not to answer any questions, or you may stop the survey at any time if you feel that you are unable or unwilling to continue.
The purpose of this study is to create an effective sound design of the planets of Extra Solar Planetary systems, which can be used as a scientific data analysis tool by Astronomers and Astrophysicists. This will form part of my PhD research in Sound Design and this information will also be used in a future study that may be published in either a journal or for a conference paper.

Sound Designers that work in the field of sonification of both genders and aged from 18 years onwards are being asked to participate in this study. The interview will take about one hour.

For the interview you will be asked a number of questions regarding your work in sonification. You will also be asked about the dataset that you sonified, what parameter mappings were used in relation to the dataset and how successful the sonification was and how it was utilised by the person, persons, company or institution that you designed the sonification for.

The interview will be recorded on an audio recorder and these recordings will be transcribed. The audio files will be immediately destroyed once the transcriptions have been made. Since the information gathered from this interview will be used as a case study for this research your name will not be anonymised.

Thank you

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School of Computing
Edinburgh Napier University

Questions for Research on Sonification Techniques

1. Can you please start by introducing yourself and describing your work as a sound designer?
2. Could you please describe who you designed the sonification for and for what purpose they wanted to use sonification?
3. How did you collect information about the project and about the data that you would be sonifying?
4. Could you describe any specific guidelines or techniques on sonification that influenced your work?
5. Could you describe how you conducted your requirements gathering process and what were the main elements that you were seeking to acquire from the exercise?
6. Could you please elaborate on the involvement of the client in the sound design process?
7. Could you please describe the nature of the data that you were given, was it numerical data, visual data or written information?
8. How did you input the data into the system that you were building?
9. How did you work out the parameter mappings in relation to the data and what was the reasoning behind the mappings?
10. What aesthetic considerations to sound did you employ in your model and were these decisions influenced by the client's decisions?
11. What software platform/ platforms did you use in order to construct your sonification and what was the reason for using this platform/ platforms?
12. What type of synthesis techniques did you use in order to aurally represent the data and what was your reason for using these techniques?
13. How did you test your sonification and what were the reasons for using this specific method of testing?
14. What reactions in relation to the sonification did you get from the people that you were testing your model on?
15. How much information were they able to discern from the sonification?
16. What were the positives and negatives of the sonification?
17. Did you create other versions of the sonification after you had received feedback from your testing?
18. How many prototypes did you make until you came to the final version of the sonification?

19. If you had created other versions of the sonification then could you please describe what changes were made to the model and on what basis these changes were made?

20. How would you rate the success of the sonification in portraying the data?

21. Could you describe whether the sonification is being used by the client or other people in the day to day work and how it is being utilised?

22. Have the users of the sonification been able to discover new insights in relation to their data from the sonification, if so then could you describe the discoveries that have been made?

23. Do you have any additional comments that you would like to add?

Questions for Research on Auditory Display Design

1. Please could you describe your research with regards to the design of auditory displays?
2. When you began working in this field what work influenced your approach?
3. Please describe any changes that you have seen in the standards of auditory display design since you began work in this field?
4. Please could you describe what would be an efficient and aesthetically pleasing sonification?
5. How would you go about designing an efficient and aesthetically pleasing sonification?
6. How would you describe an effective requirements gathering approach to develop an auditory display?
7. How important are pleasing aesthetics when designing a sonification, please give reasons for your answer?
8. Please describe any practises, methods or techniques used for the data coding obtained during the sonification requirements gathering process, and how they are implemented?
9. What sound design tools or elements are required to design an auditory display suitable for end users?
10. Could you discuss whether there any standard methods of testing sonification to ensure validity and usability?
11. What are hindrances are you aware of towards the use of sonification for traditional data analysis?
12. What fields of research are you aware of where sonification is being utilised successfully as a data analysis tool?
13. Do you believe that there should be standard guidelines for sonification design and please give reasons for your answer?
14. What are your views on the current literature regarding sonification applications and does it accurately reflect current practises?
15. What do you think would make sonification more mainstream as a data analysis tool?
16. What do you see as the future of auditory display design?
17. Do you have any additional comments that you would like to add?

Appendix C: Evaluations for sonification design studies – Ethics forms & Questions

Application for Cross-University Ethical Approval

Research Details

Name:	Michael Quinton
School or Professional service department:	School of computing
Email:	M.Quinton@napier.ac.uk
Contact number:	+44 (0) 131 455 2770
Project Title:	**The Sonification of Exo-solar Planetary Systems**
Start Date:	1st October 2015
Duration of Project:	3 years
Type of Research:	Doctoral Student

Screening Questions

Please answer the following questions to identify the level of risk in the proposed project:

If you answer 'No' to all questions, please complete Section 3a only.

If you have answered 'Yes' to any of the questions 5-14 please complete Section 3a and 3b.

If you have answered 'Yes to any of the questions 1-4, complete all of Section 3.□□□

	You Must Answer All Questions	**Yes**	**No**
1.	Is the research clinical in nature?□	☐	☒
2.	Is the research investigating socially or culturally 'controversial' topics (for example pornography, extremist politics, or illegal activities)?	☐	☒
3.	Will any covert research method be used?	☐	☒
4.	Will the research involve deliberately misleading participants (deception) in any way?	☐	☒
5.	Does the Research involve staff or students within the University?	☐	☒
6.	Does the Research involve vulnerable people? (For example people under 18 or over 70 years of age, disabled (either physically or mentally), those with learning difficulties, people in custody, migrants etc).	☐	☒
7.	Is the information gathered from participants of a sensitive or personal nature?	☒	☐
8.	Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?	☒	☐

9.	Have you identified any potential risks to the researcher in carrying out the research? (for example physical/emotional/social/economic risks?)	☐	☒
10.	Are there implications from a current or previous professional relationship i.e. staff/student/line manager/managerial position that would affect the voluntary nature of the participation?	☐	☒
11.	Will the research require the use of assumed consent rather than informed consent? (For example when it may be impossible to obtain informed consent due to the setting for the research – e.g. observational studies/videoing/photography within a public space)	☐	☒
12.	Is there any risk to respondents' anonymity in any report/thesis/publication from the research, even if real names are not used?	☒	☐
13.	Will any payment or reward be made to participants, beyond reimbursement or out-of-pocket expenses?	☐	☒
14.	Does the research require external ethics clearance? (For example from the NHS or another institution)	☐	☒
15.	Does the research involve the use of secondary data?	☐	☒

3A. Details of Project

In this section please provide details of your project and outline data collection methods, how participant consent will be given as well as details of storage and dissemination.

Please give a 300 word overview of the research project

The purpose of this study is to create and evaluate a sonification tool that represents exosolar planetary data, which can be used by astronomers. Sonification is the use of non-verbal sound to represent data. A lot of the exosolar planetary data is temporal-spatial, and sonification could be an effective way of representing these parameters. Sonifying complex exosolar planetary datasets could allow astronomers to be able to detect various aspects instantaneously, as it is possible to easily listen to multiple sound sources simultaneously to determine patterns and subtle variations. For any sonification to be effective it must be semantically comprehensible to the user. If the sonification cannot be understood then it is redundant. To overcome this problem it is important to involve potential end users in the design process. Sonifications of various aspects of exosolar planetary phenomena have been sonified. These represent different aspects of Exosolar planetary phenomena such as atmospheres and asteroid belts. In this study an astronomer will be listening to two sets of water vapour data which is found in the atmosphere of an exoplanet situated in the habitable zone of an exo-solar system. One set is a mathematical model created by the astronomers which has been cleaned of all noise. The other set of data is the raw capture of satellite data that still contains noise. Both data-sets will be played simultaneously and the astronomer will be asked about whether they can hear any specific artefacts that could not be recognised in their visual representations of the data. These different aspects of Exosolar phenomena are being tested to see whether astronomers could effectively discern data from these sonic representations and possibly discover new insights. A prototype has been developed using an object-oriented software design platform, and will be tested in an office environment using a semi-structured interview.	
Data Collection	
1.	**Who will be the participants in the research?**
	A professional astronomer who works with data about Exoplanetary atmospheres
2.	**How will you collect and analyse the research data? (please outline all methods e.g. questionnaires/focus groups/internet searches/literature searches/interviews/observation)**
	Interview
3.	**Where will the data will be gathered (e.g. in the classroom/on the street/telephone/on-line)**
	NASA Goddard Space Flight Centre
4.	**Please describe your selection criteria for inclusion of participants in the study**
	The participant is an astronomer who works in the field of Exosolar planetary atmospheres. The astronomer who had provided the data sets that have been sonified and had also been involved in the design process of the sonification toolbox.
5.	**If your research is based on secondary data, please outline the source, validity and reliability of the data set**

	N/A
Consent and Participant Information	
7.	**How will you invite research participants to take part in the study? (e.g. letter/email/asked in lecture)**
	Email
8.	**How will you explain the nature and purpose of the research to participants?**
	Participant information sheet.
9.	**How will you record obtaining informed consent from your participants?**
	Signed Informed Consent Form
Data storage and Dissemination	
10.	**How and in what format will data be stored? And what steps will be taken to ensure data is stored securely?**
	Paperwork will be stored in a locked filling cabinet in C35 Merchiston campus. Digital files will be encrypted and stored on a password protected laptop also stored in C35.
11.	**Who will have access to the data?**
	Only the researcher.
12.	**Will the data be anonymised so that files contain no information that could be linked to any participant?**
	Yes
13.	**How long will the data be kept?**
	Until successful publication expected September 2019.
14.	**What will be done with the data at the end of the project?**
	Securely destroyed.
15.	**How will the findings be disseminated?**
	The findings will be disseminated in a PhD thesis and in conference or journal papers
16.	**Will any individual be identifiable in the findings?**
	N/A

3B. Identification and Mitigation of Potential risks

This section is designed to identify any realistic risks to the participants and how you propose to deal with it.

Does this research project involve working with potentially vulnerable individuals?

Group	Yes	NO	Details (for example programme student enrolled on, or details of children's age/care situation, disability)

Students at Napier	☐	☐	
Staff at ENU	☐	☐	
Children under 18	☐	☐	
Elderly (over 70)	☐	☐	
Disabled	☐	☐	
Migrant workers	☐	☐	
Prisoners / people in custody	☐	☐	
Learning difficulties	☐	☐	

If you are recruiting children (under 18 years) or people who are otherwise unable to give informed consent, please give full details of how you will obtain consent from parents, guardians, carers etc.

N/A

Please describe any identified risks to participants or the researcher as a result of this research being carried out

Potential hearing damage and participant identification.

Please describe what steps have been taken to reduce these identified risks? (for example providing contact details for appropriate support services (e.g. University Counselling, Samaritans), reminding participants of their right to withdraw and/or not answering questions, or providing a full debriefing to participants)

The participant will be asked to listen to sonified data on headphones. A safe level of 65 dBA RMS and 100dBA peak will be kept throughout the testing. Listening levels are 20 dB below what is considered safe for an eight hour working day (Moore, p. 156, 2013[1]), and will be controlled by the researcher, participants will not be able to alter the volume. All responses will be anonymised using the convention WV1, WV2 and WV3.

If you plan to use assumed consent rather than informed consent please outline why this is necessary

N/A

If payment or reward will be made to participants please justify that the amount and type are appropriate (for example the amount should not be so high that

[1] *Moore, Brian C J, 2013.' An introduction to the Psychology of Hearing', Koninklijke Brill NV, Leiden, The Netherlands. P. 156*

participants would be financially coerced into taking part, or that the type of reward is appropriate to the research topic).

N/A

3C. Justification of High Risk Projects

If you answered 'Yes' to the screening questions 1-4 this section asks for justification on the choice of research topic and methodology.

If you have answered yes to question 1 please give a full description of all medical procedures to be used within the research and provide evidence that the project has obtained NHS ethical approval.

N/A

If you have answered yes to questions 2 (research into a controversial topic) please provide a justification for your choice of research topic, and describe how you would deal with any potential issues arising from researching that topic.

N/A

If you have answered yes to questions 3 or 4 (use of deception or covert research methods) please provide a justification for your choice of methodology, and state how you will mitigate the risks associated with these approaches.

N/A

Declaration		
☐	I consider that this project has no significant ethical implications to be brought to the attention of Research Integrity Committee	
☐	I consider that this project may have significant ethical implications to be brought to the attention of the Research Integrity Committee	
Researcher Signature:	[redacted]	**Date:** 22nd May 2018
Director of Studies:	[redacted]	**Date:** 23rd of May 2018

Checklist

All applications require the following to be submitted with the application form

Participant Information Sheet	☐
Informed Consent Form	☐
Interview/Survey Questions	☐

Sonification of Exosolar Planetary Systems: Sonification of Water Vapour Data in Exoplanetary Atmospheres - Informed Consent Form

Edinburgh Napier University requires that all persons who participate in research studies give their written consent to do so. Please read the following and sign it if you agree with what it says.

1. I freely and voluntarily consent to be a participant in this research to be conducted by Michael Quinton, who is a PhD student in the Edinburgh Napier School of Computing.
2. I have been informed of the broad goal of this research study. I have been told what is expected of me and that the study should take approximately three hours to complete.
3. I have been told that my responses will be anonymised. My name will not be linked with the research materials, and I will not be identified or identifiable in any report subsequently produced by the researcher. I have been told what these data are for and may be submitted for publication.
4. I also understand that if at any time during the interview I feel unable or unwilling to continue, I am free to leave. That is, my participation in this study is completely voluntary, and I may withdraw from it at any time without negative consequences.
5. In addition, should I not wish to answer any particular question or questions, I am free to decline.
6. I have been given the opportunity to ask questions regarding the interview and my questions have been answered to my satisfaction.
7. I have read and understand the above and consent to participate in this study. My signature is not a waiver of any legal rights. Furthermore, I understand that I will be able to keep a copy of this consent form for my records.

______________________________ ______________________

Participant's Signature Date

I have explained and defined in detail the research procedure in which the respondent has consented to participate. Furthermore, I will retain one copy of the informed consent form for my records.

______________________________ ______________________

Researcher's Signature Date

Sonification of Exosolar Planetary Systems: Sonification of Water Vapour Data in Exoplanetary Atmospheres - Participant Information

Thank you for considering taking part in this study, your participation is really appreciated.

This study explores how to create an effective sonification of data concerning Exosolar Planetary systems, which could be used as a scientific data analysis tool by Astronomers and Astrophysicists. You have been asked to take part as an Astronomer that works in the field of Exosolar Planetary research.

The interviews will take about three hours and will be split into two different sessions. The first session will consist of a trial run using the sonification toolbox. You will be interviewed about your user experience, and asked questions regarding further improvement to the toolbox and potential enhancements. The second session will be a listening test where you will be asked to listen to 40 different sonification recordings, to make comparisons between them and provide feedback concerning discernment and clarity of comprehension of the sonification. Questions will also relate to sonic aesthetics. You will be asked to listen to the sonified data on headphones. A safe sound pressure level (SPL) of 65 dBA RMS and 100 dBA peak will be kept throughout the testing. The listening levels will be 20 dB below those considered safe for an eight hour working day (Moore, p. 156, 2013) and will be controlled by the researcher and you will not be able to alter the volume. All answers will be anonymised using the convention WV.

The interviews will be recorded on an audio recorder. The audio files will be immediately deleted after the audio has been transcribed. This will form part of my PhD research in Sonification and this information will also be used in a future study, that may be published in either a journal or for a conference paper, as well as in my PhD dissertation.

Before agreeing to participate in this study please note that your participation is voluntary. This means that you can decide not to answer any questions or may stop the survey at any time if you feel that you are unable or unwilling to continue.

Thank you

Michael Quinton - PhD Candidate
School of Computing
Edinburgh Napier University
M.Quinton@napier.ac.uk
Skype: - Michael_Quinton_Napier
Telephone: - +44 (0) 131 455 2770

Sonification Test 1 Prototype for Exoplanetary Atmospheres

Personal Information

Age:- ___________

Gender:- ____________

Profession:- ____

Field of Study:- ____

How long have you been working in this field? _____________________

Do you have normal hearing for your age? _________

Do you believe that you have either normal or corrected eyesight? ______________

Do you have any experience working in professional audio?____________

Do you have any musical training?_______________

Section1 Initial impressions of the interface

Now that you have had time to use with the interface I am going to ask you some questions about the interface.

What are your first impressions of the interface?

It is not suitable for sonifying data	It is not entirely suitable for sonifying data	Neutral	It is partially suitable for sonifying data	It is suitable for sonifying data

How easy was it to understand the interface?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How easy was it to control the interface?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How would you rate the loading function on the interface?

Very poor	Poor	No Opinion	Good	Very good

How easy is it to playback the data?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How useful is it to loop the playback?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How easy is it to change the speed of the playback in real-time?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How useful is it to be able to change the speed of the playback in real-time?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful are the three mute buttons (one for each sound source)?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

What filter settings would you like to use for the noise oscillator?

Low Pass	High Pass	Band Pass	Band Stop	Peak Notch	Low Shelf	High Shelf

Which waveforms of the Oscillator would you like to use for the noise data?

Sine	Triangle	Saw	Square	Pulse

Did you find the white noise an appropriate way of representing the noise data?

Not informative at all	Slightly informative	Neutral	Informative	Very informative

Does the waveform oscillator help to make the noise data more comprehensible?

Not Helpful	Slightly Helpful	No Opinion	Helpful	Very helpful

The number of waveforms that can be chosen for playback of the noise data are?

Not enough	Too many options	No Opinion	A pulse wave could also be included	This is the right amount

To what extent do the visual representations of the data in the small black screens on either side of the filter section make the sonification easier to understand?

Don't help at all	Slightly helpful	No opinion	Helpful	Very helpful

How accurately does the sonification compare to the visual representation in the small black screens?

Not Comparable	Slight resemblance	No opinion	Similar	Exactly the same

How useful are the Spectrograms?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful are the Sonograms?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful do you find the two volume controllers for the sonifications?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

Do you agree that you should be given control of the volume of the playback with the prototype?

I don't agree	Slightly agree	No Opinion	Agree	Strongly agree

Do you find the choice of colours of the interface appropriate to recognise the different controls for the different data sets and the playback engine?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful is the information about the minimum and maximum effective transiting radii measurements in the top central box of each sonification engine?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful are the number boxes that provide information about how many columns and rows there are in the data set situated at the bottom left hand corner of each sonification engine?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful is it to have the ability to specify segments of the data set for playback based upon lines in the data set?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How effective is the selection bar for choosing the segment of the data for playback?

Not effective at all	Slightly effective	Neutral	Effective	Very effective

Section 2 What could be added to the interface in terms of functions and visuals?

We are going to investigate whether you would like to add any of these tools to the sonification toolbox.

If you had to include some form of Volume Level Meter, what type would you want?
What do you think about having control of the low, mid and high frequencies of the audio (equalisation)?
There is currently a low pass, band pass and high pass filter for the "Noise signal data". What type of filters would you want for the "Pure signal data"?
What do you think about having the 'Pure Signal' on the left speaker and the 'noise signal' on the right speaker and the ability to be able to bring them together as one signal in the centre?
How many text files (data sets) would you like to load simultaneously into the system that you can either switch between them or have them play concurrently?
Would you like to use any of these options: quadraphonic, 5.1 surround, 7.1 surround, binaural or ambisonics[2]?
What do you think about having the ability to control the sonification's pitch range?
Would you like to include a recording function for the audio and how would you like it to work?
How would you like to visualise the data sets within the interface?

[2] Ambisonics is a full sphere surround technique that not only represents the horizontal plane but also includes the vertical plane.

Which of the following functions would you consider including within the sonification toolbox, and how useful would they be in your work?

Rewind
Fast forward
Pause
Jog wheel[3]
Scrub tool[4]

Are there any other functions that you would like to add to the interface?

Are there any comments that you would like to add?

[3] Jog wheels are used to easily move back and forth through an audio file.
[4] Scrub tools allow the user to select a specific point on an audio file to listen to it.

Sonification Test 2 Prototype for Exoplanetary Atmospheres

We are now going to playback two sets of data. One set is a mathematical model representing effective transiting radius of water vapour. The other set correspond to the actual noise data captured.

- You are going to hear the two data sets played back simultaneously, separately and at various playback speed varying from 1ms to 50ms.
- We might also playback the data at slower speeds than 50ms.
- Once you have finished listening to the data sets you will be asked questions about what you have listened to
- You will also be asked about the overall sound design of the sonification

1. What are your first impressions of listening to the sonifications?
2. Can you please describe any details that you were able to discern from the playback of the two sonifications?
3. What playback speed or speeds did you find the most suitable to follow the data-stream and why?
4. What changes did you notice in the quality of the sonifications when the speed of the playback was changed?
5. In the case of the faster playback speed, can you describe any specific details that you were able to hear that were not present at the slower speed?
6. In the case of the slower playback speeds can you describe any specific details that you were able to hear that were not present at the faster speed?
7. Please describe any patterns that you were you able to hear when listening to the sonifications played simultaneously?
8. Can you please describe the aesthetics of the sonification of the 'Pure Signal' water vapour data set?
9. Can you please describe the aesthetics of the sonification of the 'Noise Signal' water vapour data set?
10. Please can you describe the pitch range of the sonification playback and whether it was clear enough for you to follow any changes in the effective transiting radius?
11. Are the larger Effective Transiting Radius measurements lower or higher in pitch?

12. Can you please describe the size of the radii from listening to the ‘Pure Signal’ sonification?
13. Can you please describe the size of the radii from listening to the ‘Noise Signal’ sonification?
14. How do you determine the highest peaks in the ‘Pure Signal’ sonification?
15. How do you determine the highest peaks in the ‘Noise Signal’ sonification?
16. What other sonic attributes can you describe from the changes in the data of the ‘Pure Signal’ data set?
17. What other sonic attributes can you describe from the changes in the data of the ‘Noise Signal’ data set?
18. How could you tell the difference between one data set and another as they were played back simultaneously?
19. How well could you follow the two data sets playing simultaneously?
20. Can you please discuss the volume level of the playback of the two data sets and whether there was a good balance between the two data sets?
21. Did you feel the sound of the two data sets moving around your head and how would you describe this movement?
22. Can you please discuss how the movement of the playback from one headphone speaker to another helped or hindered your ability to discern details from the data-set?
23. Can you please describe what playback speed was more advantageous to be able to hear any sound moving around your head?
24. Can you please describe any particular details that caught your attention when the two data sets were played simultaneously?
25. What were the advantages of using faster playback speeds, the slower playback speeds and what playback speed suits your purpose the most?
26. When listening to the sonification, especially at the lower speeds, could you elaborate on how easy it is to imagine that you are listening to water vapour in the atmosphere of an Exo Planet?
27. Can you please describe any immersive qualities of the sound design?
28. How would you describe the sound of the ‘Pure Signal’?
29. What do you associate with when you hear the ‘Pure Signal’ and what do you imagine when listening to this sound?
30. Could you please elaborate on whether you found the sound design of the ‘Pure Signal’ pleasing or unpleasant?

31. Can you please describe the 'noise-like' qualities of the noise signal and how effective they might be?
32. Could you please describe how the noise signal sounds to you and what do you imagine when you hear it?
33. Could you please elaborate on whether you found the sound design of the 'Noise Signal' pleasing or unpleasant?
34. Can you please describe whether the differences in the sonic aesthetics help to distinguish between one data set and another?
35. What other characteristics helped you to determine the sound between one data set and another?
36. What changes do you think could be made to improve the sonic aesthetics of the sonification?
37. How do you think the sonification could be altered to help you gain a deeper understanding of the data?
38. Could you please discuss whether the sonification needs to playback all the elements of the dataset or whether it would be more efficient if the higher transit radii details were given prominence only?
39. Can you please describe whether the sonification has given you any new insight regarding the data?
40. Could you please describe what you like about the sonification?
41. Could you please describe what you dislike about the sonification?
42. Can you please describe any improvements to the sonification design?
43. How would you use this tool in your daily work?
44. Do you have any further suggestions or comments that you would like to add?

Application for Cross-University Ethical Approval

Research Details

Name:	Michael Quinton
School or Professional service department:	School of computing
Email:	M.Quinton@napier.ac.uk
Contact number:	+44 (0) 131 455 2770
Project Title:	**The Sonification of Exo-solar Planetary Systems**
Start Date:	1st October 2015
Duration of Project:	3 years
Type of Research:	Doctoral Student

Screening Questions

Please answer the following questions to identify the level of risk in the proposed project:

If you answer 'No' to all questions, please complete Section 3a only.

If you have answered 'Yes' to any of the questions 5-14 please complete Section 3a and 3b.

If you have answered 'Yes to any of the questions 1-4, complete all of Section 3.□□□

	You Must Answer All Questions	**Yes**	**No**
1.	Is the research clinical in nature?□	☐	☐
2.	Is the research investigating socially or culturally 'controversial' topics (for example pornography, extremist politics, or illegal activities)?	☐	☐
3.	Will any covert research method be used?	☐	☐
4.	Will the research involve deliberately misleading participants (deception) in any way?	☐	☐
5.	Does the Research involve staff or students within the University?	☐	☐
6.	Does the Research involve vulnerable people? (For example people under 18 or over 70 years of age, disabled (either physically or mentally), those with learning difficulties, people in custody, migrants etc).	☐	☐
7.	Is the information gathered from participants of a sensitive or personal nature?	☐	☐

8.	Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?	☒	☐
9.	Have you identified any potential risks to the researcher in carrying out the research? (for example physical/emotional/social/economic risks?)	☐	☐
10.	Are there implications from a current or previous professional relationship i.e. staff/student/line manager/managerial position that would affect the voluntary nature of the participation?	☐	☐
11.	Will the research require the use of assumed consent rather than informed consent? (For example when it may be impossible to obtain informed consent due to the setting for the research – e.g. observational studies/videoing/photography within a public space)	☐	☐
12.	Is there any risk to respondents' anonymity in any report/thesis/publication from the research, even if real names are not used?	☒	☐
13.	Will any payment or reward be made to participants, beyond reimbursement or out-of-pocket expenses?	☐	☐
14.	Does the research require external ethics clearance? (For example from the NHS or another institution)	☐	☐
15.	Does the research involve the use of secondary data?	☐	☐

3A. Details of Project

In this section please provide details of your project and outline data collection methods, how participant consent will be given as well as details of storage and dissemination.

Please give a 300 word overview of the research project

The purpose of this study is to create and evaluate a sonification tool that represents exosolar planetary data, which can be used by astronomers. Sonification is the use of non-verbal sound to represent data, which in this case will take a non-musical form. The search for exosolar planets is a relatively new field and to date over three thousand planets have been discovered. A lot of the data is temporal-spatial, and sonification could be an effective way of representing these parameters. Sound is a temporal phenomenon, and works within a spatial domain. Sonifying complex exosolar planetary datasets could allow astronomers to be able to detect various aspects instantaneously, as it is possible to easily listen to multiple sound sources simultaneously to determine patterns and subtle variations. For any sonification to be effective it must be semantically comprehensible to the user. If the sonification cannot be understood then it is redundant. To overcome this problem it is important to involve potential end users in the design process. Sonifications of various aspects of exosolar planetary phenomena have been sonified. These sonifications represent different aspects of Exosolar planetary phenomena such as atmospheres and asteroid belts. Part of the research is investigating possible effective methods of sonifying Exosolar planetary data. In this study a total of 40 Asteroid belts will be compared and an astronomer will try to classify the data using sonification to identify differences or similarities between the data-sets. These different aspects of Exosolar phenomena are being tested to see whether astronomers could effectively discern data from these sonic representations and possibly discover new insights. A prototype has been developed using an object oriented software design platform, and will be tested in a laboratory environment using a semi-structured interview.	
Data Collection	
1.	**Who will be the participants in the research?**
	A professional astronomer who works with data about Asteroid belts located in Exosolar systems.
2.	**How will you collect and analyse the research data? (please outline all methods e.g. questionnaires/focus groups/internet searches/literature searches/interviews/observation)**
	Interview
3.	**Where will the data will be gathered (e.g. in the classroom/on the street/telephone/on-line)**
	C72 Merchiston campus (Auralisation suite)
4.	**Please describe your selection criteria for inclusion of participants in the study**
	The participant is an astronomer who provided the data set that has been sonified and had also been involved in the design process of the sonification toolbox.

5.	**If your research is based on secondary data, please outline the source, validity and reliability of the data set**
	N/A
Consent and Participant Information	
7.	**How will you invite research participants to take part in the study? (e.g. letter/email/asked in lecture)**
	Email
8.	**How will you explain the nature and purpose of the research to participants?**
	Informed Consent form
9.	**How will you record obtaining informed consent from your participants?**
	Signed Informed Consent Form
Data storage and Dissemination	
10.	**How and in what format will data be stored? And what steps will be taken to ensure data is stored securely?**
	Paperwork will be stored in a locked filling cabinet in C35 Merchiston campus. Digital files will be encrypted and stored on a password protected laptop also stored in C35.
11.	**Who will have access to the data?**
	Only the researcher.
12.	**Will the data be anonymised so that files contain no information that could be linked to any participant?**
	Yes
13.	**How long will the data be kept?**
	Until successful completion of the PhD, expected September 2018.
14.	**What will be done with the data at the end of the project?**
	Securely destroyed.
15.	**How will the findings be disseminated?**
	The findings will be disseminated in a PhD thesis and in conference or journal papers
16.	**Will any individual be identifiable in the findings?**
	N/A

3B. Identification and Mitigation of Potential risks

This section is designed to identify any realistic risks to the participants and how you propose to deal with it.

Does this research project involve working with potentially vulnerable individuals?

Group	Yes	NO	Details (for example programme student enrolled on, or details of children's age/care situation, disability)
Students at Napier	☐	☐	
Staff at ENU	☐	☐	
Children under 18	☐	☐	
Elderly (over 70)	☐	☐	
Disabled	☐	☐	
Migrant workers	☐	☐	
Prisoners / people in custody	☐	☐	
Learning difficulties	☐	☐	

If you are recruiting children (under 18 years) or people who are otherwise unable to give informed consent, please give full details of how you will obtain consent from parents, guardians, carers etc.

N/A

Please describe any identified risks to participants or the researcher as a result of this research being carried out

Potential hearing damage and participant identification.

Please describe what steps have been taken to reduce these identified risks? (for example providing contact details for appropriate support services (e.g. University Counselling, Samaritans), reminding participants of their right to withdraw and/or not answering questions, or providing a full debriefing to participants)

The participant will be asked to listen to sonified data on loudspeakers and headphones. A safe level of 65 dBA RMS and 100dBA peak will be kept throughout the testing. Listening levels are 20 dB below what is considered safe for an eight hour working day (Moore, P 156, 2013), and will be controlled by the researcher and participants will not be able to alter the volume. All responses will be anonymised using the convention A2.

If you plan to use assumed consent rather than informed consent please outline why this is necessary

N/A

If payment or reward will be made to participants please justify that the amount and type are appropriate (for example the amount should not be so high that participants would be financially coerced into taking part, or that the type of reward is appropriate to the research topic).

N/A

3C. Justification of High Risk Projects

If you answered 'Yes' to the screening questions 1-4 this section asks for justification on the choice of research topic and methodology.

If you have answered yes to question 1 please give a full description of all medical procedures to be used within the research and provide evidence that the project has obtained NHS ethical approval.

N/A

If you have answered yes to questions 2 (research into a controversial topic) please provide a justification for your choice of research topic, and describe how you would deal with any potential issues arising from researching that topic.

N/A

If you have answered yes to questions 3 or 4 (use of deception or covert research methods) please provide a justification for your choice of methodology, and state how you will mitigate the risks associated with these approaches.

N/A

Declaration	
☐	I consider that this project has no significant ethical implications to be brought to the attention of Research Integrity Committee

☐	I consider that this project may have significant ethical implications to be brought to the attention of the Research Integrity Committee

Researcher Signature: [redacted]	**Date:** 14th March 2018
Director of Studies: [redacted]	**Date:** 14th of March 2018

Checklist

All applications require the following to be submitted with the application form

Participant Information Sheet	☐
Informed Consent Form	☐
Interview/Survey Questions	☐

1. Moore, Brian C J, 2013.' An introduction to the Psychology of Hearing', Koninklijke Brill NV, Leiden, The Netherlands. P. 156

The Sonification of Exosolar Planetary Systems - Informed Consent Form

Edinburgh Napier University requires that all persons who participate in research studies give their written consent to do so. Please read the following and sign it if you agree with what it says.

1. I freely and voluntarily consent to be a participant in this research to be conducted by Michael Quinton, who is a PhD student in the Edinburgh Napier School of Computing.
2. I have been informed of the broad goal of this research study. I have been told what is expected of me and that the study should take no longer than one working day to complete.
3. I have been told that my responses will be anonymised. My name will not be linked with the research materials, and I will not be identified or identifiable in any report subsequently produced by the researcher. I have been told what these data are for and may be submitted for publication.
4. I also understand that if at any time during the interview I feel unable or unwilling to continue, I am free to leave. That is, my participation in this study is completely voluntary, and I may withdraw from it at any time without negative consequences.
5. In addition, should I not wish to answer any particular question or questions, I am free to decline.
6. I have been given the opportunity to ask questions regarding the interview and my questions have been answered to my satisfaction.
7. I have read and understand the above and consent to participate in this study. My signature is not a waiver of any legal rights. Furthermore, I understand that I will be able to keep a copy of this consent form for my records.

______________________________ ______________________

Participant's Signature Date

I have explained and defined in detail the research procedure in which the respondent has consented to participate. Furthermore, I will retain one copy of the informed consent form for my records.

______________________________ ______________________

Researcher's Signature Date

Sonification of Exosolar Planetary Systems: Sonification of Asteroid Belts located in Exosolar Systems - Participant Information

Thank you for considering taking part in this study, your participation is really appreciated.
This study explores how to create an effective sonification of data concerning Exosolar Planetary systems, which could be used as a scientific data analysis tool by Astronomers and Astrophysicists. You have been ask to take part as an Astronomer that works in the field of Exosolar Planetary research.
The interviews will take about one day and will be split into three different sessions. The first session will consist of a trial run using the sonification toolbox. You will be interviewed about your user experience. The second session will consist of questions regarding further improvement to the toolbox and potential enhancements. The third session will be a listening test where you will be asked to listen to 40 different sonification recordings, to make comparisons between them and provide feedback concerning discernment and clarity of comprehension of the sonification. You will also be asked about sound design aesthetics. You will be asked to listen to the sonified data on loudspeakers and headphones. A safe sound pressure level of 65 dBA RMS and 100dBA peak will be kept throughout the testing. The listening levels will be 20 dB below those considered safe for an eight hour working day (Moore, P 156, 2013) and will be controlled by the researcher and you will not be able to alter the volume. All answers will be anonymised using the convention A2. These interviews will be conducted in the Auralisation Suite, room C72, School of Computing, Edinburgh Napier University, Merchiston Campus.
The interviews will be recorded on an audio recorder. The audio files will be immediately deleted after the audio has been transcribed. This will form part of my PhD research in Sonification and this information will also be used in a future study, that may be published in either a journal or for a conference paper, as well as in my PhD dissertation.
Before agreeing to participate in this study please note that your participation is voluntary. This means that you can decide not to answer any questions or may stop the survey at any time if you feel that you are unable or unwilling to continue.

Thank you

Michael Quinton - PhD Candidate
School of Computing
Edinburgh Napier University
M.Quinton@napier.ac.uk
Skype: - Michael_Quinton_Napier
Telephone: - +44 (0) 131 455 2770

Sonification Test 1 Prototype 2 - Personal Information

Could you please provide your personal details?

Age:- ___________

Sex:- ____________

Profession:- ____

Field of Study:- ____

Do you have any hearing problems or hearing impairments?:- _________

Signature:- ______________________________________

Section1 Initial impressions of the interface

Now that you have had time to play around with the interface I am going to ask you some questions about your initial impressions of using the interface.

1. What are your first impressions of the interface?
2. How easy was it to use the interface?
3. How would you characterise the ease of use of the interface?
4. What functions do you find most useful?
5. What functions do you find least useful?
6. What is unclear about the functionality of the toolbox?
7. How would you rate your confidence in using this interface and what are the reasons for your answer?

Section 2 What could be added to the interface

I am going to show you two examples of external controller interfaces and different software that allow you to control and manipulate audio. These controllers are DJ and Music production controllers that have specific controls that give a lot of flexibility to *the playback. We are going to investigate whether you would like to add any of these tools to the sonification toolbox.*

1. What do you think about adding the ability to control the volume of the sonification playback?
2. What do you think about having a Volume Level Meter so that you can monitor how loud the playback is?
3. What do you think about having control on the low, mid and high frequencies of the sonification playback (Control on the equalisation)?
4. What do you think about having a low pass, band pass and high pass filter that would allow you to cut out certain frequency ranges of the sonification playback so that you can only listen to certain aspects of the data in isolation?
5. What do you think about having the ability to control the playback of the sonification on the left speaker, the right speaker and more speakers (Control the panning)?
6. What do you think about having a "Mute" button so that you can switch the signal of the playback on and off while it is still playing?
7. How many text files would you like to load simultaneously into the system and why?
8. How would you use a surround sound function playback for more than one text file?
9. When using the surround sound function, what do you think about having the capability to route the output of the playback of more than one sonification or sonification recording?
10. Would you consider using an external soundcard with multiple outputs as your playback system and if so why?
11. What do you think about having the ability to control the pitch range within which the sonification is played back?
12. Would you like to have more than one playback engine for the recorded audio and how would you like to control the playback?
13. Do you want to add more detail to the data section and what information would you like to visualise in this section?
14. What do you think about having a "Rewind" function or a jog-wheel controller on the sonification playback?

15. What do you think about having a speed controller that would allow you to slow down or speed up the playback by moving a jog-wheel or fader?
16. Would you like a “Solo” button so that you can listen to one sonification dataset in isolation?
17. Would you like a “Cue” button so that you can hear other sonification channels on headphones while other sonifications are playing back on speakers?
18. What do you think about having a “Crossfade” function that will allow you to cross playback between 2 different channels of sonification playback?
19. What do you think about having a “Sync” function that would allow you to synchronise the playback timing of more than one sonification?
20. What do you think about having a counter that will give you the length in seconds of the sonification?
21. Would you like a Master Volume to control all the volumes of the sonifications that are being played back?
22. Would you like to add any effects to the playback and what effects would you like to add to the sonifications?
23. What do you think about having the ability to playback the different sonifications at different start points?
24. What do you think about having the ability to playback the different sonifications at different cue points in the playback?
25. What do you think about having the ability to playback the different sonifications at different speeds?
26. Would you like to have more than one cue point that can be set as a sonification playback point and how many would you like?
27. What do you think about having the ability to visualise the sonification playback or the Audio wave recording of the sonification?
28. What do you think about having a function that would allow you to move the playback cue points on selected playback and to change the size of the playback time in particular measures?
29. Would you like an overall playback button to play all the sonification files simultaneously?
30. What do you think about controlling the sonification toolbox with an external controller?

31. If you can load more than one text file simultaneously would you like to have the same controls for each channel of playback?
32. Are there any other functions that you would like to add to the interface?

Sonification Test 2 Prototype 2

We are now going to playback one sonification file at different speeds ranging from 1 ms to 50 ms. We are also going to playback the sonification on both the stereo and the surround playback engines, and you are going to be asked questions about overall the sound design of the sonification

1. What are your first impressions of the sonification?
2. Can you describe the details that you were able to discern from the playback of the sonification?
3. Were you able to discern these details from the first playback or did you have to listen to it more than once to understand the sonification?
4. What playback speed did you find the most suitable to follow the data-stream and why?
5. What changes do you notice in the quality of the sonification when the speed of the playback is changed?
6. In the case of the faster playback speed, can you roughly hum the sonification?
7. In the case of the slower playback speeds can you describe any specific details that you were able to hear?
8. Can you describe the aesthetics of the sonification?
9. Can you discuss the pitch range of the sonification playback?
10. Are the dips higher or lower in pitch?
11. Can you describe the size of the dips from listening to sonification?
12. Are you able to pin-point the largest dips in the sonification?
13. What other sonic attributes can you describe from the changes in the data?
14. Can you discuss the volume level of the playback?
15. Can you discuss the movement of the playback from the left speaker to the right speaker when using the “Stereo” playback engine?
16. Can you discuss how the movement of the playback from left to right speaker helped or hindered your ability to discern details from the data-set?
17. Can you describe what playback speed was more advantageous when using the stereo sound system?
18. Can you describe the use of the surround sound playback engine?

19. When using the surround sound playback engine did you notice any considerable improvements or drawbacks in discerning detail from the data-set?
20. Can you describe what playback speed was more advantageous when using the surround sound system?
21. What were the advantages of using faster playback speeds?
22. What were the advantages of using the slower playback speeds?
23. In general, what playback speed suits your purposes the most?
24. When listening to the sonification, especially at the lower speeds, could you elaborate on how easy it is to imagine that you are listening to an asteroid belt?
25. Can you describe the immersive qualities of the sound design?
26. Can you describe the ‘rock-like’ or ‘sand grain’ qualities of the sound design and how effective it is?
27. Can you describe how the ‘rock-like’ or ‘sand grain’ qualities of the sound design change according to the playback speed?
28. What changes do you think could be made to improve the aesthetics of the sonification?
29. Could you discuss whether deeper immersive qualities of the sound design could improve discernment of the data or enhance the user’s perceptibility by triggering the user’s imagination?
30. Could you discuss whether the sonification needs to playback all the elements of the dataset or whether it would be more efficient if the dipper details were only given prominence?
31. Could you describe what you like about the sonification?
32. Could you describe what you dislike about the sonification?
33. Can you describe any improvements to the sonification design?
34. Do you have any further suggestions or comments that you would like to add?

Sonification Test 3 Prototype 2

Section 1 – Comparing 5 sonification datasets in 8 sets

We are now going to playback 40 different data-sets that have been recorded at 1ms each. You will use the controller to trigger different sets. We will play 8 sets of 5 sonification datasets. Then we will compare the 5 sonifications of each set to each other. From each of the 8 sets we will see how many sonifications are similar and how many are different. We will take note of the different sonifications and then we will compare them across the 8 sets to see whether there are any similarities or differences between them.

Sonification Set 1

1. Which datasets sound the same and why are they similar?
2. Which datasets sound different and why?
3. Which datasets vary the most in dipper activity?
4. Which datasets do not vary so much in dipper activity?
5. What details are you able to discern when comparing the asteroid belts to each other?
6. Please classify each sonification dataset that you have heard
7. How would you classify the information between the different datasets?
8. Which dataset has the biggest dipper?
9. How many of the 5 datasets can you remember and can you hum how they sound?
10. Which datasets are easiest to follow and why?

Sonification Set 2

1. Which datasets sound the same and why are they similar?
2. Which datasets sound different and why?
3. Which datasets vary the most in dipper activity?
4. Which datasets do not vary so much in dipper activity?
5. What details are you able to discern when comparing the asteroid belts to each other?

6. Please classify each sonification dataset that you have heard
7. How would you classify the information between the different datasets?
8. Which dataset has the biggest dipper?
9. How many of the 5 datasets can you remember and can you hum how they sound?
10. Which datasets are easiest to follow and why?

Sonification Set 3

1. Which datasets sound the same and why are they similar?
2. Which datasets sound different and why?
3. Which datasets vary the most in dipper activity?
4. Which datasets do not vary so much in dipper activity?
5. What details are you able to discern when comparing the asteroid belts to each other?
6. Please classify each sonification dataset that you have heard
7. How would you classify the information between the different datasets?
8. Which dataset has the biggest dipper?
9. How many of the 5 datasets can you remember and can you hum how they sound?
10. Which datasets are easiest to follow and why?

Sonification Set 4

1. Which datasets sound the same and why are they similar?
2. Which datasets sound different and why?
3. Which datasets vary the most in dipper activity?
4. Which datasets do not vary so much in dipper activity?
5. What details are you able to discern when comparing the asteroid belts to each other?
6. Please classify each sonification dataset that you have heard
7. How would you classify the information between the different datasets?
8. Which dataset has the biggest dipper?

9. How many of the 5 datasets can you remember and can you hum how they sound?
10. Which datasets are easiest to follow and why?

Sonification Set 5

1. Which datasets sound the same and why are they similar?
2. Which datasets sound different and why?
3. Which datasets vary the most in dipper activity?
4. Which datasets do not vary so much in dipper activity?
5. What details are you able to discern when comparing the asteroid belts to each other?
6. Please classify each sonification dataset that you have heard
7. How would you classify the information between the different datasets?
8. Which dataset has the biggest dipper?
9. How many of the 5 datasets can you remember and can you hum how they sound?
10. Which datasets are easiest to follow and why?

Section 2 – Comparing the datasets that sound different across each of the 8 sets.

We will now playback all the sonifications that we have classified as sounding different across each of the 8 sets. We will classify which of the datasets sound similar between these sonifications and which ones sound different.

1. How many of the sonifications that we have played sound similar?
2. What characteristics make them sound similar?
3. How can these similar sounding sonifications be classified?
4. How many of the sonifications sound different?
5. What characteristics make them sound different?
6. Why do the sonifications that sound different have these unique characteristics?
7. How can these different sounding sonifications be classified?
8. What other classifications can be made from the datasets that you have just listened to?

Section 3 – General questions about the test

In this last section, you will be asked general questions about your user-experience with sonification representing the 40 different asteroid belts.

1. Can you describe how easy was it to discern details about all the sonifications that you listened to?
2. Can you describe how easy was it to classify the various sonifications?
3. Can you describe how many classifications were you able to make from all the different sets that you listened to and you were able to make these classifications?
4. Could you describe how much detail you were able to understand of the nature of the asteroid belts just by listening to them?
5. Can you describe whether sonification has presented any new insights about the data and what were these insights?
6. Can you describe how you were able to understand the data without having any visual reference?
7. Can you describe whether the sonification has added any value to your work?
8. How do you think the sonification can be improved to add more value or insight to your work?
9. Can you describe how the sonification serves its purpose as a data-analysis tool?
10. Could you describe whether you would use sonification in your work, and how often?
11. Which did you prefer using headphones or speakers and why?
12. Would you be interested in further developing the sonification and what are your ideas or views about going about this?
13. Please describe any further applications that you can think of for astronomical sonification.
14. Would you like to add any additional suggestions or comments?

Application for Cross-University Ethical Approval

Research Details

Name:	Michael Quinton
School or Professional service department:	School of computing
Email:	M.Quinton@napier.ac.uk
Contact number:	+44 (0) 131 455 2770
Project Title:	**The Sonification of Exo-solar Planetary Systems**
Start Date:	1st October 2015
Duration of Project:	3 years
Type of Research:	Doctoral Student

Screening Questions

Please answer the following questions to identify the level of risk in the proposed project:

If you answer 'No' to all questions, please complete Section 3a only.

If you have answered 'Yes' to any of the questions 5-14 please complete Section 3a and 3b.

If you have answered 'Yes to any of the questions 1-4, complete all of Section 3.

	You Must Answer All Questions	**Yes**	**No**
1.	Is the research clinical in nature?	☐	☒
2.	Is the research investigating socially or culturally 'controversial' topics (for example pornography, extremist politics, or illegal activities)?	☐	☒
3.	Will any covert research method be used?	☐	☒
4.	Will the research involve deliberately misleading participants (deception) in any way?	☐	☒
5.	Does the Research involve staff or students within the University?	☐	☒
6.	Does the Research involve vulnerable people? (For example people under 18 or over 70 years of age, disabled (either physically or mentally), those with learning difficulties, people in custody, migrants etc).	☐	☒
7.	Is the information gathered from participants of a sensitive or personal nature?	☒	☐

8.	Is there any realistic risk of any participants experiencing either physical or psychological distress or discomfort?	☒	☐
9.	Have you identified any potential risks to the researcher in carrying out the research? (for example physical/emotional/social/economic risks?)	☐	☒
10.	Are there implications from a current or previous professional relationship i.e. staff/student/line manager/managerial position that would affect the voluntary nature of the participation?	☐	☒
11.	Will the research require the use of assumed consent rather than informed consent? (For example when it may be impossible to obtain informed consent due to the setting for the research – e.g. observational studies/videoing/photography within a public space)	☐	☒
12.	Is there any risk to respondents' anonymity in any report/thesis/publication from the research, even if real names are not used?	☒	☐
13.	Will any payment or reward be made to participants, beyond reimbursement or out-of-pocket expenses?	☐	☒
14.	Does the research require external ethics clearance? (For example from the NHS or another institution)	☐	☒
15.	Does the research involve the use of secondary data?	☐	☒

3A. Details of Project

In this section please provide details of your project and outline data collection methods, how participant consent will be given as well as details of storage and dissemination.

Please give a 300 word overview of the research project

The purpose of this study is to create and evaluate a sonification tool that represents exosolar planetary data, which can be used by astronomers. Sonification is the use of non-verbal sound to represent data. A lot of the exosolar planetary data is temporal-spatial, and sonification could be an effective way of representing these parameters. Sonifying complex exosolar planetary datasets could allow astronomers to be able to detect various aspects instantaneously, as it is possible to easily listen to multiple sound sources simultaneously to determine patterns and subtle variations. For any sonification to be effective it must be semantically comprehensible to the user. If the sonification cannot be understood then it is redundant. To overcome this problem it is important to involve potential end users in the design process. Sonifications of various aspects of exosolar planetary phenomena have been sonified. These sonifications represent different aspects of Exosolar planetary phenomena such as atmospheres and asteroid belts. Part of the research is investigating possible effective methods of sonifying Exosolar planetary data. In this study one astronomer will be listening to a dataset that represents the collision of asteroids due to planetary rotation and to explore whether these collisions accurately represent the movement of a planet through an asteroid belt. The astronomer will be asked to determine the different sizes of the asteroids, which has been represented by using pitch. Lower pitches for the bigger asteroids and vice versa. The purpose of using sonification is to determine whether it is capable of representing these asteroid collisions accurately so that astronomers can obtain a deeper understanding of planet detection by monitoring asteroid collisions, and possibly discover new insights. A prototype has been developed using an object oriented software design platform, and will be tested in an office environment using a semi-structured interview.	
Data Collection	
1.	**Who will be the participants in the research?**
	A professional astronomer who works with data about Exoplanet detection in Asteroid belts
2.	**How will you collect and analyse the research data? (please outline all methods e.g. questionnaires/focus groups/internet searches/literature searches/interviews/observation)**
	Interview
3.	**Where will the data will be gathered (e.g. in the classroom/on the street/telephone/on-line)**
	Office environment at Astronomer's place of work.
4.	**Please describe your selection criteria for inclusion of participants in the study**
	The participant is an astronomer who works in the field of Exosolar planetary atmospheres and who has had provided the data sets that have been sonified. The

	astronomer was involved in the design process of the sonification toolbox, which is also being tested.
5.	**If your research is based on secondary data, please outline the source, validity and reliability of the data set**
	N/A
Consent and Participant Information	
7.	**How will you invite research participants to take part in the study? (e.g. letter/email/asked in lecture)**
	Email
8.	**How will you explain the nature and purpose of the research to participants?**
	Participant information sheet
9.	**How will you record obtaining informed consent from your participants?**
	Signed Informed Consent Form
Data storage and Dissemination	
10.	**How and in what format will data be stored? And what steps will be taken to ensure data is stored securely?**
	Paperwork will be stored in a locked filling cabinet in C35 Merchiston campus. Digital files will be encrypted and stored on a password protected laptop also stored in C35.
11.	**Who will have access to the data?**
	Only the researcher.
12.	**Will the data be anonymised so that files contain no information that could be linked to any participant?**
	Yes
13.	**How long will the data be kept?**
	Until successful publication of the data, expected September 2019.
14.	**What will be done with the data at the end of the project?**
	Securely destroyed.
15.	**How will the findings be disseminated?**
	The findings will be disseminated in a PhD thesis and in conference or journal papers
16.	**Will any individual be identifiable in the findings?**
	N/A

3B. Identification and Mitigation of Potential risks

This section is designed to identify any realistic risks to the participants and how you propose to deal with it.

Does this research project involve working with potentially vulnerable individuals?

Group	Yes	NO	Details (for example programme student enrolled on, or details of children's age/care situation, disability)
Students at Napier	☐	☒	
Staff at ENU	☐	☒	
Children under 18	☐	☒	
Elderly (over 70)	☐	☒	
Disabled	☐	☒	
Migrant workers	☐	☒	
Prisoners / people in custody	☐	☒	
Learning difficulties	☐	☒	

If you are recruiting children (under 18 years) or people who are otherwise unable to give informed consent, please give full details of how you will obtain consent from parents, guardians, carers etc.

N/A

Please describe any identified risks to participants or the researcher as a result of this research being carried out

Potential hearing damage and participant identification.

Please describe what steps have been taken to reduce these identified risks? (for example providing contact details for appropriate support services (e.g. University Counselling, Samaritans), reminding participants of their right to withdraw and/or not answering questions, or providing a full debriefing to participants)

The participant will be asked to listen to sonified data on loudspeakers and headphones. A safe level of 65 dBA RMS and 100dBA peak will be kept throughout the testing. Listening levels are 20 dB below what is considered safe for an eight hour working day (Moore, p. 156,

2013), [5]and will be controlled by the researcher and participants will not be able to alter the volume. All responses will be anonymised using the convention A3.

If you plan to use assumed consent rather than informed consent please outline why this is necessary

N/A

If payment or reward will be made to participants please justify that the amount and type are appropriate (for example the amount should not be so high that participants would be financially coerced into taking part, or that the type of reward is appropriate to the research topic).

N/A

3C. Justification of High Risk Projects

If you answered 'Yes' to the screening questions 1-4 this section asks for justification on the choice of research topic and methodology.

If you have answered yes to question 1 please give a full description of all medical procedures to be used within the research and provide evidence that the project has obtained NHS ethical approval.

N/A

If you have answered yes to questions 2 (research into a controversial topic) please provide a justification for your choice of research topic, and describe how you would deal with any potential issues arising from researching that topic.

N/A

If you have answered yes to questions 3 or 4 (use of deception or covert research methods) please provide a justification for your choice of methodology, and state how you will mitigate the risks associated with these approaches.

[5] *Moore, Brian C J, 2013.' An introduction to the Psychology of Hearing', Koninklijke Brill NV, Leiden, The Netherlands. P. 156*

N/A

Declaration		
☐	I consider that this project has no significant ethical implications to be brought to the attention of Research Integrity Committee	
☐	I consider that this project may have significant ethical implications to be brought to the attention of the Research Integrity Committee	
Researcher Signature: [redacted]		**Date:** 22nd May 2018
Director of Studies: [redacted]		**Date:** 23rd of May 2018

Checklist

All applications require the following to be submitted with the application form

Participant Information Sheet	☐
Informed Consent Form	☐
Interview/Survey Questions	☐

Sonification of Exosolar Planetary Systems: Sonification of Asteroid Collisions Exosolar Systems - Informed Consent Form

Edinburgh Napier University requires that all persons who participate in research studies give their written consent to do so. Please read the following and sign it if you agree with what it says.

1. I freely and voluntarily consent to be a participant in this research to be conducted by Michael Quinton, who is a PhD student in the Edinburgh Napier School of Computing.
2. I have been informed of the broad goal of this research study. I have been told what is expected of me and that the study should take approximately three hours to complete.
3. I have been told that my responses will be anonymised. My name will not be linked with the research materials, and I will not be identified or identifiable in any report subsequently produced by the researcher. I have been told what these data are for and may be submitted for publication.
4. I also understand that if at any time during the interview I feel unable or unwilling to continue, I am free to leave. That is, my participation in this study is completely voluntary, and I may withdraw from it at any time without negative consequences.
5. In addition, should I not wish to answer any particular question or questions, I am free to decline.
6. I have been given the opportunity to ask questions regarding the interview and my questions have been answered to my satisfaction.
7. I have read and understand the above and consent to participate in this study. My signature is not a waiver of any legal rights. Furthermore, I understand that I will be able to keep a copy of this consent form for my records.

______________________________ _______________________

Participant’s Signature Date

I have explained and defined in detail the research procedure in which the respondent has consented to participate. Furthermore, I will retain one copy of the informed consent form for my records.

______________________________ _______________________

Researcher’s Signature Date

Sonification of Exosolar Planetary Systems: Sonification of Asteroid Collisions located in Exosolar Systems - Participant Information

Thank you for considering taking part in this study, your participation is really appreciated.

This study explores how to create an effective sonification of data concerning Exosolar Planetary systems, which could be used as a scientific data analysis tool by Astronomers and Astrophysicists. You have been asked to take part as an Astronomer that works in the field of Exosolar Planetary research.

The interviews will take about three hours and will be split into two different sessions. The first session will consist of a trial run using the sonification toolbox. You will be interviewed about your user experience and asked questions regarding further improvement to the toolbox and potential enhancements. The second session will be a listening test where you will be asked to listen to the sonified data sets of asteroid collisions. You will be asked to provide feedback concerning discernment, clarity of comprehension and sonic aesthetics. You will be asked to listen to the sonified data on headphones and loudspeakers. A safe sound pressure level of 65 dBA RMS and 100 dBA peak will be kept throughout the testing. The listening levels will be 20 dB below those considered safe for an eight-hour working day (Moore, p. 156, 2013). The levels will be controlled by the researcher and you will not be able to alter the volume. All answers will be anonymised using the convention A3. These interviews will be conducted in a room of your choice.

The interviews will be recorded on an audio recorder. The audio files will be immediately deleted after the audio has been transcribed. This will form part of my PhD research in Sonification and this information will also be used in a future study, that may be published in either a journal or for a conference paper, as well as in my PhD dissertation.

Before agreeing to participate in this study please note that your participation is voluntary. This means that you can decide not to answer any questions or may stop the survey at any time if you feel that you are unable or unwilling to continue.

Thank you

Michael Quinton - PhD Candidate
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Edinburgh Napier University
M.Quinton@napier.ac.uk
Skype: - Michael_Quinton_Napier
Telephone: - +44 (0) 131 455 2770

Sonification Test 1 Prototype for Asteroid Collision Data

Personal Information

Age:- ___________

Gender:- ____________

Profession:- ____

Field of Study:- ____

How long have you been working in this field? _____________________

Do you believe that you have normal hearing for your age? _________

Do you believe that you have either normal or corrected eyesight? ______________

Do you have any experience working in professional audio?____________

Do you have any musical training?_______________

Section1 Initial impressions of the interface

Now that you have had time to use with the interface I am going to ask you some questions about the interface.

What are your first impressions of the interface?

It is not suitable for sonifying data	It is not entirely suitable for sonifying data	Neutral	It is partially suitable for sonifying data	It is suitable for sonifying data

How easy was it to understand the interface?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How easy was it to control the interface?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How would you rate the loading function on the interface?

Very poor	Poor	No Opinion	Good	Very good

How easy is it to playback the data?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How useful is it to loop the playback?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How easy is it to change the speed of the playback in real-time?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How useful is it to be able to change the speed of the playback in real-time?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful are the number boxes providing all the information from the dataset?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

Do you find the choice of colours of the interface appropriate for the playback engine?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful is the information about the minimum and maximum collision sizes in the area entitled 'Collision Data Values' of the sonification engine?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful are the number boxes that provide information about how many columns and rows there are in the dataset, situated at the bottom left hand corner of the loading section?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How useful is it to have the ability to specify segments of the dataset for playback based upon lines in the data set?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How effective is the selection bar for choosing the segment of the data for playback?

Not effective at all	Slightly effective	Neutral	Effective	Very effective

How useful is it to have a recording capability to record the sonification?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

How do you rate the ease of use of the recording function?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

How easy is it to playback a recording of the sonification?

Difficult	Fairly difficult	Neutral	Fairly easy	Easy

Do you find the ability to playback a recording of the sonification useful?

Not useful at all	Slightly useful	Neutral	Useful	Very useful

Section 2 What could be added to the interface in terms of functions and visuals?

We are going to investigate whether you would like to add any of these tools to the sonification toolbox.

What do you think about adding a volume controller to be able to regulate the level of the sonification playback?

If you had to include some form of Volume Level Meter, what type would you want?

What do you think about having control of the low, mid and high frequencies of the audio (equalisation)?

What do you think about having low pass, band pass and high pass filters that could allow you to highlight frequency ranges of the sonification playback?

What do you think about having the ability to control the playback of the sonification on the left speaker, the right speaker (Control the panning)?

How many text files (data sets) would you like to load simultaneously into the system that you could either switch between, or play concurrently?

Would you like to use any of these options: quadraphonic, 5.1 surround, 7.1 surround, binaural or ambisonics[1]?

What do you think about having the ability to control the sonification's pitch range?

What type of visualisation would you like to include within the interface, if any?

Which of the following functions would you like in the sonification toolbox, and how useful would they be in your work?

Rewind
Fast forward
Pause
Jog wheel[2]
Scrub tool[3]

Are there any other functions that you would like to add to the interface?

Are there any comments that you would like to add?

[1]Ambisonics is a full sphere surround technique that not only represents the horizontal plane but also includes the vertical plane.

[2]Jog wheels are used to easily move back and forth through an audio file.

[3]Scrub tools allow the user to select a specific point on an audio file to listen to it.

Sonification Test 2 Prototype for Asteroid Collision Data

We are now going to playback the data.

- You are going to hear the dataset played back at various speeds

1. What are your first impressions of the sonifications?
2. Can you please describe any details that you were able to discern from the playback of the two sonifications?
3. What playback speed or speeds did you find the most suitable to follow the dataset and why?
4. What changes did you notice in the quality of the sonifications when the speed was changed?
5. Could you please describe any details that you were able to hear at faster playback speeds that were not obvious at slower speeds?
6. Could you please describe any details that you were able to hear at slower playback speeds that were not obvious at faster speeds?
7. Please describe any overall patterns that you were you able to hear?
8. Can you please give your opinion about the aesthetics of the sonification?
9. Please can you give your opinion about the pitch range of the sonification playback and whether it was clear enough for you to follow the different asteroid collisions?
10. Did you hear the larger asteroid collisions as lower or higher in pitch?
11. How large do the Asteroids appear to be within the sonification?
12. What other sonic attributes did you notice within the sonification?
13. Please can you describe any variation of the spatial location of the sound?
14. Did this movement help or hinder your ability to discern details from the dataset?
15. What was the optimal speed to interpret the movement?
16. How easy was it to imagine that you are listening to colliding asteroids in Exosolar asteroid belt?
17. What was the optimal speed to allow you to listen to colliding asteroids?
18. To what extent does the sonification help you imagine what is occurring within the asteroid belt?
19. How would you describe the sound of the ‘asteroid collisions’?

20. What do you associate with when you hear the ‘Asteroid Collisions’ and what do you imagine when listening to this sound?

21. Could you please elaborate on whether you found the sound design of the ‘Asteroid Collisions’ pleasing or displeasing?

22. Can you please describe whether the differences in the sonic aesthetics help to distinguish different details about the data set?

23. What other characteristics helped you to determine the data from the sonification?

24. What changes do you think could be made to improve the sound of the sonification?

25. How do you think the sonification could be altered to help you gain a deeper understanding of the data?

26. Can you please describe whether the sonification has given you any new insights regarding the data?

27. Could you please describe what you like about the sonification?

28. Could you please describe what you dislike about the sonification?

29. Can you please describe any improvements that could be made to the sonification?

30. How would you could you use this tool in your daily work?

31. Do you have any comments that you would like to add?